STATE OF CLIMATE ACTION 2021

Systems Transformations Required to Limit Global Warming to 1.5°C

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Systems Transformations Required to Limit Global Warming to 1.5°C

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Please cite as: Boehm, S., K. Lebling, K. Levin, H. Fekete, J. Jaeger, R. Waite, A. Nilsson, J. Thwaites, R. Wilson, A. Geiges, C. Schumer, M. Dennis, K. Ross, S. Castellanos, R. Shrestha, N. Singh, M. Weisse, L. Lazer, L. Jeffery, L. Freehafer, E. Gray, L. Zhou, M. Gidden, and M. Gavin. 2021. *State of Climate Action 2021: Systems Transformations Required to Limit Global Warming to 1.5°C*. Washington, DC: World Resources Institute: https://doi.org/10.46830/wrirpt.21.00048.

ACKNOWLEDGEMENTS

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

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PUBLISHED UNDER THE SYSTEMS CHANGE LAB, THIS REPORT IS a joint effort between the High-Level Climate Champions, Climate Action Tracker, ClimateWorks Foundation, the Bezos Earth Fund, and World Resources Institute.

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

- The High-Level Climate Champions, Nigel Topping and Gonzalo Muñoz, provided critical thought leadership and guidance, as did several members of their team, including Jen Austin, Frances Way, Steve Martineau, Sarah Goodenough, Matthew Phillips, Olga Galin, and Eden Cottee-Jones.
- The report benefited not only from ClimateWorks Foundation's financial support but also from the work of its Global Intelligence team, Dan Plechaty and Surabi Menon, who were pivotal in conceiving the idea for the analysis and provided guidance throughout the research and writing process.
- Pankaj Bhatia, Helen Mountford, and Rhys Gerholdt from WRI, Louise Jeffery, Niklas Höhne, and Takeshi Kuramochi from NewClimate Institute, and Matthew Gidden and Bill Hare from Climate Analytics provided valuable conceptual inputs, review, and strategic guidance.
- Aleh Cherp, Paul Drummond, Michael Grubb, Dmitri Kucharavy, Simon Sharpe, and Laura Malaguzzi Valeri provided valuable expertise to help inform the S-curves methodology.

We thank our reviewers who have shared their expertise and insights: Shimon Anisfeld, Jon Baines, Ignace Beguin, Federico Bellone, Lori Bird, Robert Boyd, Caroline Bryant, Victoria Burrows, Zachary Byrum, Robin Chase, Kieran Coleman, Victoria Cuming, Ed Davey, Rebecca Dell, Haldane Dodd, Daniel Fahey, Lauren Gifford, Dheeraj Kumar Gupta, Joo Hyun Ha, Karl Hausker, Liesbeth Huisman, Angela Hultberg, Norma Hutchinson, Bharath Jairaj, Alex Joss, Aki Kachi, Fridolin Krausmann, Dan Lashof, Haley Leslie-Bole, Todd Litman, Rui Luo, Steve Martineau, Jacob Mason, Nikola Medimorec, Seth Monteith, Erika Myers, Natalie Nehme, Clay Nesler, Sanna O'Connor-Morberg, Peder Osterkamp, Sandeep Pai, Katharine Palmer, Nikita Pavlenko, Liqing Peng, Maria Potouroglou, Peter Psarras, Rachel Ramage, Taylor Reich, Tristan Smith, Fred Stolle, Bella Tonkonogy, Francesco Tubiello, Stan Turner, Frances Wang, David Waskow, Benjamin Welle, Debbie Weyl, Michael Wolosin, Karl Zammit-Maempel, Daniel Zarin, and Jessica Zionts.

While the contributions from reviewers are greatly appreciated, the views presented in this paper are those of the authors alone.

The authors are grateful to WRI colleagues Emily Matthews, Laura Malaguzzi Valeri, Gregory Taff, and Carlos Muñoz Piña for their research advice and guidance. We also wish to acknowledge 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, Abby Sharp, and Yuke Kirana. We received communications and outreach support from Rhys Gerholdt, Sarah Goodenough, Matthew Phillips, Cindy Baxter, Anthony Yazaki, Lauren Zelin, Helen Morgan, and Mollie Freeman.

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

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FROM DOING BETTER TO DOING ENOUGH

How much action against climate change is enough?

COMBATTING THE CLIMATE CRISIS requires us to rapidly transform the systems that propel our economy, including power generation, buildings, industry, transport, land use, and agriculture—as well as the immediate scale-up of technological carbon removal. But by how much? And how can decision-makers unlock the transformational change that is required?

The *State of Climate Action 2021*, published under the Systems Change Lab, answers these fundamental questions. The report identifies 40 indicators across key sectors that must transform to address the climate crisis, and assesses how current trends will impact how much work remains to be done by 2030 and 2050 to deliver a zero-carbon world in time. It also outlines the required shifts in supportive policies, innovations, strong institutions, leadership, and social norms to unlock change.

The encouraging news is that we are seeing a number of bright spots. For example, wind and solar power have experienced exponential growth over the past two decades, and sales of electric vehicles have also increased rapidly since 2015. Time and time again, the exponential growth of such innovations have outpaced analysts' projections. But these changes didn't come out of nowhere. They were nurtured—by supportive policy and regulatory environments, by investments, by leadership that came together to improve technologies, reduce costs, and ramp up adoption, creating economies of scale in which change becomes, we hope, inevitable and unstoppable.

At the same time, the hard truth is that for many other transformations, action is incremental at best, and headed in the wrong direction altogether at worst. In fact, none of the 40 indicators this report assessed are

on track to reach our 2030 targets. For instance, to meet targets that align with limiting warming to 1.5 degrees Celsius the world must—among other actions—phase out unabated coal electricity generation five times faster than current trends, accelerate the increase of annual gross tree cover gain three times faster, and boost crop productivity nearly two times faster.

The rapid transformations we need will require significant financial investments, technology transfer, and capacity-building, especially for developing countries. While climate finance continues to increase, it remains far from sufficient. The report finds that climate finance needs to increase thirteen times faster to meet the estimated $5 trillion needed annually by 2030. As leaders continue to grapple with the COVID-19 pandemic, it is essential, then, that stimulus packages not only address the current health and economic crises, but also steer trillions of dollars toward investments to build a net-zero economy. The good news is that the economic and social benefits of taking bold climate action are enormous.

The *State of Climate Action 2021* arms countries, businesses, philanthropy, and others with a clear-eyed view on the state of systems transformation for climate action and what supportive measures, from public policies to technological innovations to behavior changes, will enable us to get there. We know that there is no silver bullet to realizing the change we need; instead, we need to put in place the necessary puzzle pieces for catalyzing and sustaining change. And while the scale of the required transition is unprecedented, history has shown that when we all pull together—governments, corporations, and citizens—the seemingly impossible becomes within reach. At COP26 and beyond we need leaders to make a true step change in their own ambition and accelerate us toward a safer, prosperous and more equitable future. But we must not only do better. We must do what it takes.

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EXECUTIVE SUMMARY

Highlights

- Limiting global warming to 1.5°C requires far-reaching transformations across power generation, buildings, industry, transport, land use, coastal zone management, and agriculture, as well as the immediate scale-up of technological carbon removal and climate finance. This report translates these transitions into 40 targets for 2030 and 2050, with measurable indicators.
- Transformations, particularly those driven by new technology adoption, often unfold slowly before accelerating after crossing a tipping point. Nearly a quarter of indicators assessed focus on new technology adoption, with some already growing exponentially. This report considers such nonlinear change in its methodology.
- The transitions required to avoid the worst climate impacts are not happening fast enough. Of the 40 indicators assessed, none are on track to reach 2030 targets. Change is heading in the right direction at a promising but insufficient speed for 8 and in the right direction but well below the required pace for 17. Progress has stagnated for 3, while change for another 3 is heading in the wrong direction entirely. Data are insufficient to evaluate the remaining 9.
- This report also identifies underlying conditions that enable change—supportive policies, innovations, strong institutions, leadership, and shifts in social norms. Annual increases in finance for climate action, for example, must accelerate 13-fold to meet the estimated need in 2030.

The need for transformational change

This decade is our make-or-break opportunity to limit warming to 1.5°C and steer the world toward a net-zero future. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) shows that limiting global temperature rise to 1.5°C by the end of the century is still possible, but it will require rapid, immediate, and economy-wide greenhouse gas (GHG) emissions reductions, as well as the removal of carbon from the atmosphere. Near-term actions to halve GHG emissions by 2030 must be pursued alongside longer-term strategies to achieve deep decarbonization by 2050. Should we fail to act now and GHG emissions continue to rise unabated, warming could climb to between 3.3°C and 5.7°C above preindustrial levels by the end of the century—temperatures that would bring catastrophic and inequitable impacts to communities and ecosystems around the world, beyond anything seen so far (IPCC 2021).

The decisions made today will determine the severity of climate change impacts that will affect us all for decades to come. Many countries have submitted more ambitious nationally determined contributions (NDCs), as well as long-term low-emissions development strategies. An increasing number of nonstate actors, including companies, cities, regions, and financial institutions, have also pledged to reduce GHG emissions, for example, through the Race to Zero campaign of the United Nations Framework Convention on Climate Change (UNFCCC) High-Level Climate Champions. It is critical that, at COP26 and beyond, all decision-makers begin transforming these commitments into action.

At this critical time, decision-makers are also grappling with the highly unequal impacts of the COVID-19 pandemic. As some countries begin to focus on rebuilding their communities and economies, their recovery efforts will shape the global economy for decades to come. It is essential, then, that these stimulus packages not only address the current health and economic crises but also disrupt the carbon lock-in that is common to nearly all economic sectors by steering trillions of dollars toward investments in a net zero-carbon, just future. Fortunately, a growing body of evidence shows that green stimulus investments can deliver more jobs and better growth than investing in the traditional carbon-intensive economy (IEA 2020j; IFC 2021; Jaeger et al. 2021). But an understanding of what different sectors can and should contribute to curbing GHG emissions through midcentury will be needed to guide this transition to a low-carbon, more resilient society.

We're not starting from a standstill—recent years have witnessed notable progress, despite relatively low levels of overall ambition and investments. Already, we have seen increasingly dynamic action occur within a handful of sectors, across some regions, and from individual companies, cities, states, investors, and civil society organizations, all proving that faster-than-expected progress is possible. For example, several low-emissions technologies, including wind and solar power, have grown in a nonlinear fashion over the past two decades, and sales of electric vehicles (EVs) have also increased rapidly since 2015. These innovations have all benefited from supportive measures—early investments in research and development, favorable policies, and leadership from key public and private sector decision-makers, for example—that helped drive improvements in performance, reductions in price, and subsequently, increased adoption. And these bright spots show us what's possible when decision-makers deploy the many tools at their disposal to accelerate the transition to a net-zero future.

But much more could be achieved if all decision-makers around the world gave climate action the high priority it is due. Globally, climate action to date has largely failed to spur the rapid, far-reaching transformations needed across all sectors to avoid the worst impacts of global warming. In some industries, the technologies, practices, and approaches needed to accelerate decarbonization are well understood but have not yet seen the levels of investment and political support needed to rapidly scale up mitigation action. In others, innovations needed to catalyze systemwide transitions are still at relatively early stages in their development and are not yet ready to displace emissions-intensive incumbents. All hands are urgently needed on deck to speed up this progress, as well as expand it to all sectors and regions.

Accelerating these transformations to mitigate climate change also offers an opportunity to create a more equal world. But to realize these benefits, policies must be designed with equity and a just transition in mind. It will be essential, for example, to tackle the challenges faced by workers and communities whose livelihoods are tied to high-carbon industries. Promising examples of just transition initiatives are emerging around the world. These must become widespread to ensure that the costs and benefits of these transformations are equitably distributed.

Our ever-shrinking carbon budget does not accommodate delay. To reach a net-zero future, we must ignite fundamental change across nearly all systems, from how we move around the world and build cities to how we grow food and power industry. These systemwide transitions will depend on the massive scale-up of finance, technology, and capacity building for countries that need support.

About this report

This report from the Systems Change Lab is a joint effort of the High-Level Climate Champions, Climate Action Tracker (CAT, an independent analytic group comprising Climate Analytics and the NewClimate Institute), ClimateWorks Foundation, the Bezos Earth Fund, and World Resources Institute. It provides an overview of how we are collectively doing in addressing the climate crisis. Taking stock of change to date is critical for informing where best to focus our attention and change our future course of action. The report begins with an explanation of transformational change to frame the evaluation of progress. It then assesses the pace 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 and avoid the worst climate impacts. 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.

The report builds upon and updates previous assessments (Lebling et al. 2020; CAT 2020b). It identifies targets and associated indicators for power, buildings, industry, transport, technological carbon removal, land and coastal zone management, agriculture, and finance that the literature suggests are the best available to monitor sectoral decarbonization pathways. Designed to be compatible with limiting global warming to 1.5°C, these targets for each sector were developed by the CAT consortium, WRI, and the High-Level Climate Champions based on the Marrakesh Partnership Climate Action Pathways and the Race to Zero campaign's 2030 Breakthroughs (UNFCCC Secretariat 2021b; Race to Zero 2021a).

This year, we added 18 new targets and indicators to Lebling et al. (2020), bringing the total to 40. The report also improves upon the methodology from the previous assessment to consider the potential of exponential change across some sectors and, accordingly, updates the rating categories. It also identifies financing needs to support the transformations, and considers how the transitions needed can be approached in a just and equitable manner.

The report aims to support decision-makers in government, companies, investing firms, and funding institutions who are considering how to accelerate climate action. A secondary audience is subject experts who support these decision-makers in strengthening implementation of existing commitments and increasing ambition.

Key findings

While numerous countries, cities, and companies have committed to step up mitigation, 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. Progress on reducing GHG emissions, as well as removing carbon dioxide (CO_2) from the atmosphere, is uneven across indicators in power, buildings, industry, transport, technological carbon removal, land use, coastal zone management, agriculture, and finance.

While national progress varies, we assess indicators at the global level as follows (Figure ES-1).

FIGURE ES-1. Assessment of 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 **8 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 **17 indicators**, the rate of change is heading in the right direction at a rate well below the required pace to achieve their 2030 targets.

STAGNANT: Change is stagnating, and a step change in action is needed

For **3 indicators**, the rate of change has stagnated.

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

For **3 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 **9 indicators**, data are insufficient to assess the rate of change relative to the required action.

FIGURE ES-1. Assessment of progress toward 2030 targets (continued)

TRAJECTORY OF CHANGE — ACCELERATION FACTOR

Exponential Likely

Because they track technology adoption directly, these indicators are most likely to follow an S-curve. Our assessment relies on the literature and expert judgment.

1.8x 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.

1.5x 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" as shorthand for various forms of rapid, non-linear change. But not all non-linear change will be perfectly exponential.

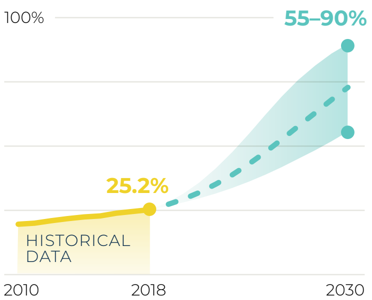
ON TRACK: Change is occurring at or above the pace required to achieve the 2030 targets

None

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

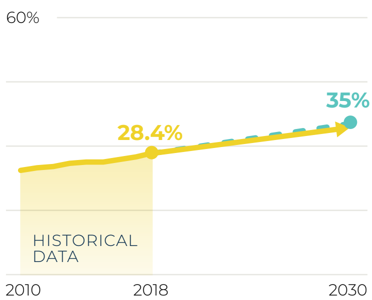
POWER N/A

Increase the share of renewables in electricity generation to 55–90%



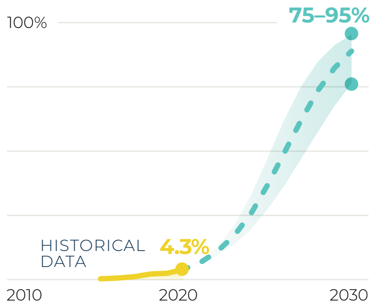
INDUSTRY 1.1x

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



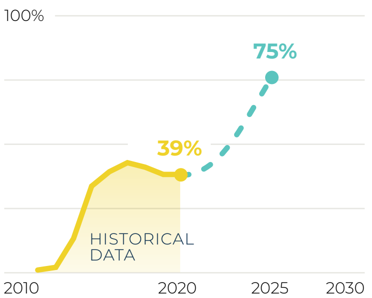
TRANSPORT N/A

Increase the share of electric vehicles to 75–95% of total annual light-duty vehicle sales



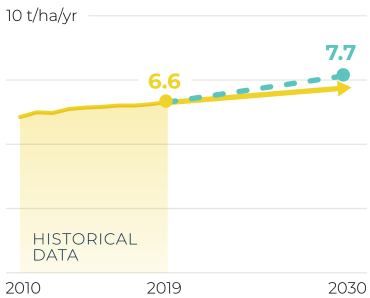
TRANSPORT N/A[a]

Boost the share of battery and fuel cell electric vehicles to reach 75% of global annual bus sales by 2025



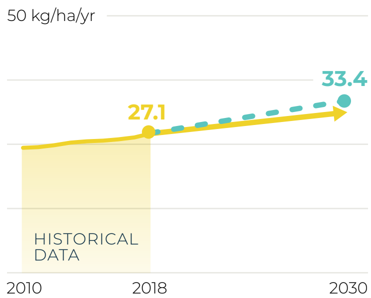
AGRICULTURE 1.9x

Increase crop yields by 18%, relative to 2017



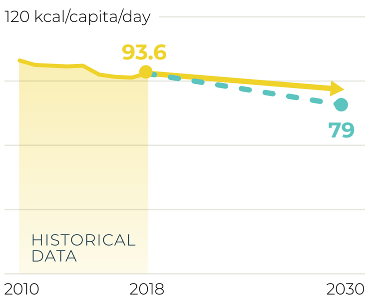
AGRICULTURE 1.6x

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



AGRICULTURE 1.5x

Reduce ruminant meat consumption in high-consuming regions to 79 kcal/capita/day by 2030[b]



FINANCE 1.1x

Phase out public financing for fossil fuels, including subsidies, by 2030, with G7 countries and international financial institutions achieving this by 2025[c]

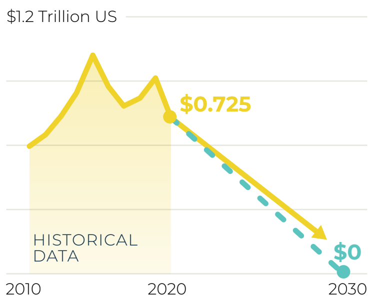
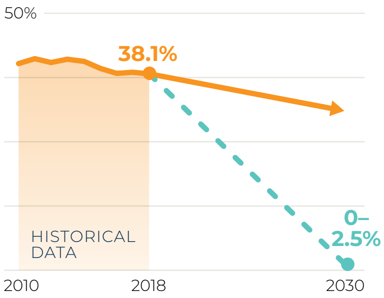


FIGURE ES-1. Assessment of progress toward 2030 targets (continued)

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

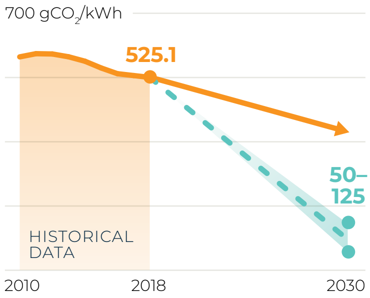
POWER 5.2x

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



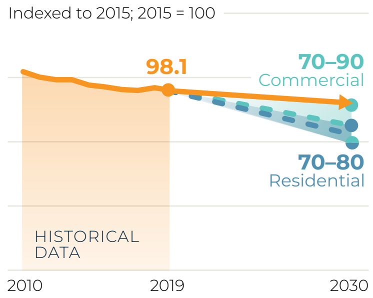
POWER 3.2x

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



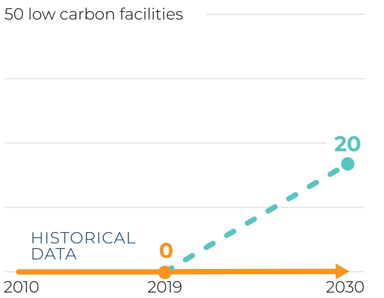
BUILDINGS 2.7x[d]

Decrease the energy intensity of operations in key countries and regions by 20–30% in residential buildings and by 10–30% in commercial buildings, relative to 2015



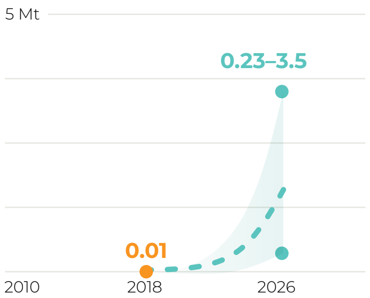
INDUSTRY Ins. data[e]

Build and operate 20 low-carbon commercial steel facilities, with each producing at least 1 million tonnes annually



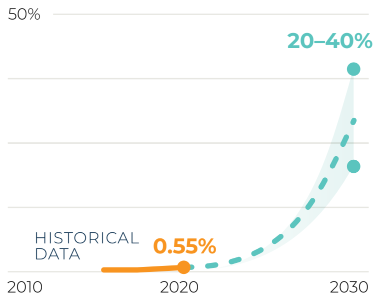
INDUSTRY N/A

Boost green hydrogen production capacity to 0.23–3.5 Mt (25 GW cumulative electrolyzer capacity) by 2026



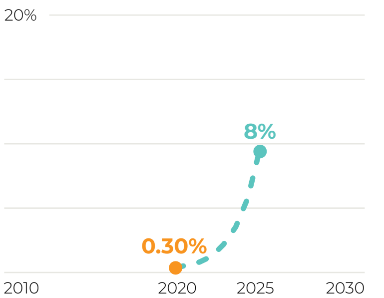
TRANSPORT N/A[f]

Expand the share of electric vehicles to account for 20–40% of total light-duty vehicle fleet



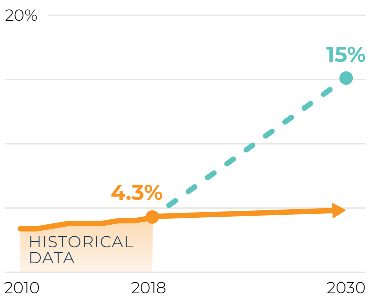
TRANSPORT N/A

Increase the share of battery and fuel cell electric vehicles to 8% of global annual medium- to heavy-duty vehicle sales by 2025



TRANSPORT 12x

Raise the share of low-emissions fuels in the transport sector to 15%



TRANSPORT N/A

Increase sustainable aviation fuel's share of global aviation fuel supply to 10%

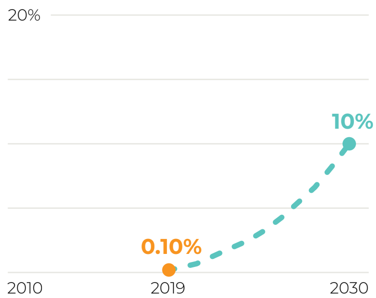
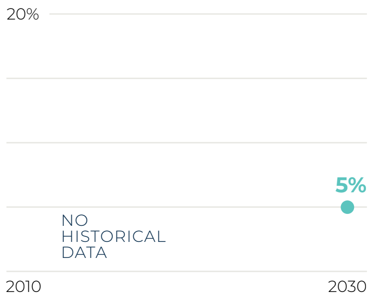


FIGURE ES-1. Assessment of progress toward 2030 targets (continued)

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

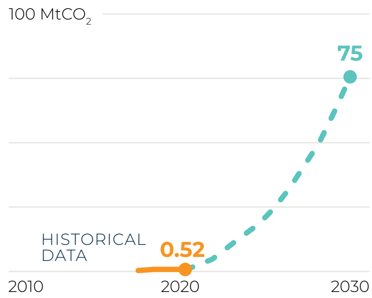
TRANSPORT N/A

Raise zero-emissions fuel's share of international shipping fuel to 5%



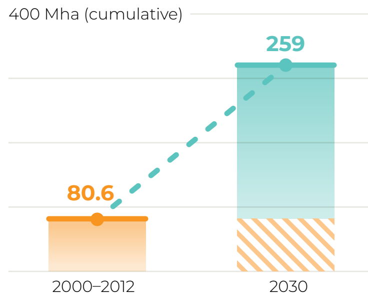
TECHNOLOGICAL CARBON REMOVAL N/A

Scale up technological carbon removal to 75 $MtCO_2$ annually



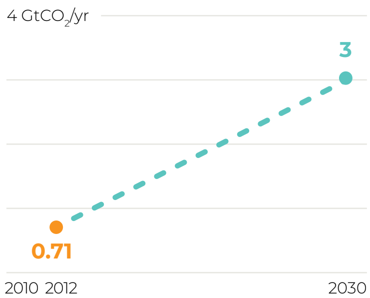
LAND USE AND COASTAL ZONE MANAGEMENT 3.2x[g]

Reforest 259 Mha of land, relative to 2018[h]



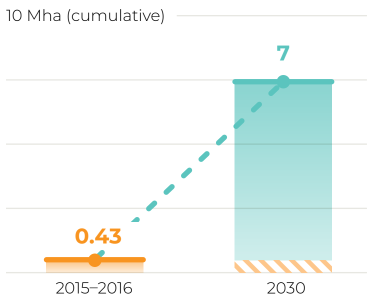
LAND USE AND COASTAL ZONE MANAGEMENT 4.2x[g]

Remove 3.0 $GtCO_2$ annually through reforestation



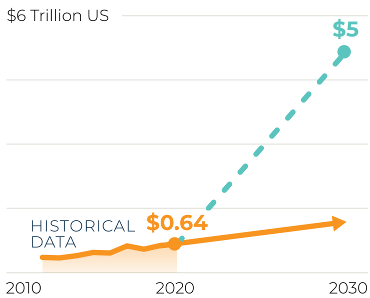
LAND USE AND COASTAL ZONE MANAGEMENT 2.7x[g]

Restore 7 Mha of coastal wetlands, relative to 2018[h]



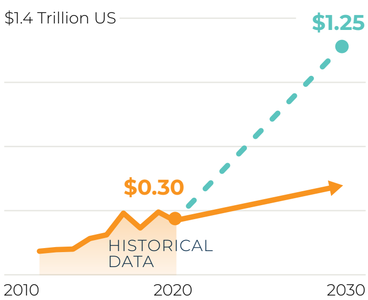
FINANCE 13x

Increase total climate finance flows to $5 trillion per year



FINANCE 5x

Raise public climate finance flows to at least $1.25 trillion per year



FINANCE 23x

Boost private climate finance flows to at least $3.75 trillion per year

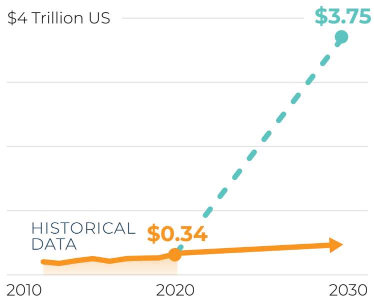
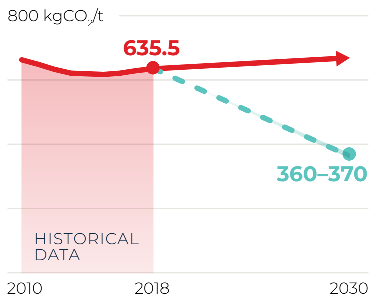


FIGURE ES-1. Assessment of progress toward 2030 targets (continued)

STAGNANT: Change is stagnating, and a step change in action is needed

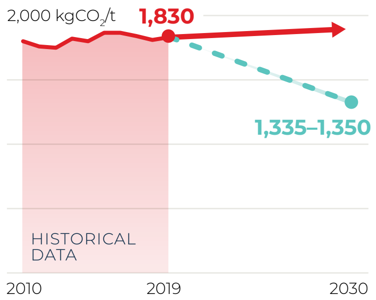
INDUSTRY N/A

Reduce carbon intensity of global cement production by 40%, relative to 2015



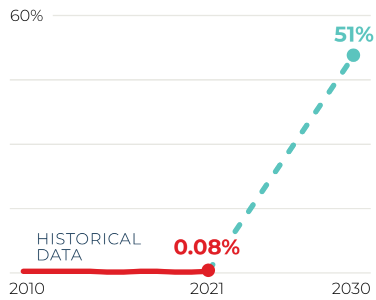
INDUSTRY N/A

Reduce carbon intensity of global steel production by 25–30%, relative to 2015



FINANCE N/A

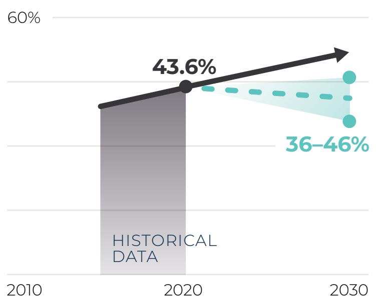
Ensure that a carbon price of at least \$135/tCO_2e covers the majority of the world's GHG emissions



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

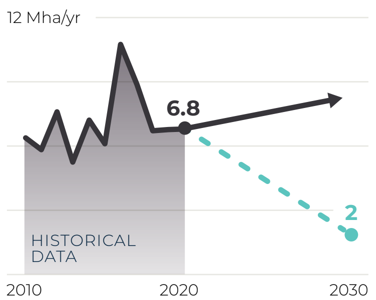
TRANSPORT N/A

Reduce the percentage of trips made by private light-duty vehicles to between 4% and 14% below BAU levels



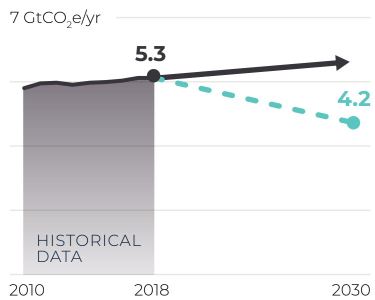
LAND USE AND COASTAL ZONE MANAGEMENT N/A

Reduce the rate of deforestation by 70%, relative to 2018



AGRICULTURE N/A

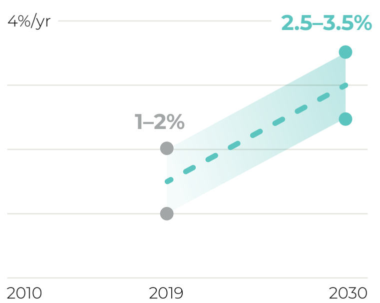
Reduce agricultural production emissions by 22%, relative to 2017



INSUFFICIENT DATA: Data are insufficient to assess the gap in action required for 2030[i]

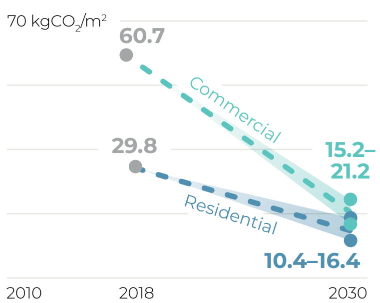
BUILDINGS Ins. data

Increase buildings' retrofitting rate to 2.5–3.5% annually



BUILDINGS Ins. data

Reduce the carbon intensity of operations in select regions by 45–65% in residential buildings and by 65–75% in commercial buildings, relative to 2015 (kgCO_2/m²)



TRANSPORT Ins. data

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

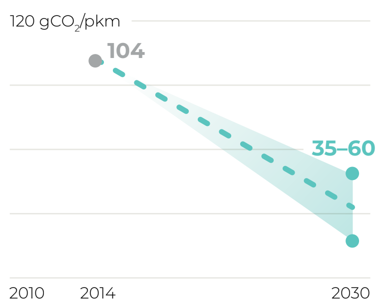
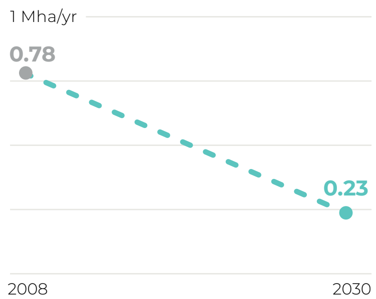


FIGURE ES-1. Assessment of progress toward 2030 targets (continued)

INSUFFICIENT DATA: Data are insufficient to assess the gap in action required for 2030[i]

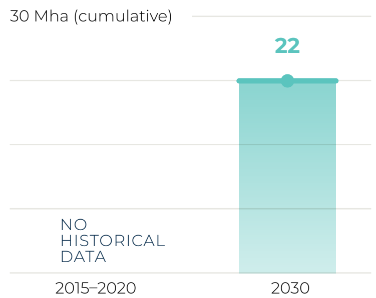
LAND USE AND COASTAL ZONE MANAGEMENT — Ins. data

Reduce degradation and destruction of peatlands by 70%, relative to 2018[h]



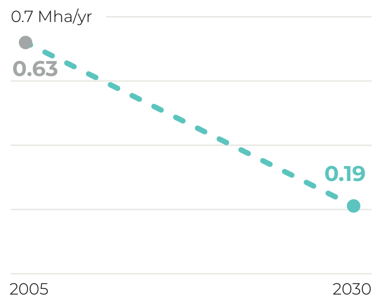
LAND USE AND COASTAL ZONE MANAGEMENT — Ins. data

Restore 22 Mha of peatlands, relative to 2018



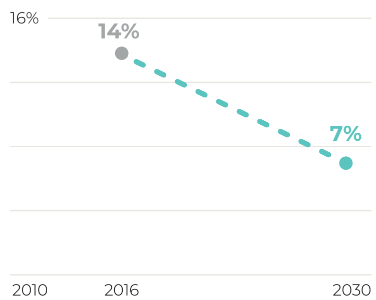
LAND USE AND COASTAL ZONE MANAGEMENT — Ins. data

Reduce the conversion of coastal wetlands by 70%, relative to 2018[h]



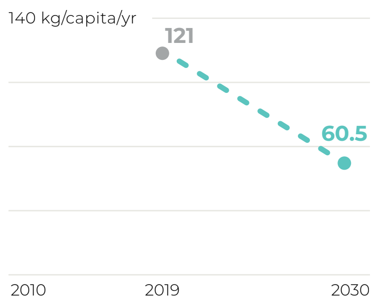
AGRICULTURE — Ins. data

Reduce share of food loss by 50%, relative to 2016



AGRICULTURE — Ins. data

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



FINANCE — Ins. data

Jurisdictions representing three-quarters of global emissions mandate TCFD-aligned climate risk reporting, and all of the world's 2,000 largest public companies report on climate risk in line with TCFD recommendations

Note: BAU = business as usual; n/a = not applicable; EV = electric vehicle; LDV = light-duty vehicle; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle; MHDV = medium- and heavy-duty vehicle; kg/ha/yr = kilograms per hectare per year; kcal/capita/day = kilocalories per capita per day; gCO_2/kWh = grams of carbon dioxide per kilowatt-hour; Mt = million tonnes; GW = gigawatts (billion watts); Mha = million hectares; $GtCO_2$/yr = gigatonnes (billion tonnes) of carbon dioxide per year; t/ha/yr = tonnes per hectare per year; $kgCO_2$/t = kilograms of carbon dioxide per tonne; tCO_2e = tonnes of carbon dioxide equivalent; $GtCO_2e$ = gigatonnes (billion tonnes) of carbon dioxide equivalent; $kgCO_2/m^2$ = kilograms of carbon dioxide per square meter; gCO_2/pkm = grams of carbon dioxide per passenger kilometer; TCFD = Task Force on Climate-Related Financial Disclosures; G7 = Group of 7 countries.

a BEV/FCEV buses have grown nonlinearly in China but have not yet taken off elsewhere. They already make up 39 percent of global bus sales due to the strong sales in China.

b This indicator is only applicable in regions where ruminant meat consumption is above the 60 kcal/capita/day target for 2050.

c While consumption subsidies have been declining in recent years, which has led to the overall decrease, production subsidies have continued to increase (OECD 2021a). Furthermore, part of the fall in consumption subsidies is due to declining oil prices, which fell substantially as a result of the pandemic (IEA 2020h). If oil prices rise again, absent further reforms, consumption subsidies are likely to increase.

d The acceleration factor refers to the full range of the targets across commercial and residential buildings, because historical data are not available for the two building types separately.

e The indicator is marked as "well off track" because while no low-carbon steel facilities are currently in operation, 18 are expected to be operational by 2030. Of these 18 projects, data on production capacity are only available for 4, all of which meet the production criteria of at least 1 million tonnes annually. However, data are insufficient to calculate an acceleration factor.

f The nonlinear historical growth in EV stock is coming from a very low base, and is only due to rapid growth in the share of EV sales, with little progress on the removal of internal combustion engine vehicles from the road.

g For indicators with targets defined against a baseline year and with limited data availability, we use the average annual rate of change across the most recently available time period (e.g., 2000–2012) to estimate the annual rate of change during the target's baseline year (e.g., 2018), and we calculate the future rate of change required to reach the 2030 target against this estimated baseline year rather than the most recent year of data.

h Targets for 2030 and 2050 are derived from Roe et al. (2019) and Griscom et al. (2017), which define them against the baseline year of 2018. But for some targets, data are not available for 2018. We, therefore, use the most recently available data point (e.g., 80.6 Mha in 2012) or the most recently available annual average (e.g., an average of 0.78 Mha of peatlands lost per year from 1990-2008) to estimate the indicator's value in 2018.

i Although some have one historical data point and/or qualitative research that shows they are not on track, these indicators do not have enough information to assess how much recent progress must accelerate to achieve their 2030 targets. Accordingly, we classify them as having "insufficient data."

Source: Authors' analysis based on data sources listed in each chapter; see Appendix C for the methodology used to design targets and the literature from which they are derived.

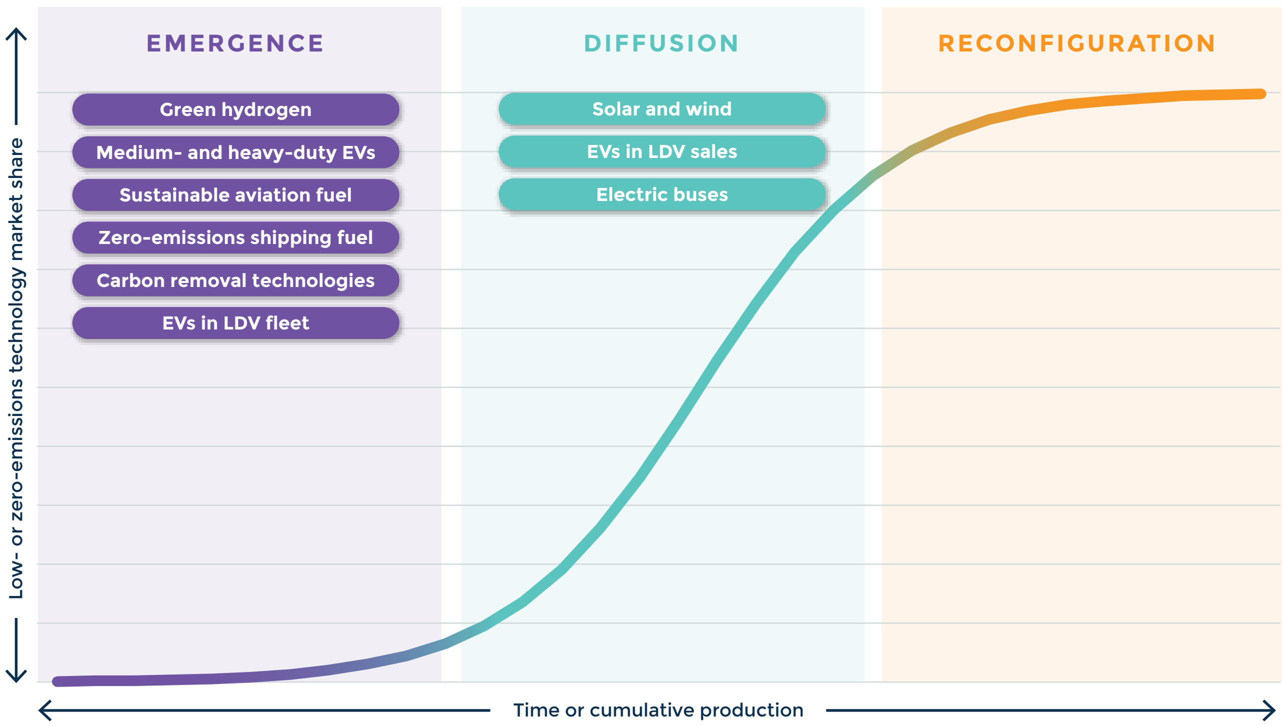
How we assess different trajectories of future change

In evaluating progress of indicators, we consider the likelihood that they will experience exponential change in the future, and we group indicators into three categories that correspond to these expected trajectories. Note that we are using the term *exponential* as shorthand for various types of rapid, nonlinear growth. Not all of this nonlinear change will be perfectly exponential.

Exponential change likely. Past transitions, particularly those driven by the advent and widespread adoption of new technologies (e.g., the automobile, radio, and the smartphone), have often followed an S-curve trajectory of growth: rates of change are initially quite low as entrepreneurs develop new technologies, then accelerate as these innovations begin to diffuse across society. After growth reaches its maximum speed, it eventually slows down as it approaches a saturation point. A wide range of positive, self-amplifying feedbacks, such as achieving economies of scale or the advent and adoption of complementary technologies, often play a significant role in accelerating such transformations (Victor et al. 2019). Nine of the indicators in this report directly track the adoption of innovative technologies and, therefore, have a good chance of following S-curve dynamics. Adoption of some of these technologies, such as solar and wind power and EVs, has grown at a rapid, nonlinear pace in several countries already. For others, it's too early to tell if they will experience nonlinear growth, as they are still within the emergence phase of their development and have limited data (Figure ES-2). All indicators have the potential to take off quickly, but following an S-curve is not guaranteed for any technology. It is critical, then, that decision-makers across the private and public sectors provide the right support—investments in research and development, a regulatory environment that supports adoption, and strong institutions to enforce these policies, for example—to help these technologies reach the diffusion stage, cross positive tipping points, and rapidly displace emissions-intensive incumbents.

At these initial stages, it is impossible to predict the path of an S-curve with any level of certainty, but it is also inaccurate to ignore the potential for rapid, nonlinear change for some indicators assessed in this report. Recognizing this tension,

FIGURE ES-2. Illustration of the stages of S-curve progress for low-carbon technologies



Note: EV = electric vehicle; LDV = light-duty vehicle. These labels include technologies that are directly tracked by our nine indicators that may follow an S-curve.
Source: Authors' judgment, based on Victor et al. (2019) and ETC (2020).

we use expert judgment informed by the nascent literature on low-carbon technology S-curves to categorize progress in these nine indicators, with the understanding that this is an initial step in developing more rigorous methods to assess nonlinear change.

- **Exponential change unlikely.** Other indicators, such as those that focus on deforestation, coastal wetlands restoration, or cropland productivity, track activities and practices and are not as closely related to technology adoption and are unlikely to experience rapid, nonlinear change. To assess progress for these 22 indicators, we calculate the historical linear rate of change over the most recent five years of available data (or in some cases slightly longer or shorter due to data limitations) and compare this current rate of change to the linear rate of change required to reach 2030 targets. For those with historical rates of change that are heading in the right direction but at insufficient speeds, we calculate acceleration factors, which show how much the historical linear pace of change must accelerate to achieve the 2030 target.

- **Exponential change possible.** Finally, nine indicators do not fall neatly within the first two categories. These indicators are dependent on some element of technology adoption, albeit in a more indirect way than indicators that could follow an S-curve. They often depend on both technology and other factors, such as activities, practices, and demand patterns. For example, reducing the carbon intensity of building operations requires not only the increased adoption of renewable heating and cooling technologies but also energy efficiency improvements. For these indicators, we calculate the acceleration factors needed, but if and when rapid, nonlinear change begins, progress may unfold at significantly faster rates than expected and the gap between the existing rate of change and required action may decline.

Data gaps

Our assessment also makes data gaps apparent. Nearly a quarter of the indicators assessed lack sufficient, publicly accessible data to categorize global progress, with major gaps in the buildings, land, and agriculture sectors (Box ES-1).

BOX ES-1. A call for improved, accessible data

Accessible, comprehensive, and high-quality data offer the following advantages:

1. **Well-informed decisions.** A robust knowledge base that makes the status of climate action, as well as its benefits and costs, transparent and allows policymakers, companies, and investors to make evidence-based decisions.
2. **Clarity regarding the required direction, scale, and pace of climate action.** Many initiatives, including this report, illustrate that progress needs to accelerate rapidly to avoid the worst climate impacts. The more accurate the data underpinning these analyses, the clearer our understanding of where shifts are accelerating, stalling, or lagging behind will be, and the better we can highlight good examples of what's working and why.
3. **An effective and inclusive global stocktake.** The global stocktake called for in the Paris Agreement is a key tool to increase ambition over time. For this process to be effective and inclusive, all Parties and observers need access to data. Information behind paywalls and data gaps will hinder a transparent discussion and make it more difficult to challenge countries to ratchet up their climate mitigation targets.

Sectoral takeaways

Power

- Share of renewables in electricity generation (%)
- Carbon intensity of electricity generation (gCO_2/kWh)
- Share of unabated coal in electricity generation (%)

- Electricity and heat production account for a third of global GHG emissions (ClimateWatch 2021).
- Decarbonization will be achieved by increasing the share of renewables, particularly wind and solar, in electricity generation, as well as through the complete phaseout of coal-fired power and significant reduction of gas-fired supply. In addition, power grids and storage will need to be extended and adapted to sustain the high supply of variable power generation.
- Many countries, particularly advanced economies, have already made progress in reducing the carbon intensity of electricity generation. However, although headed in the right direction, the recent rate of decline (of –11 grams of carbon dioxide per kilowatt-hour [gCO_2/kWh] per year in 2014–18) is far from what is needed to achieve the 2030 target for this sector.

Current levels of 525 gCO_2/kWh (IEA 2020d) should fall to 50–125 gCO_2/kWh by 2030 and to below zero by 2050 to align with the Paris Agreement's 1.5°C goal. Achieving those targets will require rates of decline in carbon intensity of electricity generation three times faster than we currently see.

- Renewable sources of power are now the generation technologies of choice, accounting for 82 percent of new capacity installed in 2020. The share of global electricity generation from solar and wind, in particular, has grown at a rate of 15 percent per year over the last five years. Building new solar and wind energy capacity is now more cost-effective than generating electricity from existing coal-fired power plants in most places (IRENA 2021b).
- By 2021, 165 countries had set national renewable capacity and/or generation targets, and 161 countries had adopted policies to achieve these goals, including regulatory and pricing instruments such as feed-in tariffs, premium payments, renewable portfolio standards for utilities, net metering and billing, and renewable power tenders and auctions (REN21 2020).
- Despite very promising signs, it appears that growth in renewables must still accelerate. The share of renewables in electricity generation is currently about 29 percent in 2020 for all renewables and needs to reach 55–90 percent by 2030 and 98–100 percent by 2050.
- At the same time, the share of unabated coal in electricity generation, currently at 38 percent, must fall to 0–2.5 percent by 2030. We are well off track to achieve this target. Recent rates of decline in coal generation must accelerate by a factor of five if we are to achieve our 2030 target.
- Despite progress in some developed countries and new commitments to reduce coal capacity, worldwide coal buildout has not sufficiently slowed in recent years. In 2020, for example, newly installed coal capacity still outpaced retirements (Global Energy Monitor 2021a). More worryingly, 180 gigawatts (GW) of coal-fired capacity is under construction and another 320 GW has been announced, received a prepermit or a permit, for a total of around 500 GW in development globally. And even as governments, businesses, and banks are committing to accelerating the transition to clean energy, coal plants continue to receive finance—to the tune of US$332 billion since the Paris Agreement was adopted in 2015 (BankTrack 2021).

Buildings

!	Energy intensity of building operations (% change indexed to 2015, for which 2015 equals 100)
?	Carbon intensity of building operations ($kgCO_2/m^2$)
?	Retrofitting rate of buildings (%/yr)

- Buildings are responsible for 5.9 percent of global GHG emissions (ClimateWatch 2021).[1]
- The building sector is highly diverse; decarbonization trends vary greatly among regions and so do the required actions to reduce the sector's emissions.

- Although emissions intensities have decreased when averaged across the world, the pace of this improvement is insufficient to counteract increases in floor area and, therefore, reduce total emissions to reach the targets for this indicator. Through a transition to zero-carbon energy sources and highly efficient building envelopes, the carbon intensity of residential and commercial building operations in select regions needs to decrease quickly—by 65–75 percent (commercial) and by 45–65 percent (residential) below 2015 levels by 2030 and to zero by 2050—to be aligned with a 1.5°C-compatible pathway.
- Globally, energy intensity of buildings decreased by 19 percent from 2000 to 2015 and another 2 percent by 2019 (IEA 2020a). But declines in energy intensity have slowed in recent years and need to accelerate again to fully meet the targets. Recent rates of decline need to accelerate by a factor of three in the next decade: falling to between 10 and 30 percent below 2015 for commercial buildings and between 20 and 30 percent below 2015 for residential buildings by 2030. Reductions in energy demand of new buildings can be achieved by improving the efficiency of appliances and equipment (e.g., cooking stoves, electrical equipment, lighting, and equipment for heating and cooling) and by reducing the heating and cooling demand of buildings by improving the building design and envelope. Smart controls further limit energy demand and alleviate the risk of wasteful user behavior.
- Directly related to energy and emissions intensity improvements, retrofitting the building stock is a major requirement to enable the building sector to get on a 1.5°C-compatible pathway. By 2050, all buildings should be energy efficient and designed to meet zero-carbon standards. To that end, the retrofitting rate needs to increase from about 1–2 percent today to 2.5–3.5 percent per year in 2030, and to 3.5 percent in 2040. Retrofitting is more important where most of the building stock that will exist in 2050 has already been built; this includes most European countries, the United States, Canada, Japan, and Australia, but also, and increasingly, China (Liu et al. 2020).

Industry

- Share of electricity in the industry sector's final energy demand (%)
- Low-carbon steel facilities in operation (# of facilities)
- Green hydrogen production (Mt)
- Carbon intensity of global cement production (kgCO_2/t cement)
- Carbon intensity of global steel production (kgCO_2/t steel)

- GHG emissions from industry have grown the fastest of any sector since 1990 (Ge and Friedrich 2020). Direct emissions from industrial processes, as well as from manufacturing and construction, account for 18.5 percent of global GHG emissions (ClimateWatch 2021). Heavy industry is often characterized as "hard-to-abate," but some solutions are readily available and can lead to cost savings.
- As the largest energy-consuming sector, industry requires high temperatures for many of its processes and so is highly dependent on fossil fuels for its energy consumption. For some applications, this dependence can be reduced through a shift to electric technologies coupled with a decarbonization of the power sector.
- Over the last five decades, the share of electricity in the industry sector's final energy demand has slowly increased through the introduction of electricity-dependent technologies, including digitalization, automation, and machine drive (McMillan 2018; IEA 2017b). Electricity demand rose from 15 percent of industry's energy demand in 1971 to about 28 percent in 2018. To follow a 1.5°C-compatible pathway, industry needs to adopt electric technologies that can push this share to 35 percent in 2030, 40–45 percent in 2040, and 50–55 percent in 2050. Such a trajectory suggests an average annual growth rate of 0.6 percentage points between 2018 and 2030, and 0.9 percent between 2030 and 2050, compared to a historical average growth rate of 0.5 percent.
- Two heavy industries—steel and cement production—account for more than half of direct GHG emissions from the industry sector (ClimateWatch 2021). Although the cement industry has made improvements over time, for example in energy efficiency and increasing the share of supplementary cementitious materials, the carbon intensity of cement has declined slowly and even increased during the last three years. There are about nine categories of novel cements under

development, with various emissions reduction potentials and limitations. Some could only marginally reduce carbon intensity, while others actively sequester carbon (Material Economics 2019; Lehne and Preston 2018). But without investments or large-scale demonstration projects, most novel cement technologies have yet to enter the market. And even when they do, carbon capture and storage (CCS) will likely still be needed to decarbonize cement production. For this industry to follow a 1.5°C-compatible pathway, the carbon intensity of cement needs to decrease 40 percent below 2015 levels by 2030 and 85–91 percent, with an aspiration to reach 100 percent, by 2050 (CAT 2020a; CAT 2020b).

- For a 1.5°C-compatible pathway, the carbon intensity of steel will need to decline 25–30 percent below 2015 levels by 2030 and 93–100 percent by 2050. Between 2010 and 2019, the carbon intensity of steel increased slightly, but achieving these targets will require a steep drop in the coming years. Encouragingly, the number of announced low- and zero-carbon steel projects has increased rapidly, from 1 in 2016 to 23 in 2020 to 45 as of August 2021. By 2030, 18 full-scale projects are planned to be operational. Although still uncertain, a maintained pace in low- and zero-carbon steel announcements could indicate the emergence of a nonlinear trend.
- In addition to electrification, green hydrogen—a zero-carbon fuel produced through water electrolysis powered by renewable energy—can help decarbonize hard-to-abate industrial sectors by replacing fossil fuels. Still in its early phases of development, green hydrogen accounts for less than 0.1 percent of current production (IEA 2019b). Scenarios aligned with limiting global temperature rise to 1.5°C suggest that hydrogen will supply 15–20 percent of the world's final energy demand by 2050. Recent analysis from the Energy Transitions Commission estimates that this equates to a total annual hydrogen demand of 500–800 million tonnes (Mt)—a massive increase from today's levels (ETC 2021b). Large-scale demonstration projects are being developed in the European Union, Australia, Saudi Arabia, and South Korea (COAG Energy Council 2019; European Commission 2020a; Stangarone 2021; Robbins 2020). Multistakeholder partnerships, such as HyDeal Ambition and the Green Hydrogen Catapult, are also helping to create an enabling environment for green hydrogen.

Transport

- Share of EVs in LDV sales (%)
- Share of BEVs and FCEVs in bus sales (%)
- Share of EVs in the LDV fleet (%)
- Share of BEVs and FCEVs in MHDV sales (%)
- Share of low-emissions fuels in the transport sector (%)
- Share of SAF in global aviation fuel supply (%)
- Share of ZEF in international shipping fuel supply (%)
- Share of trips made by private LDVs (%)
- Carbon intensity of land-based transport (gCO_2/pkm)

- Transport accounts for 16.9 percent of global GHG emissions (ClimateWatch 2021) and is the fastest growing source of emissions after industry (Ge and Friedrich 2020).
- Decarbonization will be achieved by avoiding the need to travel; shifting travel toward more efficient, less carbon-intensive modes of travel, such as public transport, walking, and cycling; and improving the carbon-intensity of the remaining travel modes with new technologies, such as EVs and cleaner fuels.
- Historically, due to the preponderance of investments and policies that prioritize motor vehicles, the percentage of people who use private motor vehicles as their primary mode of transportation has increased worldwide. To be aligned with the Paris Agreement, the percentage of trips by private light-duty vehicles needs

to be reduced by up to 8 percent from current levels by 2030, whereas projections suggest trends are headed in the wrong direction altogether.

- The carbon intensity of land-based transport needs to fall from 104 grams of carbon dioxide per passenger kilometer (gCO_2/pkm) in recent years to 35–60 gCO_2/pkm by 2030 and near zero by 2050. Achieving this benchmark will require different approaches fit for purpose in individual countries and their existing transport mix.
- EV sales have been growing rapidly, reaching 4.3 percent of global light-duty vehicle sales in 2020 and growing at a compound annual growth rate of 50 percent from 2015 to 2020. Over 20 countries have committed to completely phasing out the sale of internal combustion engine (ICE) passenger vehicles by or before 2040. And several companies, including General Motors, Volkswagen, Volvo, and BMW have committed to launching new EV models, investing in battery research and development, and limiting or eliminating ICE production entirely (Race to Zero 2021b). These are promising signs, but it does appear that growth in EV sales must accelerate. The EV share of light-duty vehicle sales is currently about 4 percent and needs to reach 75–90 percent by 2030 and 100 percent by 2035. Similarly, the share of EVs in the light-duty vehicle fleet is 0.6 percent today and needs to grow to 20–40 percent by 2030 and 85–100 percent by 2050 to be aligned with the Paris Agreement's goals. Key actions for increasing sales of EVs include decreasing battery prices, developing charging infrastructure, and implementing supply- and demand-side policies to incentivize EV adoption. Setting ICE phaseout dates, electrifying corporate and government fleets, managing electricity demand to support increasing numbers of EVs, and coordinating the preowned ICE vehicle market will prove critical to shifting the overall vehicle stock.
- Regarding electric buses, in 2020, the share of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) in global bus sales was 39 percent. This strong level of demand comes primarily from China, where sales of these types of buses were almost 50 percent higher than sales of fossil fuel equivalents (BloombergNEF 2020a). To be aligned with the Paris Agreement's 1.5°C temperature goal, the share of BEVs and FCEVs in global bus sales would need to reach 75 percent by 2025, and in leading markets, they would need to hit 100 percent by 2030. With no other country in the world coming close to China's advanced position in the transition away from fossil fuel buses, urgent intervention will be required in other countries, particularly in leading markets, such as the European Union, Japan, and the United States.
- In 2020, the share of BEVs and FCEVs in global sales of medium- and heavy-duty vehicles (MHDVs)[2] was 0.3 percent (BloombergNEF 2021a). As with buses, the bulk of global demand in 2019 came from China, which accounted for 60 percent of total sales. Europe accounted for 23 percent of sales. To be aligned with the Paris Agreement's 1.5°C temperature goal, the share of BEVs and FCEVs in global MHDV sales would need to reach 8 percent by 2025, and in leading markets, they would need to hit 100 percent by 2040. With BEVs constituting such a small percentage of total current sales, there is an urgent need to bring these technologies to commercial maturity and stimulate their adoption across the world if this transport subsector is to achieve 1.5°C compatibility.
- In addition to modal shifts and EVs, low-emissions fuels will need to start rapidly displacing fossil fuels to reach a 15 percent share by 2030, climbing to between 70 percent and 95 percent by 2050. Low-carbon electricity, which is considered a low-emissions fuel, will play a critical role in decarbonizing newly purchased passenger vehicles, while there is also potential for advanced biofuels to reduce emissions from the existing stock of fossil fuel vehicles. Over the medium and long term, hydrogen and synthetic fuels made with hydrogen are likely to be required to decarbonize harder-to-abate transport emissions from the shipping, aviation, and long-distance land freight sectors.
- Sustainable aviation fuel (SAF)—a well-researched, partially developed low-carbon solution—offers a viable medium-term contribution to a decarbonization pathway for aviation. Today, SAF comprises under 0.1 percent of the global aviation fuel supply. However, experts project that global SAF uptake will need to reach 10 percent by 2030 and 100 percent by 2050 to drive the decarbonization of aviation (Race to Zero 2021b). A diverse portfolio of both supply- and demand-side measures will be necessary to lower costs, accelerate development, and promote widespread uptake of this technology.

Technological carbon removal

Rate of technological carbon removal ($MtCO_2$ removed/yr)

- Reducing GHG emissions is essential and should be a top priority, but it is not enough to avoid the worst impacts of climate change. We will also need to pull carbon out of the air to deal with excess CO_2 already in the atmosphere and to counterbalance emissions that will be very difficult to mitigate in coming decades (e.g., long-haul aviation).
- Carbon removal includes natural approaches, like tree planting or restoring wetlands, as well as technological solutions like direct air capture; both will play critical roles in a broader carbon removal portfolio.
- The amount of technological carbon removal needed by 2050 depends on the level of decarbonization reached by midcentury, as well as the amount of carbon removed through natural solutions, among other things. Considering the Paris-compatible scenarios assessed by the IPCC that meet sustainability criteria set out in Fuss et al. (2018), removal of around 4.5 gigatonnes (billion tonnes) of carbon dioxide ($GtCO_2$) per year by technological methods may be needed by 2050 (roughly equivalent to the combined emissions of Japan and India), with an interim target of 75 million tonnes of carbon dioxide ($MtCO_2$) per year in 2030 (IPCC 2018) (roughly equivalent to the GHG emissions of Austria in 2018) (ClimateWatch 2021).[3] The amount of CO_2 removed and stored through these approaches today is a fraction of a percent of what will be needed, but recent project announcements and federal and private investment point to growing momentum.
- Government investment in research, development, and demonstration (RD&D) is needed to develop entirely new carbon removal approaches and refine proposed and existing ones to help optimize technologies and bring down costs. Bright spots exist: in the United States, for example, federal investment in direct air capture RD&D has increased from around a total of $10 million between 2009 and 2019 to $43 million in 2020 alone. Additionally, supportive policies can incentivize deployment in a variety of ways: reducing investment or operating costs, creating regulation that enhances certainty for project development, reducing financing costs, or providing incentives to procure certain products, among others.
- Corporate commitments and investments in carbon removal technology have increased in the past few years. Companies like Microsoft and Amazon have pledged to reduce their own emissions and have also invested in carbon removal projects to help them reach net-zero and even net-negative emissions for Microsoft. Other companies, like the financial services provider Stripe, not only have pledged to purchase tonnes of carbon removal but also have provided upfront investments to support project development.
- Enabling infrastructure, such as CO_2 pipelines, geological storage, and abundant renewable and zero-carbon energy to power carbon removal projects, is also critical to scaling up carbon removal technology.
- While dedicated storage in underground geologic formations maximizes net carbon removal, building up the market for products made with captured CO_2 can help compensate for high capture costs in the near term.
- As a nascent suite of approaches, carbon removal technologies must be developed in a way that acknowledges and minimizes environmental and social risks and uncertainties.

Land use and coastal zone management

Reforestation (cumulative Mha)

Rate of carbon removal from reforestation ($GtCO_2$ /yr)

Coastal wetlands restoration (cumulative Mha)

Deforestation rate (Mha/yr)

Peatlands conversion rate (Mha/yr)

Peatlands restoration (cumulative Mha)

Coastal wetlands conversion rate (Mha/yr)

- Land is both a major source of emissions and a major natural carbon sink (Roe et al. 2019; IPCC 2019; Griscom et al. 2017; Searchinger et al. 2019; IPCC 2018). Between 2007 and 2016, annual net CO_2 emissions from land use and land-use change were approximately 5.2 ± 2.6 $GtCO_2$ (IPCC 2019).
- Improved protection, restoration, and sustainable management of forests, peatlands, and coastal wetlands are essential for limiting warming to 1.5°C by the end of the century. A top priority is to stop the loss of these critical ecosystems and then increase restoration.

- To be aligned with the Paris Agreement, the rate of deforestation needs to decline 70 percent by 2030 and 95 percent by 2050, relative to 2018. Instead, it has been heading in the wrong direction: annual deforestation and associated emissions have risen since 2010. More than 96 percent of deforestation since 2001 has occurred in the tropics, where the vast majority of forest loss is driven by conversion to agriculture, with much of the production destined for international markets (WRI 2021c). Some of the world's most important landscapes for biodiversity and carbon, humid tropical primary forests specifically (Barlow et al. 2007; Gibson et al. 2011; Berenguer et al. 2014; Harris et al. 2021), have been lost at an alarming rate. The rate of losses within these forests has remained around 3 million hectares (Mha) per year since record keeping began in 2002, and increased by 12 percent between 2019 and 2020 (WRI 2021d).
- Global reforestation efforts are also falling short—neither on track to fulfill earlier pledges nor to reach the report's target to reforest 259 cumulative Mha. On average, just 6.7 Mha of gross tree cover gain occurred annually from 2000 to 2012, a rate that will need to more than triple in the coming decade. Failure to change course this decade would put limiting global warming to 1.5°C out of reach.
- Similarly, although data are largely insufficient to assess the gap in required action, efforts to protect and restore the world's carbon-rich peatlands are also falling short. An estimated 15 percent of peatlands have been drained for agriculture, plantation forestry, and other uses, with the most recent conversion occurring in tropical regions (Griscom et al. 2017). Limiting warming to 1.5°C would require reducing annual rates of peatland degradation 70 percent by 2030 and 95 percent by 2050. Additionally, peatlands restoration across 22 cumulative Mha (roughly the area of Guyana) is estimated to be needed by 2030 to align with global climate goals (Griscom et al. 2017; Roe et al. 2019).
- The world loses an estimated 0.63 Mha of coastal wetlands annually—an area roughly half the size of Vanuatu (Griscom et al. 2017). But achieving Paris-compatible targets will require this historical rate of loss to drop sharply, reaching 0.19 Mha in 2030 and 0.03 Mha in 2050. Restoration of these highly productive, carbon-rich ecosystems, which include mangrove forests, salt marshes, and seagrass meadows, is also needed to limit global warming to 1.5°C. Restoring 7 cumulative Mha of coastal wetlands by 2030 could enable these ecosystems to begin sequestering 0.2 $GtCO_2$ annually by 2030 (Roe et al. 2019; Griscom et al. 2017). Protecting and restoring mangrove forests, salt marshes, and seagrass meadows would also generate a wide range of co-benefits: improving water quality protecting shorelines from erosion, safeguarding coastal communities from sea level rise and storm surges, and providing nursery grounds for fisheries.

Agriculture

—	Crop yields (t/ha/yr)
—	Ruminant meat productivity (kg/ha/yr)
—	Ruminant meat consumption in the Americas, Europe, Oceania (kcal/capita/day)
⇩	Agricultural production GHG emissions ($GtCO_2e$/yr)
?	Share of food production lost (%)
?	Food waste (kg/capita/yr)

- The agriculture sector is responsible for 12 percent of global GHG emissions, and up to a quarter of global GHG emissions when also considering those from associated land-use change (IPCC 2019).
- Limiting global warming to 1.5°C will depend, in large part, on peaking and then reducing agriculture's global land footprint, even as food demand continues to grow. Doing so entails sustainably intensifying agricultural production through boosting both crop and livestock productivity, as well as changing food consumption patterns, including reducing food loss and waste and shifting diets high in ruminant meat toward plant-based foods.
- The agriculture sector will also need to peak and then lower agricultural production emissions—including those from livestock, fertilizers, rice production, and energy use—by 22 percent by 2030 and 39 percent by 2050. While the emissions intensity of agricultural production is steadily falling, absolute agricultural production emissions continue to rise, pointing to a need to increase funding for emissions mitigation in agriculture.

- Crop yields per hectare need to increase by 18 percent by 2030 and 45 percent by 2050 to avoid further cropland expansion, necessitating a near-doubling of the recent rate of yield growth—even as climate impacts intensify. Yet recent global yield growth masks wide variation among regions, and yields in sub-Saharan Africa remain very low, warranting particular attention. Similarly, ruminant meat production per hectare of pasture also needs to rise—by 27 percent by 2030 and 58 percent by 2050—and while productivity is growing, progress between now and 2030 needs to be 1.6 times faster than in recent years. Programs to support productivity improvements—whether of cropland or pastureland—should be linked whenever possible to policies that support forest or other ecosystem protection.
- The world's rate of food loss and waste needs to be halved by 2030. Recent estimates suggest that 14 percent of global food produced was lost between the farm and the retail stage of the supply chain in 2016, while 17 percent of the food available at the retail level was wasted (in retail, households, or food service) in 2019. While some countries, most notably the United Kingdom and the Netherlands, have had early success in reducing food loss and waste at the national level, data availability needs to improve to track progress at the global scale.
- Production of ruminant meats, such as beef, goat, and sheep meat, is both land- and GHG-intensive. If ruminant meat consumption in high-consuming countries declined by 2050 to the equivalent of 1.5 burgers per person per week, it would significantly reduce agricultural land demand and GHG emissions. Across the Americas, Europe, and Oceania, per capita ruminant meat consumption has already receded from its peak, declining to about 2.3 burger-equivalents per person per week in 2018. However, to reach 2030 and 2050 targets, the rate of decline in consumption across these regions would need to accelerate by 1.5 times the rate in recent years, allowing room for modest growth in countries where meat consumption is currently low.

Finance

—	Total public financing for fossil fuels (billion $)
!	Total climate finance (billion US$)
!	Public climate finance (billion $)
!	Private climate finance (billion $)
✕	Share of global emissions covered by a carbon price of at least $135/tCO_2e (%)
?	Corporate climate risk disclosure

- Underlying all of these transitions is the availability of sufficient finance from both public and private sources.
- Total global flows of climate finance reached $640 billion in 2020, an average increase of $33.6 billion per year over the previous five years (CPI 2021). By comparison, total global investment in fossil fuels was estimated at $726 billion in 2020 (IEA 2021f), 13 percent more than all tracked climate finance.
- The amount of global climate finance would need to increase nearly eightfold to reach the target of at least $5 trillion per year by 2030, an average increase of $436 billion a year between 2020 and 2030. This is 13 times the historical rate of increase. To meet such goals, based on available data, annual increases in public climate finance would need to accelerate fivefold, and yearly gains in private climate finance would need to accelerate 23 times faster by 2030 to meet their respective shares of the total climate finance needed.
- Finance must also be aligned with Paris temperature goals by phasing out public financing for fossil fuels, pricing carbon, and disclosing and managing climate-related finance risks.
- Over 250 financial institutions collectively responsible for more than $80 trillion in assets have committed to interim and long-term goals to reach net-zero portfolios no later than 2050 under the Glasgow Financial Alliance for Net Zero (Carney 2021). Meeting these commitments could help align finance flows with climate objectives.
- Many companies and financial institutions have endorsed or adopted recommendations related to disclosure, but data are currently insufficient to assess the extent to which governments' and companies' risk reporting meets the indicator target.
- In 2021, carbon pricing through a carbon tax or an emissions trading scheme (ETS) covered 21.5 percent

of global CO_2e emissions, a significant increase from the 2020 coverage of 15.1 percent, largely due to China's launch of a national ETS (World Bank 2021b). However, prices in the majority of schemes remain insufficient to fully account for the costs associated with rising GHG emissions; nor do they provide the right price signal for a 1.5°C pathway. If carbon pricing is to make a meaningful contribution to climate action, both its scope and level would need to be significantly increased.

- Governments also need to show leadership in phasing out public finance for fossil fuels. Fossil fuel consumption subsidies have declined in recent years, but production subsidies and state-owned entities' investments in fossil fuels have continued to rise.

These systemwide transitions to a net-zero future will generally increase equity and improve outcomes for vulnerable communities, which are already disproportionately impacted by climate change. However, they can also create winners and losers. The benefits of decarbonization may not always be equitably shared, and some transformations that reduce emissions could have disproportionate negative impacts on poor or disadvantaged populations, or those whose livelihoods are tied to a fossil fuel–intensive future (IPCC 2018; Markkanen and Anger-Kraavi 2019). Prioritizing equity and justice across the required transformations, then, is not only a moral imperative but also essential to build and sustain public support for climate action, and to make those actions more effective (Levin et al. 2012; World Bank 2021c). Such efforts to ensure a just transition must be part of decarbonization strategies from the start.

Fortunately, momentum to build a just transition is already growing. A relatively small but growing number of just transition commissions have been established and are dedicated to strengthening inclusive dialogue among key stakeholders and supporting affected communities and workers, including in Canada, the European Union, Scotland, and the U.S. states of Colorado and New York (Environment and Climate Change Canada 2018; European Commission 2021a; Scottish Government 2021; CDLE 2021). Momentum toward a just transition is also building across sectors and levels of government. Some countries, such as Chile, South Africa, and Indonesia, have incorporated the just transition into their NDCs or national economic development strategies, while in others, notably India and Morocco, subnational just transition initiatives and grassroots campaigns have emerged to ensure that local communities can benefit from large-scale renewable energy projects (Athawale et al. 2019; Burton et al. 2019; Elliott and Setyowati 2020; Swilling et al. 2016; Tongia et al. 2020; Zhang and Wang 2018; WRI 2021i). This is starting to bring much-needed attention to the challenges and opportunities that are prevalent in developing country contexts, which may include a lack of social safety nets, a higher prevalence of informal work, and rising rates of urbanization or industrialization. However, across all countries, significant and additional effort is need to ensure that the transition to a net-zero future is both equitable and just.

Enablers of climate action

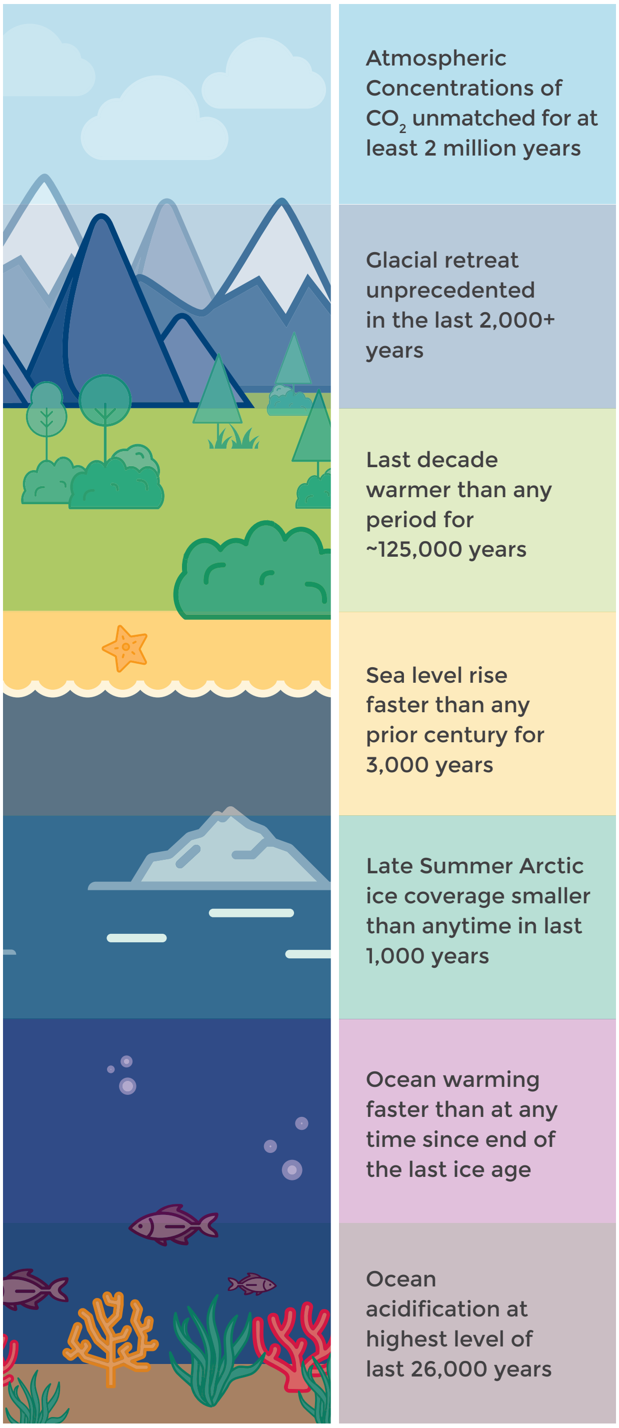
For each set of targets, this year's report also provides a snapshot of what conditions would enable us to achieve these sector targets and help keep warming below 1.5°C. These include supportive policies, innovations in technology, strong institutions, leadership from key change agents, and shifts in social norms. The report highlights priority actions that can support transformational change across all systems. It also outlines measures that, if implemented, can help make these transitions more just and equitable.

The IPCC's Sixth Assessment Report is clear that the window for staying below 1.5°C of global warming, which avoids the most catastrophic levels of warming, is closing faster than we had realized. However, we have a fighting chance of realizing this safer world. The scale and pace of change required can be achieved through urgent, concerted, collaborative action.

SNAPSHOT OF A CHANGING CLIMATE

In 2020, global average temperature tied with 2016 for the highest level in the modern record: 1.25°C (2.25°F) warmer than preindustrial levels (NASA 2021).[4] Record-high upper ocean temperatures were also reached in 2020 (Cheng et al. 2021). And 2021 is shaping up to easily fall within the top 10 warmest years in recorded history (NOAA 2021).

FIGURE 1. Evidence of climate change already underway



Note: CO_2 = carbon dioxide.
Source: IPCC (2021).

IN ITS MOST RECENT REPORT, *CLIMATE CHANGE* *2021: The Physical Science Basis*, the Intergovernmental Panel on Climate Change (IPCC) finds that the scale of these changes is unprecedented in recent history (Figure 1). There is now more than a 50 percent chance that 1.5°C will be reached or exceeded between 2021 and 2040 (IPCC 2021). Whether we limit warming to this level and prevent the most severe climate impacts will depend on the actions that we take this decade.

While greenhouse gas (GHG) emissions fell significantly as governments around the world implemented emergency measures to slow the spread of COVID-19 (fossil fuel carbon dioxide [CO_2] emissions in 2020 were 7 percent below 2019 levels), we are now witnessing a reversal as some countries begin to lift their temporary pandemic restrictions (Le Quéré et al. 2021). And although COVID-19 recovery packages have somewhat increased global investments in clean energy, total amounts still fall well below what is needed to meet climate goals, and many countries are still channeling far too much stimulus spending into the emissions-intensive, business-as-usual economy (IEA 2020h). New policy choices, then, are urgently needed if we are to embrace a more sustainable pathway forward and avoid the worst impacts of climate change.

To have a good chance of limiting global temperature rise to 1.5°C above preindustrial levels with no or limited overshoot, the world must halve global GHG emissions by 2030 and reach net-zero CO_2 by midcentury.[5] The sooner these emissions peak and the lower they are when they peak, the greater the likelihood of reaching net zero in time. Achieving these deep emissions reductions will require rapid, far-reaching transitions of unprecedented scale across nearly all major sectors—power, buildings, industry, transport, land use, coastal zone management, and agriculture—as well as the immediate scale-up of technological carbon removal to compensate for the significant proportion of the carbon budget that we have already spent down and residual emissions that are difficult to eliminate altogether (IPCC 2018). More specifically, each of these global systems must transform from one that delivers critical, yet highly unequal services to society, while releasing increasingly dangerous levels of GHGs, to one that more equitably provides the same services to a rapidly growing population, while rapidly bending our GHG emissions trajectories downward (Box 1).

This report highlights a critical set of shifts for each system that, together, will help accelerate the transformations required to avoid the worst climate change impacts. It also outlines key changes needed across the global financial sector to fund these transitions. In total, 40 required shifts are identified within this report, and almost all must happen simultaneously to overcome the deep-seated carbon lock-in common to these systems (Seto et al. 2016). Transforming the global food system from its current state to one that can feed nearly 10 billion people and reduce GHG emissions, for example, will entail significant gains in cropland and livestock productivity, substantial reductions in food loss and waste, limits on the overconsumption of ruminant meat, and dramatic declines in emissions from a wide range of agricultural production processes, such as rice cultivation or chemical fertilizer application. Similarly, the transition to a new, qualitatively different transportation system

BOX 1. What is transformational change?

Calls for rapid, far-reaching transformational change have gained traction among the global climate change research community and policymakers (e.g., IPCC 2018; Sachs et al. 2019; Steffen et al. 2018; Victor et al. 2019; Otto et al. 2020; Future Earth 2020; Sharpe and Lenton 2021; IEA 2021c; Rocky Mountain Institute 2019; Mersmann et al. 2014a; Puri 2018; Independent Group of Scientists Appointed by the Secretary-General 2019; ICAT 2020; UNFCCC Secretariat 2021a; WBCSD 2021), reflecting an emerging consensus that current efforts have failed to spur deep emissions reductions at the speed and scale required to avoid the worst climate change impacts.

But while most scientists and policymakers broadly agree that transformation refers to a fundamental, systemic change, a lack of conceptual clarity persists. There is no single, widely accepted definition of this term (see Appendix A), which is often used interchangeably with transition and systems change, nor is there a shared understanding of how this process unfolds in practice (Feola 2015; Patterson et al. 2017; Few et al. 2017; Hölscher et al. 2018). At what point does large-scale change become transformational? Do these transitions follow the same trajectory? And can they be steered toward specific, desirable outcomes? Not only will different answers to these questions generate confusion when decision-makers begin implementing strategies to catalyze transformational change, but this conceptual plurality also risks rendering these powerful terms vague buzzwords that can be co-opted to describe any shift, including business-as-usual actions (Feola 2015; Few et al. 2017).

To avoid diluting these terms' utility in challenging the status quo, this report draws on commonalities across well-cited definitions in global environmental change research (see Appendix A) to conceptualize transformation, transition, and systems change as a single process—the reconfiguration of a system, including its component parts and the interactions between these elements, such that it leads to the formation of a new system that produces a qualitatively different outcome. Put simply, all terms describe a shift from one system to another—for example, shifting from a shrimp pond that degrades nearby coastal ecosystems to a restored mangrove forest that sequesters CO_2 or from a transportation network of horse-drawn carriages to one dominated by automobiles. Such systems change entails "breaking down the resilience of the old and building the resilience of the new" (Folke et al. 2010).

These transitions are often demarcated from incremental changes, defined as adjustments to elements or processes within an existing system that do not fundamentally alter its essence or integrity (Few et al. 2017; IPCC 2018). New policies that increase energy efficiency, for example, can help reduce greenhouse gases emitted from the current energy system, but efforts to phase out fossil fuels represent a transition to an entirely new system that supplies energy without releasing carbon dioxide into the atmosphere. Although often conceptualized as a binary, these typologies of change are not mutually exclusive. Incremental shifts can create an enabling environment for future transformations, and in some instances, a progressive series of these lower-order changes can come together in ways that successfully trigger a transition to a new system (Levin et al. 2012; ICAT 2020; Termeer et al. 2017).

that moves people and goods around the world without increasing atmospheric concentrations of CO_2 will necessitate shifts to other forms of mobility, such as bicycling or walking, to electric vehicles, and to more sustainable fuels for shipping and aviation. It must also encompass changes in the built environment, for example, that reduce the need to travel altogether.

For each of these key shifts, this report identifies global targets, all of which are aligned with limiting global temperature rise to 1.5°C. It assesses progress toward these targets for 2030 and 2050 by calculating the historical rate of change for each target and then comparing it to the rate of change required to reach these critical targets (see more in chapter 2, "Methodology for assessing progress"). Although this quantitative analysis does not directly measure transformational change from these predominant, emissions-intensive systems to qualitatively different ones, it does provide a snapshot of progress and allows us to take stock of collective efforts, including a wide range of supportive measures, to accelerate these transitions to a net-zero CO_2 world.

Because many of these systems are interconnected (e.g., the expansion of agricultural lands drives deforestation or the amount of GHG emissions from buildings depends partly on the energy sources that power utilities use to generate electricity), small changes within the bounds of one system can have wide-ranging impacts. These effects can be positive, in some instances accelerating transitions to net-zero CO_2 emissions in other systems, protecting biodiversity, or supporting sustainable development. But they can also cause harm, creating unwanted and unintended consequences that decision-makers must manage. This report considers these interconnections in its assessment of progress by sector, identifying key co-benefits, dependencies, and trade-offs that must be addressed to ensure that transformation to a net-zero CO_2 future is sustainable. Additionally, it outlines essential components of a just transition across all systems, as well as highlights emerging examples of efforts to more equitably distribute the costs and benefits of limiting global temperature rise to 1.5°C.

METHODOLOGY FOR ASSESSING PROGRESS

The following chapter provides an update on the *State of Climate Action* (Lebling et al. 2020).

While the science indicates what is required to limit global temperature rise to 1.5°C, taking stock of global progress is needed to inform decision-making across government, civil society, and the private sector. This report presents a set of global targets with indicators that help measure progress toward transforming key sectors to lower GHG atmospheric concentrations to a level aligned with the Paris Agreement's goals. It reviews trends in recent years and assesses progress toward—or away from—sectoral climate mitigation goals established primarily for 2030 and 2050. In doing so, this report also considers where zero- and low-carbon technology adoption has the potential to experience exponential change and tracks progress accordingly.

WE HAVE CHOSEN TO ASSESS progress against 2030 and 2050 targets to inform near-term action, especially in the context of ratcheting up ambition and implementing enhanced nationally determined contributions (NDCs) during this decade, and to indicate the longer-term shifts required to support the transformation to a net-zero CO_2 world.

Design of targets and selection of indicators

The report assesses progress toward global targets in power, buildings, industry, transport, technological carbon removal, land use and coastal zone management, agriculture, and climate finance for 2030 and 2050. These benchmarks were developed by the Climate Action Tracker (CAT) consortium, the United Nations Framework Convention on Climate Change's (UNFCCC) High-Level Climate Champions based on the Climate Action Pathways of the Marrakesh Partnership, and World Resources Institute (WRI) to be compatible with limiting warming to 1.5°C (see Appendix B, "Target design by institution," for a list of which institution designed each target).[6] All are informed by the 2030 breakthrough outcomes and 2050 sector goals outlined in the High-Level Climate Champions' Race to Zero campaign focused on Sector Breakthroughs (UNFCCC Secretariat 2021a).

This report's targets are not comprehensive but rather represent a critical set of actions needed to avoid the worst climate impacts. While any choice of mitigation pathway is subjective, these indicators and targets were selected by assessing their potential contributions to GHG emissions reduction, avoidance, and removal. Both supply- and demand-side shifts, including those that promote greater efficiency, were considered. In the transportation sector, for instance, this includes transitions that reduce unnecessary vehicle travel, encourage shifts to more sustainable forms of mobility, and increase adoption of cleaner, more efficient technologies to meet remaining transport demand (e.g., electric vehicles and sustainable aviation fuels).

Targets were then established for actions with the greatest mitigation potential and with measurable indicators. Designed to represent the highest plausible ambition and to increase our chances of meeting the Paris Agreement's long-term temperature goals, these targets also take into account technology and infrastructure, as well as food security, biodiversity, and other safeguards. Finally, it is critical to note that the targets are not completely independent, since progress toward one could further another (or vice versa); for example, penetration of renewables on the electric grid would enable significant progress in decarbonizing industrial processes. See Appendix C, "Methodology for designing targets," for more detailed information.

To track progress toward these targets, indicators were selected from those that the literature suggests are among the best available to monitor these decarbonization pathways. However, as in the case of target design, the indicator selection is not comprehensive due to practical constraints, such as data limitations.

Since last year's report (Lebling et al. 2020), we have added several new targets and indicators, including those related to hard-to-abate sectors (e.g., low-carbon steel facilities, hydrogen, aviation, shipping, medium- and heavy-duty vehicles and buses), technological carbon removal, land use and coastal zone management (e.g., peatlands and coastal wetlands), as well as climate finance (see Appendix C, "Methodology for designing targets"). We have also updated several targets in line with the latest, best available science (see Appendix D, "Changes in targets and indicators between this and last year's report").

Assessment of progress toward 2030 and 2050 targets

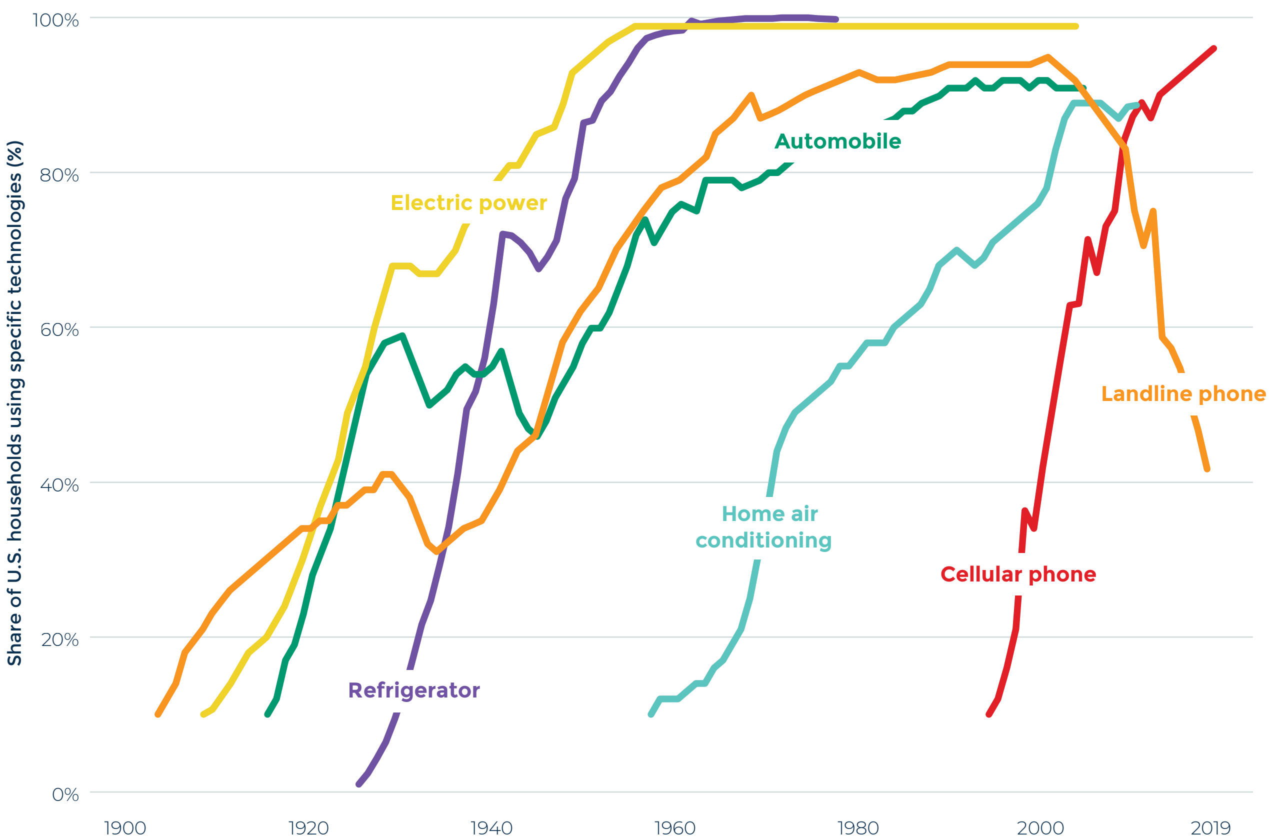
To provide a snapshot of global progress, we first collected historical data for each indicator.[7] In some cases, data limitations prevented us from assessing how the current level of effort measures up against a particular target, and this has been noted accordingly. The historical data sets included in this report are those that are open, independent of bias, reliable, and consistent.

There is often a time lag before data become available (between 1 and 3 years for most indicators assessed, but a handful lag behind by 5 to 16 years), and as such, the year of most recent data varies among indicators. Similarly, another lag between implementation of climate action and its impacts exists across indicators.

Trajectories of change: The possibility of exponential growth

Although it is difficult to predict the shape of future change, it is unlikely that all indicators will follow a linear trajectory. Past transformations, particularly those driven by the advent and widespread adoption of new technologies, have often followed an S-curve, with rates of change that are initially quite low as entrepreneurs develop new technologies, but then accelerate as these innovations begin to diffuse across society. After reaching a maximum speed, growth eventually slows down again as it approaches a saturation point (Victor et al. 2019; CAT 2019) (see Figure 2).

FIGURE 2. Historical examples of S-curves



Note: EV = electric vehicle. S-curves rarely look like a perfect S, but these historical examples provide a general framework for viewing technology adoption dynamics.
Source: Ritchie and Roser (2017).

Positive, self-amplifying feedbacks can help accelerate these transformations, driving down costs, enhancing performance of new low- and zero-emissions technologies, and increasing social acceptance (Box 2) (Arthur 1989). 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 (Sharpe and Lenton 2021). Similarly, as complementary technologies (e.g., batteries) become increasingly available, they can boost functionality and accelerate uptake of new entrants (e.g., electric vehicles). These gains allow industries for once-radical innovations 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 capital back into these new technologies (Butler-Sloss et al. 2021). These reinforcing feedbacks spur adoption and help niche innovations to supplant existing technologies (Victor et al. 2019).

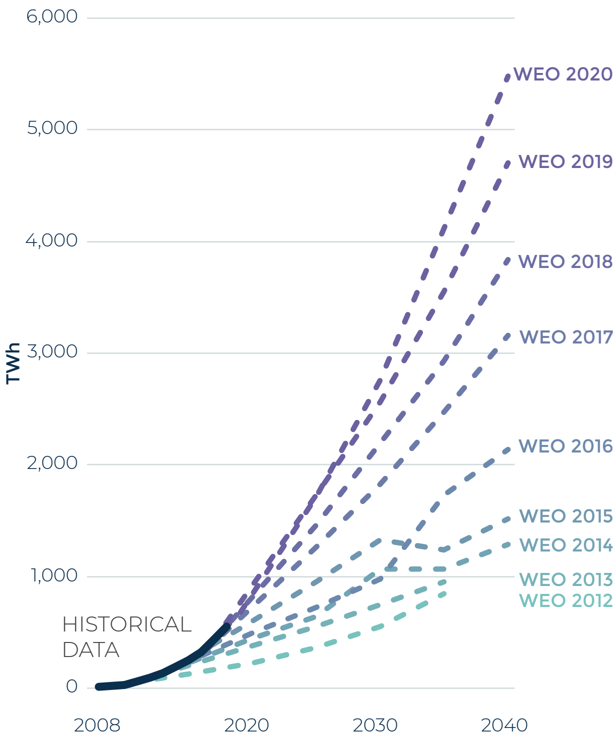
Widespread adoption of new technologies, in turn, can have cascading effects, requiring the uptake of complementary innovations, the construction of supportive infrastructure, the adoption of new policies, and the creation of regulatory institutions. It can also prompt changes in business models, availability of jobs, behaviors, and social norms, thereby creating a new community of people who may resist future 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 assume that future uptake will follow a linear trajectory (Abramczyk et al. 2017; Mersmann et al. 2014b; Trancik 2014). Yet many mainstream assessments still use linear assumptions. For example, in its Stated Policies Scenarios, the International Energy Agency (IEA) has historically assumed that future growth in solar photovoltaic (PV) generation would be largely linear, but it has had to repeatedly increase these forecasts as growth in solar PV has accelerated (Figure 3). In 2012,

BOX 2. From horse-drawn carriages to the internal combustion engine: A historical S-curve

The transition from horse-drawn carriages to gasoline-fueled cars across the United States in the late 19th and early 20th centuries provides an illustrative example of an S-curve trajectory of change. Starting in the 1880s, entrepreneurs began building "expensive toys for the rich" by adding internal combustion engines to carriages that the wealthy used for speed and long-distance racing, as well as to travel to their rural estates. In these protected niches, learning processes generated improvements in performance, particularly in horsepower, speed, power transmission, and battery storage. As automobiles' functionality improved, the middle class expanded, and the popularity of racing grew, car sales began to increase, and this growing demand prompted a decade-long effort to build more affordable, durable cars. These initiatives culminated in the advent of Henry Ford's Model T in 1908. Learning-by-doing in manufacturing, this car design led to incremental improvements in performance and reductions in cost, while new policies designed to improve public safety (e.g., licensing, speed limits, and traffic rules) strengthened social acceptance. As adoption of the automobile grew, so too did the construction of roads and the power of its lobbying group of cement, asphalt, and construction businesses, urban planners, and highway engineers. Both cities and rural communities were built to accommodate travel by cars, and over time, a car-centric culture took root in America, with automobiles becoming embedded in the average household's daily life. The car industry gained economic prominence, political influence, and private investment, eventually reconfiguring the U.S. transportation system to one dominated by the internal combustion engine (Victor et al. 2019; Geels 2005).

FIGURE 3. The International Energy Agency's Stated Policies Scenarios have not accounted for the possibility of rapid, nonlinear growth in solar photovoltaic



Note: tWh = terawatt-hour (10^{12} watt-hours); WEO = *World Energy Outlook*.
Source: Author analysis of *World Energy Outlook* reports from 2012 to 2020, all of which can be accessed through IEA (2020p).

for example, the IEA estimated that global solar energy generation would increase to 550 terawatt-hours in 2030, but that number was reached by 2018. Other institutions have similarly underestimated the path of solar and wind, such as the U.S. Energy Administration in its Annual Energy Outlook (Saha and Jaeger 2020).

In categorizing indicators for this report, we evaluate historical data, as well as the literature on S-curves, to assess the likelihood that each one will experience exponential change (Table 1). This is a key addition to this year's report, when compared to Lebling et al. (2020).

Exponential change likely: We first 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. These technologies are innovative, often displacing incumbent technologies.

Exponential change unlikely: We then identify indicators that we do not expect to follow the S-curve dynamics seen in technology diffusion, given that they do not track technology adoption in a major way. These fall primarily within the land use, coastal zone management, and agriculture sectors.

Exponential change possible: Finally, we identify indicators that do not fall neatly within the first two categories, with most tracking technology adoption indirectly. Several indicators, for example, track carbon or emissions intensity of a particular industry. While many factors, such as increases in resource efficiency, may impact changes in these indicators, adoption of zero- or low-emissions technologies may also have a considerable impact on their future trajectories. These indicators have generally experienced linear growth in the past but could potentially experience some unknown form of nonlinear, exponential growth in the future. The following sections explain our methodology for evaluating indicators that progress in two different ways: first, indicators unlikely to experience exponential change or for which exponential change is possible, given that they are indirectly tracking technology adoption, and, second, indicators likely to experience exponential change that follows S-curve dynamics, which are tracking technology adoption (see Appendix E).

TABLE 1. Expected trajectories of change for indicators

Expected trajectory of change	Reason	Method used to evaluate progress	Number of indicators	Where to find evaluations
Exponential change unlikely	Less reliant on technology	Acceleration factor	22	Table 2
Exponential change possible	Indirectly tracks technology adoption but also reflects other factors	Acceleration factor	9	Table 2
Exponential change likely	Directly tracks technology adoption	Expert judgment based on the literature	9	Table 3

Note: We are using the term *exponential* as shorthand for various types of rapid, nonlinear growth. Not all of this nonlinear change will be perfectly exponential.
Source: Authors' analysis.

Methodology for tracking progress of indicators with acceleration factors

For indicators whose future change is unlikely to be exponential or for which some exponential change is possible but in an unknown form, we use the same methodology as last year's assessment, based on linear extrapolation of historical data (Lebling et al. 2020). Accordingly, to assess progress toward the 2030 and 2050 targets, we calculate the historical linear rate of change for each indicator—over the most recent 5 years of available data (or in some cases, between 3 and 16 years due to data limitations) to assess the current rate of change—and compare that to the linear rate of change required to reach the targets for 2030 and 2050 (Table 2).[8] See Appendix F for changes in acceleration factors between Lebling et al. (2020) and this report.

In the majority of cases, the historical rate of change needs to increase to reach the targets, and to understand how much acceleration is needed, we calculate "acceleration factors" for each indicator by dividing the rate of change needed by the historical linear rate of change, which provides an indication of the gap in effort. These acceleration factors show whether the historical rate of change needs to increase 2-fold or 20-fold, for example, from the historical rate to meet 2030 targets.

We did not calculate acceleration factors needed to reach 2050 targets, primarily because some targets for 2030 are "front-loaded," such that the magnitude of change required by 2030 is significantly larger than what is needed by 2050 (e.g., deforestation). In these instances, the acceleration factors are considerably lower if calculated from the 2030 target to the 2050 target than if estimated from the most recent year of data to 2050. The latter approach would yield an acceleration factor that would indicate the pace required to achieve midcentury targets from the most recent year of data, but if decision-makers focused global efforts on achieving this acceleration factor, they would fall short of delivering the 2030 targets. For a small set of indicators (e.g., coastal wetlands restoration), the reverse is also true—the magnitude of change required to reach 2050 targets is greater than that needed to achieve 2030 targets. In these instances, we established these midcentury targets, with the assumption that the 2030 targets would be reached along the way, and note that progress must accelerate from 2030 to 2050 to stay aligned with efforts to limit global temperature rise to 1.5°C. This is a key difference from last year's report.

It is also critical to note that, for the nine indicators that may experience some unknown form of rapid, nonlinear change (i.e., those within the "exponential change possible" category), these acceleration factors form a baseline. If and when nonlinear change begins, progress may unfold at significantly faster rates than expected and the gap between the existing rate of change and required action may decline.

We then use these acceleration factors to group our indicators into six categories of progress toward 2030 targets. Proving another update to Lebling et al. (2020), we further differentiate among indicators whose historical rates of change are heading in the right direction but well below the pace required. These new classifications offer an additional level of detail, allowing those in government, the private sector, and civil society to distinguish between those indicators whose historical rate of change is close to on track from those for needing a significant increase in effort. These new categories include:

- **On track.** The recent historical rate of change is equal to or above the rate of change needed.
- **Off track.** The historical rate of change is heading in the right direction at a promising yet insufficient pace, which we define as those indicators with acceleration factors of less than 2.
- **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.
- **Stagnant, step change needed.** The historical rate of change is largely flat.
- **Wrong direction, U-turn needed.** The historical rate of change is heading in the wrong direction entirely.
- **Insufficient data.** Limited data make it difficult to estimate the historical rate of change relative to the required action.

TABLE 2. Summary of progress toward 2030 and 2050 for indicators with acceleration factors

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 historical rate of 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)[a]	**Acceleration factor** (how much the pace of recent average annual change needs to accelerate to achieve 2030 target)	**Evaluation** (based on acceleration factors and, in some cases, expert judgment)
POWER								
Carbon intensity of electricity generation (gCO_2/kWh)	525.11 (2018)[b]	50-125	<0[c]	Exponential change possible	−11.24 (2013-2018)	−36.47	3.2x	!
Share of unabated coal in electricity generation (%)	38.13 (2018)[b]	0-2.50	0	Exponential change possible	−0.59 (2013-18)	−3.07	5.2x	!
BUILDINGS[d]								
Carbon intensity of building operations ($kgCO_2/m^2$)	60.70 (commerical 2017)	15.17-21.24 (commercial)	0	Exponential change possible	Insufficient data	−3.27 (commercial)	Insufficient data	?[e]
	29.79 (residential 2017)	10.40-16.38 (residential)				−1.30 (residential)		
Energy intensity of building operations (% change indexed to 2015, for which 2015 equals 100)[f]	98.14 (2019)	70-90 (commercial)	50-85 (commercial)	Exponential change unlikely	−0.62 (2014-19)	−1.65	2.7x	!
		70-80 (residential)	40-80 (residential)					
Retrofitting rate of buildings (%/yr)	1-2 (2019)	2.50-3.50	3.50 (by 2040)	Exponential change unlikely	Insufficient data	Insufficient data	Insufficient data	?[e]
INDUSTRY								
Share of electricity in the industry sector's final energy demand (%)	28.35 (2018)	35	50-55	Exponential change possible	0.49 (2013-18)	0.55	1.1x	–

TABLE 2. Summary of progress toward 2030 and 2050 for indicators with acceleration factors (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 historical rate of 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)[a]	**Acceleration factor** (how much the pace of recent average annual change needs to accelerate to achieve 2030 target)	**Evaluation** (based on acceleration factors and, in some cases, expert judgment)
INDUSTRY (continued)								
Carbon intensity of global cement production (kgCO_2/t cement)	635.47 (2018)	360–370	55–90	Exponential change possible	2.86 (2013–18)	−22.54	n/a	
Carbon intensity of global steel production (kgCO_2/t steel)	1830 (2019)	1335–1350	0–130	Exponential change possible	6.0 (2014–19)	-44.32	n/a	
Low-carbon steel facilities in operation (# of facilities)	0 (2019)	20	All facilities	Exponential change possible	Insufficient data	2	Insufficient data	[g]
TRANSPORT								
Share of low-emissions fuels in the transport sector (%)	4.26 (2018)	15	75–95	Exponential change possible	0.07 (2013–18)	0.90	12x	
Carbon intensity of land-based transport (gCO_2/pkm)	104 (2014)	35–60	Near 0	Exponential change possible	Insufficient data	−3.53	Insufficient data	
Share of trips made by private LDVs (%)	43.60 (2020)	36–46	No target established (insufficient data)	Exponential change unlikely	0.86[h]	−0.26	n/a, U-turn needed	
LAND USE AND COASTAL ZONE MANAGEMENT								
Deforestation rate (Mha/yr)	6.77 (2020)	2.01	0.33	Exponential change unlikely	0.14 (2015–20)	−0.48	n/a, U-turn needed	
Reforestation (cumulative Mha)	80.60 (cumulative gain, 2000–2012)	259[i]	678[i]	Exponential change unlikely	6.70 (average annual rate of change, 2000–2012)[j]	21.58[a]	3.2x	
Rate of carbon removal from reforestation ($GtCO_2$/yr)	0.71 (annual sequestration rate as of 2012)	3	7.85	Exponential change unlikely	0.06 (average annual rate of change, 2000–2012)[k]	0.25[a]	4.2x	
Peatlands conversion rate (Mha/yr)	0.78 (1990–2008 annual average)	0.23[i]	0.04[i]	Exponential change unlikely	0.78 (average annual rate of change, 1990–2008)[l]	−0.05[a]	Insufficient data	
Peatlands restoration (cumulative Mha)	No data	22	46	Exponential change unlikely	Insufficient data	Insufficient data	Insufficient data	

TABLE 2. Summary of progress toward 2030 and 2050 for indicators with acceleration factors (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 historical rate of 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)[a]	**Acceleration factor** (how much the pace of recent average annual change needs to accelerate to achieve 2030 target)	**Evaluation** (based on acceleration factors and, in some cases, expert judgment)
LAND USE AND COASTAL ZONE MANAGEMENT (continued)								
Coastal wetlands conversion rate (Mha/yr)	0.63 (1990–2005 annual average)	0.19[i]	0.03[i]	Exponential change unlikely	0.63 (average annual rate of change, 1990–2005)[m]	−0.04[a]	Insufficient data	
Coastal wetlands restoration (cumulative Mha)	0.43 (cumulative gain, 2015–16)	7[i]	29[i]	Exponential change unlikely	0.21 (average annual rate of change, 2015–16)[n]	0.58[a]	2.7x	
AGRICULTURE								
Agricultural production GHG emissions ($GtCO_2e$/yr)	5.35 (2018)	4.17	3.27	Exponential change unlikely	0.04 (2013–18)	−0.09	n/a, U-turn needed	
Crop yields (t/ha/yr)	6.64 (2019)	7.67	9.44	Exponential change unlikely	0.05 (2014–19)	0.09	1.9x	
Ruminant meat productivity (kg/ha/yr)	27.07 (2018)	33.42	41.57	Exponential change unlikely	0.35 (2013–18)	0.55	1.6x	
Share of food production lost (%)	14 (2016)	7	7	Exponential change unlikely	Insufficient data	Insufficient data	Insufficient data	
Food waste (kg/capita/yr)	121 (2019)	60.50	60.50	Exponential change unlikely	Insufficient data	Insufficient data	Insufficient data	
Ruminant meat consumption in the Americas, Europe, and Oceania (kcal/capita/day)	93.55 (2018)	78.98	60	Exponential change unlikely	−0.63 (2013–18)	−0.95	1.5x	
FINANCE								
Total climate finance (billion US$)	640 (2020)	5,000	5,000	Exponential change unlikely	33.60 (2015-2020)	436	13x	
Public climate finance (billion $)	300 (2020)	1,250	1,250	Exponential change unlikely	19 (2015–20)	95	5x	
Private climate finance (billion $)	340 (2020)	3,750	3,750	Exponential change unlikely	14.60 (2015–20)	341	23x	

TABLE 2. Summary of progress toward 2030 and 2050 for indicators with acceleration factors (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 historical rate of 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)[a]	**Acceleration factor** (how much the pace of recent average annual change needs to accelerate to achieve 2030 target)	**Evaluation** (based on acceleration factors and, in some cases, expert judgment)
FINANCE (continued)								
Corporate climate risk disclosure	No data	Jurisdictions representing three-quarters of global emissions mandate climate risk reporting aligned with TCFD, and all of the world's 2,000 largest public companies report on climate risk in line with TCFD	No target defined	Exponential change unlikely	Insufficient data	Insufficient data	n/a	
Share of global emissions covered by a carbon price of at least $135/tCO_2e$[o] (%)	0.08 (2021)	51% of global emissions at a price of at least $135/tCO_2e$	51% of global emissions at a price of at least $245/tCO_2e$	Exponential change unlikely	0 (2015–20)	5.10	n/a	
Total public financing for fossil fuels[p] (billion $)	725 (2019)[q]	0	0	Exponential change unlikely	−58.40 (2014–19)	−65.91	1.1x	

Note: n/a = not applicable; gCO_2/kWh = grams of carbon dioxide per kilowatt-hour; $kgCO_2/m^2$ = kilograms of carbon dioxide per square meter; $kgCO_2/t$ = kilograms of carbon dioxide per tonne; gCO_2/pkm = grams of carbon dioxide per passenger kilometer; Mha/y = million hectares per year; LDV = light-duty vehicle; GHG = greenhouse gas; kg/ha/yr = kilograms per hectare per year; kg/capita/yr = kilograms per capita per year; kcal/capita/day = kilocalories per capita per day; $GtCO_2/yr$ = gigatonnes (billion tonnes) of carbon dioxide per year; Mha = million hectares; $GtCO_2e/yr$ = gigatonnes (billion tonnes) of carbon dioxide equivalent per year; t/ha/yr = tonnes per hectare per year; TCFD = Task Force on Climate-Related Financial Disclosures ;tCO_2e = tonnes of carbon dioxide equivalent.

a For indicators with targets defined against a baseline year and with limited data availability, we use the average annual rate of change across the most recently available time period (e.g., 2000–2012) to estimate the annual rate of change during the target's baseline year, and we calculate the future rate of change required to reach the 2030 target against this estimated baseline year rather than the most recent year of data.

b This data analysis is based on historical data collected before 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 Achieving below zero-carbon intensity implies biomass power generation with carbon capture and storage.

d The data for buildings refer to the full range of the targets across commercial and residential buildings, because historical data are not available for the two building types separately.

e This indicator has one historical data point that indicates it is not on track and must accelerate action, but we do not have enough information to assess how much it must accelerate (so cannot categorize it into the yellow, orange, or red). Thus it is in the "insufficient data" category.

f Building energy intensity is indexed to 2015 because there are no separate historical data for residential and commercial buildings.

g The indicator is marked as "well off track" because, while no low-carbon steel facilities are currently in operation, 18 are expected to be operational by 2030. Of these 18 projects, data on production capacity are only available for 4, all of which meet the production criteria of at least 1 million tonnes annually. However, data are insufficient to calculate an acceleration factor.

h Only two historical data points were available to calculate this historical rate of change.

i Targets for 2030 and 2050 are derived from Roe et al. (2019) and Griscom et al. (2017), which define them against the baseline year of 2018. But for some targets, data are not available for 2018. We, therefore, use the most recently available data point (e.g., 80.6 Mha in 2012) or the most recently available annual average (e.g., an average of 0.78 Mha of peatlands lost per year from 1990-2008) to estimate the indicator's value in 2018.

j Data for gross tree cover gain over a 12-year time period are available; historical annual rate of change is averaged over this time period.

k Data for CO_2 sequestered from gross tree cover gain rely on data over the same 12-year time period; historical annual rate of change is averaged over this time period.

l Data are only available as a total rate of change over 18 years, which we divide to find the average rate. Because the annual rate of change is averaged, we cannot calculate an acceleration factor (i.e., we don't know if the rate of change is increasing or decreasing over time).

m The historical rate of change is assessed over a 15-year period for mangrove forests (1990–2005) but over significantly longer periods for salt marshes and seagrass meadows. Annual data for all three ecosystems are not available. Because annual data for all three ecosystems are not available and the annual rate of change is averaged, we cannot calculate an acceleration factor (i.e., we do not know if the rate of change is increasing or decreasing over time).

n Historical rate of change is assessed as an annual average over two years of available data and, due to data limitations, for mangroves only.

o The Intergovernmental Panel on Climate Change identified the undiscounted carbon price consistent with achieving 1.5°C as being $135–$6,050/tCO_2e in 2030 and $245–$14,300/tCO_2e in 2050, in 2010 US$ (IPCC 2018).

p Public financing for fossil fuels includes production and consumption subsidies, 81 economies; public fossil fuel finance from multilateral development banks and G20 countries' export credit agencies and development finance institutions; and state-owned entity fossil fuel investment, G20 (see Chapter 10, "Finance").

q Data for public fossil fuel finance from multilateral development banks and G20 countries' export credit agencies and development finance institutions were unavailable for 2019, so this figure comprises only production and consumption subsidies for 81 economies and state-owned entity fossil fuel investment for G20 countries.

Source: Authors' analysis based on data sources listed in each chapter; see Appendix C for the methodology used to design targets and the literature from which they are derived.

Additionally, for the indicators with targets that are defined by 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. Much of this target uncertainty stems from the different assumed transition speeds across various sectors; when targets are presented as a range of values, the lower end of the range represents what can be achieved with current technologies and strategies. Efforts to reach the lower bound of all targets will likely fall short of achieving the Paris Agreement's 1.5°C temperature goal. Consequently, only by achieving the upper bound of some targets (e.g., phasing out coal even more quickly) will we create room for some systems to achieve their lower target bounds where decarbonization is difficult and therefore slower.

Methodology for tracking progress of indicators that could possibly follow S-curve dynamics

For the remaining nine indicators tracking the adoption of new technologies and, therefore, more likely to experience change that follows S-curve dynamics, we do not assume that future growth will be linear (see Appendix E). As such, we do not calculate acceleration factors for these indicators, as they would likely underestimate the pace of future change, as well as overestimate the gap in required action.

Based on the literature and the data, the majority of these indicators track technologies currently in either the emergence or early diffusion phases of an S-curve (Victor et al. 2019; ETC 2020). S-curves cannot predict future trajectories of new technology adoption in such early stages of growth with any level of certainty. Any small fluctuations in the initial growth rate will create statistical noise, which introduces uncertainty into predictions that reaches orders of magnitude (Kucharavy and De Guio 2011; Crozier 2020; Cherp et al. 2021). It is not until growth has reached the steepest part of the S-curve that robust evaluations can be made (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, such as supply chain constraints, that alter or limit the shape of the growth, but these challenges are similarly difficult to anticipate.

We do not use S-curves to calculate future rates of change required to reach our 2030 and 2050 targets, but rather, to illustrate the significant acceleration needed.

Given the considerable uncertainty in predicting S-curves, this report only uses S-curves to illustrate the power of nonlinear change to transform economic sectors and to illustrate one possible pathway to reach the climate targets. But we neither use S-curves to calculate historical rates of change nor estimate future rates of change required to reach the 2030 and 2050 targets. Instead, we categorize indicators based on a review of the literature and available data, and we follow the same color categories to classify progress (Table 3).

TABLE 3. Summary of progress toward 2030 and 2050 targets for indicators focused on technology adoption that could possibly follow an S-curve

Indicator	Most recent historical data point (year)	2030 target	2050 target	Stage of S-curve	Average historical compound annual growth rate (over most recent 5 years)	Evaluation (based on expert judgment)	Sources informing assessment of progress: These sources informed expert judgment; in some instances, models and data were adjusted to meet this report's 2030 target.
POWER							
Share of renewables in electricity generation (%)	25.17 for all renewables, 7.03 for solar and wind (2018)[a]	55–90 for all renewables, 37 to 72 for solar and wind	98–100 for all renewables, 80 to 82 for solar and wind	Diffusion	14.75% for solar and wind (2013–18)	–	IEA (2020n); Cherp et al. (2021); Grubb et al. (2020)
INDUSTRY							
Green hydrogen production (Mt)	0.07 (2018)	0.23–3.50 by 2026	500–800	Emergence	Insufficient data	!	ETC (2021b); BloombergNEF (2020b)
TRANSPORT							
Share of EVs in LDV sales (%)	4.26 (2020)	75–95	100 by 2035	Diffusion	49.58% (2015–20)	–	BloombergNEF (2020g); Grubb et al. (2021)
Share of EVs in the LDV fleet (%)	0.55 (2020)	20–40	85–100	Diffusion	59.02% (2015–20)	!	BloombergNEF (2020g); Grubb et al. (2021)
Share of BEVs and FCEVs in MHDV sales (%)	0.30 (2020)	8 by 2025	100 in leading markets by 2040	Emergence	Insufficient data	!	BloombergNEF (2021a)
Share of BEVs and FCEVs in bus sales (%)	39 (2020)	75 by 2025	100 in leading markets by 2030	Diffusion	Irregular; historical growth has been exponential at times, with geographic variation	–	BloombergNEF (2020a, 2021a)
Share of SAF in global aviation fuel supply (%)	0.10 (2019)	10	100	Emergence	Insufficient data	!	WEF (2020); ETC (2019d); Race to Zero (2021b); BloombergNEF (2021d)
Share of ZEF in international shipping fuel supply (%)	No data	5	100	Emergence	Insufficient data	!	BloombergNEF (2020c); CAT (2021); ETC (2019b); UNEP and UNEP DTU Partnership 2020)
TECH CDR							
Rate of technological carbon removal ($MtCO_2$ removed/yr)	0.52 (2020)	75	4500	Emergence	Insufficient data	!	EPA (2020); Doyle (2021); IEA (2021a)

Note: Mt = million tonnes; EV = electric vehicle; LDV = light-duty vehicle; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle; MDHV = medium- and heavy-duty vehicle; SAF = sustainable aviation fuel; ZEF = zero-emissions fuel; $MtCO_2$/yr = million tonnes of carbon dioxide per year.

a This data analysis is based on historical data collected before IEA's most recent 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.

Source: Authors' analysis based on data sources listed in each chapter; see Appendix C for the methodology used to design targets and the literature from which they are derived.

Of these nine indicators, we have multiple years of historical data for only four: renewables, light-duty electric vehicle sales, light-duty electric vehicle stock, and electric buses. All have experienced some form of nonlinear growth in recent years, although in some cases the growth rates have fluctuated. We categorize these indicators' progress by expert judgment, interpreting the data and the relatively small amount of literature on S-curves in these sectors (Cherp et al. 2021; Grubb et al. 2020, 2021), as explained further in their respective chapters.

For the remaining five indicators, which are primarily in the emergence phase, either global data on adoption are not yet available or just one historical data point exists. However, even without these time series data, the literature suggests that these technologies are advancing in development or adoption, and so we can safely place them in the orange category (off track, with historical change headed in the right direction but well below levels required for 2030) and note that S-curve growth is possible.

For indicators with at least one historical data point, we present the historical data and construct a hypothetical S-curve to illustrate one possible pathway to reach the climate targets, but we do not predict future growth rates in any specific way. We construct these hypothetical S-curves using a simple logistic formula (as described in Appendix E), which is purely generic and perfectly mirrored around the midpoint; this is not the only shape that an S-curve could take to meet the targets. This analysis also does not consider the changes in the carbon budget over time to know whether it is truly a 1.5°C trajectory in every year. But the S-curves presented do provide a general sense of indicators' historical trajectory, as compared to where it needs to be to help avoid the worst climate impacts.

As data availability improves and the literature on S-curves increases, future reports will seek to assess more indicators with S-curves, as well as refine this methodology. This is a rapidly developing field, and considerable methodological improvements will likely occur in the near future. Given the need to move beyond linear thinking, this report takes a first step in exploring alternative methods, while also recognizing that they entail considerable uncertainties.

Identification of key enablers of climate action for each target

To support efforts to translate these 2030 and 2050 targets into action, this report identifies key enablers of change for each indicator. The selection of these drivers was informed by an extensive review of the academic literature on transformation, transition, and systems change theory in the global environmental change research. We also assessed case studies of historical transitions in both sociotechnical systems (e.g., power, transport, and industry) and social-ecological systems (e.g., management of land, freshwater wetlands, and coastal ecosystems). Although the exact determinants of these transformations have ranged widely across these case studies, some ingredients appear to be common, including innovation, regulations and incentives, strong institutions, leadership from key change agents, and shifts in behavior and social norms (Table 4).

TABLE 4. Enablers of climate action

Categories of enablers	Examples of specific enablers	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 market-based instruments to create incentives (or disincentives) can also shape action by 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 sector and region.
	Noneconomic incentives, including removal of bureaucratic hurdles, transitional support to affected communities, or giving 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 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, specifically and 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 stand the most to gain from transitions to new systems—to steer transformations to a net-zero future.
	Creation of national ministries, agencies, or interagency task forces	
	Changes in governance, such as more participatory, transparent decision-making processes and 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, 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 and implementing ambitious climate commitments	
	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 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: Drivers were identified from a synthesis of the following studies: Chapin et al. (2010); Few et al. (2017); Folke et al. (2010); Geels et al. (2017a); 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).

Exogenous changes, including both shocks (e.g., economic recessions or pandemics) and slower-onset changes (e.g., demographic shifts), can also enable change by destabilizing the existing system and creating windows of opportunity for transformation. 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 gain power. However, given that such crises are often immediate, unforeseen, and disruptive, we do not include them in our assessment of underlying conditions that enable climate action.

After identifying common ingredients of systems change, we reviewed 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., Energy Transitions Commission and the High-Level Panel for a Sustainable Ocean Economy) to systematically identify the enablers for each target and indicator across these five overarching categories of ingredients common to historical transformations. See Appendix G for more details on the keywords used for each sector, languages in which the literature review was conducted, and repositories searched.

While the enablers selected are by no means conclusive in terms of illustrating the complex set of drivers of change required to meet each target, the ones we highlight have either proven effective in catalyzing and sustaining past transitions (e.g., in forest landscape restoration) or, for those transitions that are just beginning (e.g., the transition to green hydrogen), represent a subset of recommended interventions prioritized in the literature.

In many sectors, for example, a clear transition away from traditional technologies toward new innovations is required, such as the shift to green hydrogen in heavy industry or the emergence of carbon removal technologies. Drivers of these shifts, then, focus primarily on interventions that can support research and development efforts to improve performance, while reducing costs. For other systems, low-carbon solutions, such as electric vehicles, are already commercially available but are just beginning to diffuse across markets. Actions that support greater social acceptance and uptake—efficiency standards, subsidies, and corporate commitments, for example—often enable progress toward these targets. And finally, achieving some targets will entail widespread adoption of technologies, practices, or approaches that have already gained traction in some regions, such as renewable energy technologies for electricity generation, but require greater efforts to spread to all regions, become mainstream, and accelerate their adoption globally. Prioritized drivers within these systems generally center on actions that will accelerate rates of change until it reaches a positive tipping point (Box 3).

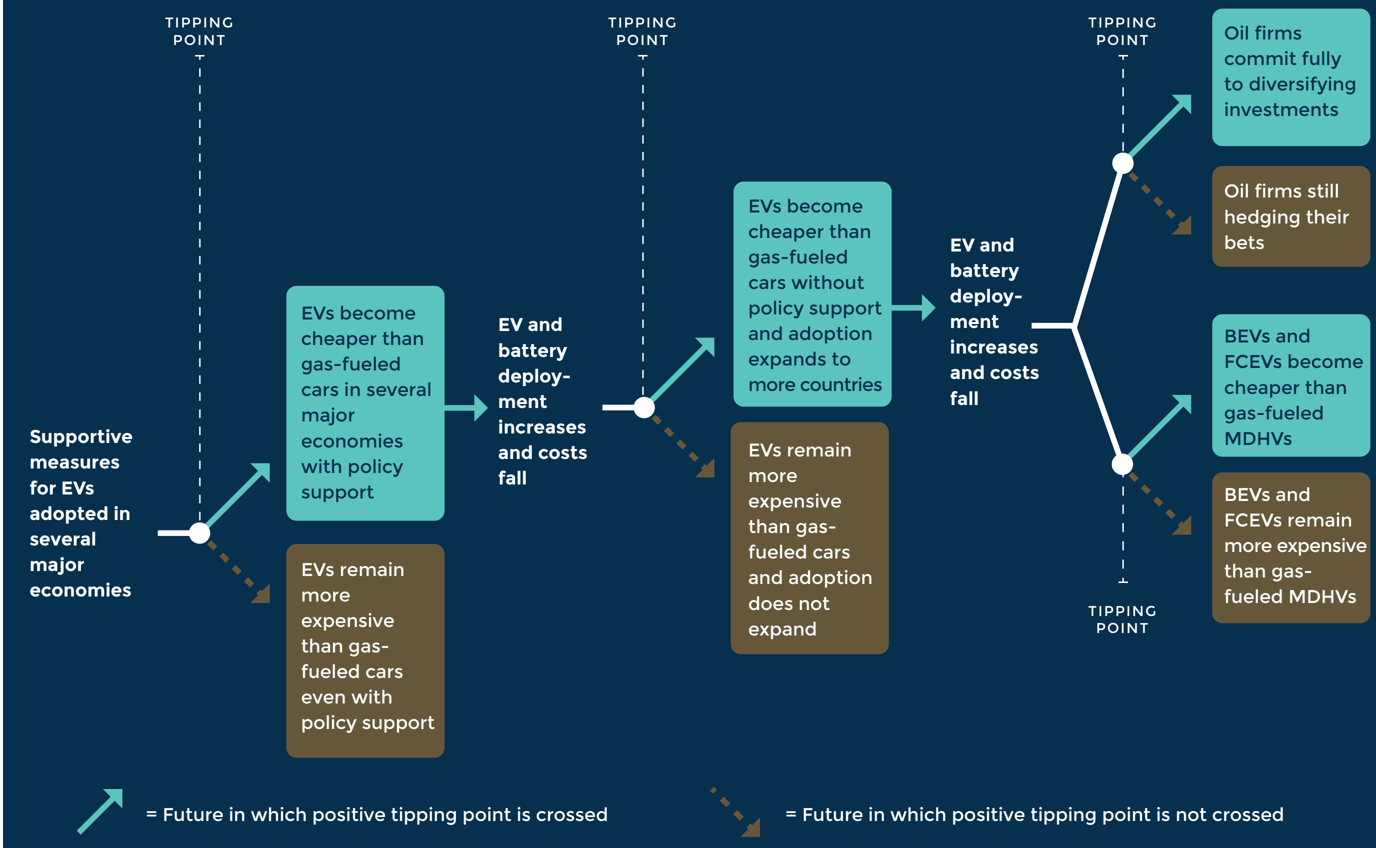
BOX 3. Tipping points

Tipping points occur when small disturbances trigger disproportionately large responses within systems, pushing them into qualitatively different future states. Positive, self-amplifying feedbacks switch on once these critical thresholds are crossed and accelerate transformations (Lenton et al. 2008; Lenton 2020). In some nested systems, the activation of one tipping point has the potential to trigger a cascade of tipping points across systems at progressively larger scales. In the power sector, for instance, a few early movers, including Denmark, Germany, Spain, and California, implemented policy portfolios that supported deployment of solar and wind energy technologies. Other countries, such as China and India, soon followed suit, causing global demand for renewables to increase and prices to drop. These rapid declines in cost, in turn, have spurred widespread adoption of renewables, as solar and wind energy have supplanted coal and natural gas as the cheapest sources of electricity for at least two-thirds of the world's population (Sterl et al. 2017; Eckhouse 2020).

These knock-on effects can also catalyze change between interconnected systems. For example, electric vehicles reaching price parity with gasoline-fueled cars in a small number of countries that account for the majority of automobile sales could trigger a global transition away from the internal combustion engine. Following this transformation in road transportation, oil companies would likely lose their largest market, which in turn could prompt investors to divest and channel their funds into more sustainable fuels for aviation, shipping, and heavy industry (Sharpe and Lenton 2021).

BOX 3. Tipping points (continued)

FIGURE B3.1. Positive tipping points



Source: Adapted from Sharpe and Lenton (2021).

These drivers can also come together in ways that increase collaboration and alignment with limiting global temperature rise to 1.5°C, while derisking action. Accordingly, understanding the state of the enabling environment for each indicator can help build a shared vision of what is needed and a sense of how the journey is progressing. Arguably, this in itself could contribute to progress in a positively reinforcing manner, driving further change.

Key limitations

Transformations across the power, buildings, transportation, industry, land use and coastal zone management, agriculture, and finance systems will unfold within broader social, political, and economic systems. These complex, dynamic entities determine, for example, who holds power in society, who has a voice in decision-making processes, how the costs and benefits of change are distributed, how progress will be measured, and what is valued—dynamics that, in turn, can either support or stymie efforts to limit global temperature rise to 1.5°C. Indeed, successful transition to a net-zero future requires contending with power and politics (Patterson et al. 2017; Meadowcroft 2011). A central limitation of this report, then, is that it does not address the transformations across social, political, and economic systems that may be required to realize the Paris Agreement's goals. These include redefining economic prosperity; shifting to a new decision-making model with community leadership at the center; resetting the social contract between governments, corporations, and citizens; and dramatically reducing consumption through lifestyle changes. Looking ahead, members of the climate community must pay greater attention to these transformations—and intentionally consider how these transitions can accelerate (or stymie, if stalled) critical shifts within key sectors—if we are to avoid the worst climate impacts.

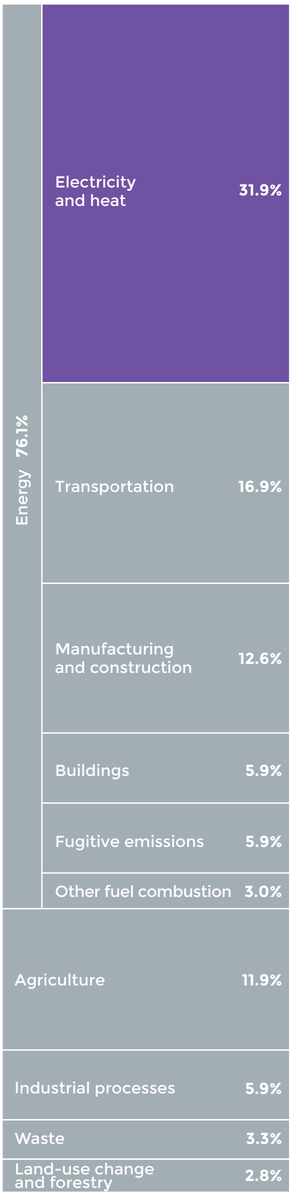
Additionally, this report focuses solely on climate change mitigation targets and does not establish benchmarks for adaptation.

3

POWER

The transformation of the power (electricity generation) sector is central to limiting warming to 1.5°C. The sector is responsible for around 32 percent of global GHG emissions (15.6 gigatonnes (billion tonnes) of carbon dioxide equivalent [$GtCO_2e$] in 2018) (ClimateWatch 2021). The power sector is also the single largest source of energy-related CO_2 emissions today (Figure 4) (IEA 2021c); even more importantly, decarbonization of other sectors relies on electricity supplied from a carbon-free power sector. Coal-based electricity generation plays an outsized role in emissions from the sector, accounting for 74 percent of the sector's energy-related CO_2 emissions, followed by gas (21 percent) and then oil (5 percent) (IEA 2021c). Emissions from electricity generation are on the rise due to increasing demand, linked with expanding populations and climbing living standards (IEA 2021c).

FIGURE 4. **Role of the power sector in global greenhouse gas emissions**



Source: ClimateWatch (2021).

EMISSIONS IN THE POWER SECTOR ARE determined by the amount of energy generation, the efficiency of this generation, and the carbon content of the fuel that is used. Mitigating emissions in the power sector will require both supply- and demand-side measures. From a supply side, there must be a rapid and significant uptake of clean energy sources alongside a steep decline in fossil-based electricity generation. From a demand side, enhanced energy efficiency measures can slow increasing electricity demand as other sectors are electrified and reduce the per capita consumption in developed economies.

In this chapter we examine the power sector transition through three indicators related to electricity generation: the overall carbon intensity of electricity generation (indicator 1), the share of renewables in electricity generation (indicator 2), and share of unabated coal, or coal power without carbon capture technology (indicator 3). Energy efficiency is addressed in this report on the demand side, specifically in Chapters 4, 5, and 6 on buildings, industry, and transport, respectively. For all three indicators, historical rates of change are headed in the right direction but are below the levels needed to reach 2030 targets (Table 5).

TABLE 5. Summary of progress toward 2030 power targets

Indicator	Most recent historical data point (year)	2030 target	2050 target	Trajectory of change	Status	Acceleration factor
Carbon intensity of electricity generation (gCO_2/kWh)	525.11 (2018)[a]	50–125	<0[b]	Exponential change possible		3.2x
Share of renewables in electricity generation (%)	25.17 for all renewables, 7.03 for solar and wind (2018)[a]	55–90 for all renewables, 37–72 for solar and wind	98–100 for all renewables, 80 to 82 for solar and wind	Exponential change likely		n/a; in diffusion stage of S-curve for solar and wind
Share of unabated coal in electricity generation (%)	38.13 (2018)[a]	0–2.50	0	Exponential change possible		5.2x

Note: n/a = not applicable; gCO_2/kWh = grams of carbon dioxide per kilowatt-hour.

a This data analysis is based on historical data collected before IEA's most recent 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 Achieving below zero-carbon intensity implies biomass power generation with carbon capture and storage.

Sources: For data, IEA (2020n); for targets, CAT (2020b).

Despite increasing demand (and thus emissions), the power sector could be the first to reach net-zero GHG emissions, mainly because of the low costs, widespread policy support, and maturity of an array of renewable energy technologies (IPCC 2018; IEA 2021c). However, this also requires coal power capacity to be retired before its planned life span (especially in regions that are currently constructing new coal power plants) and preferably replaced with solar and wind. Solar photovoltaics (PV) are already the cheapest new source of electricity in most markets even without policy support or financial subsidies, and also receive policy support in more than 130 countries. Onshore wind is also a market-ready, low-cost technology that is generally widely supported and can be scaled up quickly (IEA 2021c).

A transition toward renewables and increased efficiency will also result in significant co-benefits. Increasing clean energy sources while phasing out coal-based power will reduce local air pollution and improve human health—benefits that typically outweigh the cost of the transition in all regions (Markandya et al. 2018). Improving energy efficiency is also a "no regrets" option, which often leads to increased employment and economic activity (IEA 2021b), and is linked with the achievement of many Sustainable Development Goals (SDGs) (IPCC 2018).

At the same time, difficult trade-offs in the power sector must be managed responsibly, with consideration of the poorest and most vulnerable. For example, recent studies suggest that increased use of bioenergy, often coupled with carbon capture and storage (BECCS), will play a role in supporting the power sector transition and limiting warming to 1.5°C (IPCC 2018; IEA 2021c). However, there are constraints associated with expanding bioenergy as a sustainable source of power supply, particularly around increased competition for land and food production and proper accounting of emissions. Accordingly, this report envisages very modest uses of biomass-based energy (see Appendix C). Additionally, the significant push for end-use electrification may cause emissions in the power sector to rise in the short term, before the grid is fully decarbonized. These emissions should be abated through stringent mitigation measures (including switching from fossil fuel to clean energy), rather than an overreliance on natural or technological carbon removals to offset them, due to the limitations on the volume that each removal approach can be scaled. Finally, for regions that are highly dependent on fossil fuels for electricity generation, revenue, and employment, some difficult transitions lie ahead (see Chapter 11, "Equity and just transition"). Policies that promote the diversification of these economies and electricity sectors can help address these challenges (IPCC 2018), ensuring that additional hardships are not imposed on fossil fuel workers, their families, and their surrounding communities, including local economies that are dependent on livelihoods along the value chain of coal.

POWER INDICATOR 1:

Carbon intensity of electricity generation

Targets: 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.

Carbon intensity is one of the primary indicators used to monitor decarbonization of the power sector: it describes the amount of CO_2 per unit of electricity produced based on the combination of energy sources—including renewables, coal, oil, and gas—that generate power.

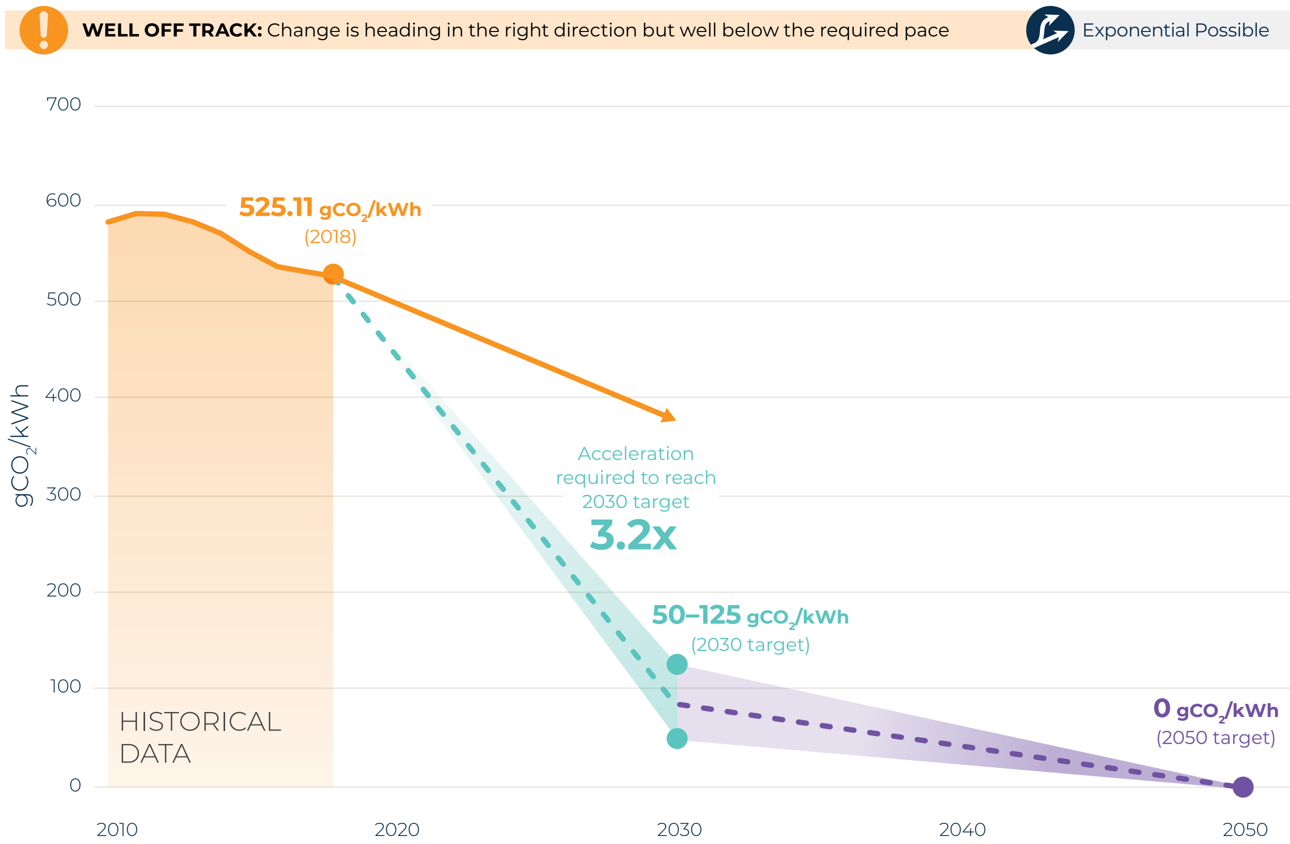
Transitioning to zero-emissions electricity will require a broad mix of technologies that reduce carbon intensity, but long-term decarbonization will rely on increasing the share of renewables, particularly wind and solar, in electricity generation, as well as the complete phaseout of coal-fired power (see Power Indicators 2 and 3) and significant reduction of gas-fired supply. Other options to decrease carbon intensity in this sector include large-scale carbon capture and storage (CCS) and nuclear power. However, both technologies are constrained by high costs, by economic feasibility of clear and credible systems of tracking and accountability, and by economically accessible subsurface storage sites. It is also not clear whether CCS will reach commercial viability in a relevant timeframe (CAT 2020a). The technology might thus be applied only in hard-to-abate sectors. In the short term, reducing electricity demand—through energy efficiency gains, for example—can also offset higher levels of carbon intensity by reducing the power generation needed and allowing for faster retirement of fossil generation capacity. But in the long term, all power generation must reach net zero to enable economy-wide decarbonization.

Many countries, particularly advanced economies, have already made progress in reducing the carbon intensity of electricity generation. The European Union, for example, reduced carbon intensity of electricity by 40 percent from 1990 to 2017, while in China, the power sector's carbon intensity continues to decline despite sustained high rates of economic growth.[9] However, the global view shows a slower decline in carbon intensity of electricity generation, from 643 gCO_2/kWh in 1990 to 525 gCO_2/kWh in 2018. Although headed in the right direction, this historical rate of decline is far from what is needed to achieve the 2030 target (Figure 5). Current levels of 525 gCO_2/kWh (IEA 2020d) should fall to 50–125 gCO_2/kWh by 2030 and to below zero[10] by 2050 to align with the Paris Agreement's 1.5°C target. Plans for new coal-fired capacity in some countries are incompatible with this target.

Enablers of climate action

The combination of energy sources used to generate electricity determines the power sector's carbon intensity levels, so achieving these 2030 and 2050 targets will depend, in large part, on increasing the share of renewables in electricity generation (see Power Indicator 2) and phasing out coal-fired power (see Power Indicator 3). Thus, measures that enable these critical shifts also support efforts to lower carbon intensity in electricity generation while still allowing for economic growth in developing countries.

FIGURE 5. **Historical progress toward 2030 and 2050 targets for carbon intensity of electricity generation**



Note: gCO_2/kWh = grams of carbon dioxide per kilowatt-hour.
Sources: For data, IEA (2020n); for targets, CAT (2020b).

POWER INDICATOR 2: Share of renewables in electricity generation

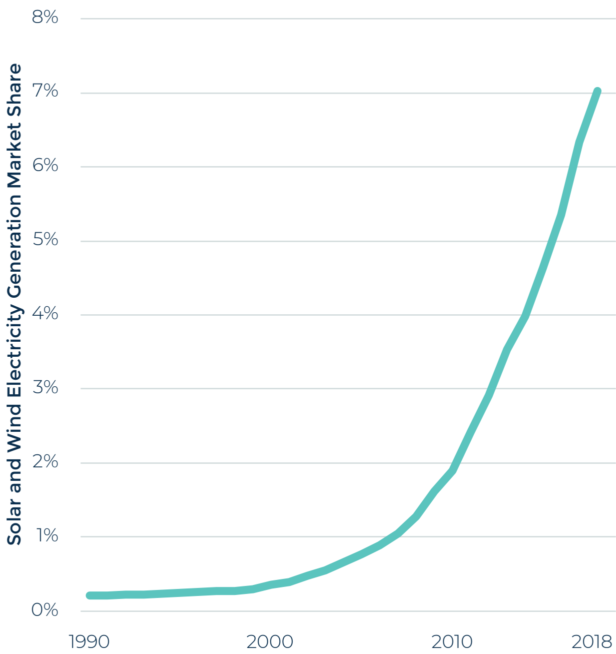
Targets: The share of renewables in electricity generation reaches between 55 and 90 percent by 2030 and between 98 and 100[11] percent by 2050.

In 2020, renewables reached a new all-time record, generating 29 percent of the world's electricity (IEA 2021d). Renewable sources of power—including hydropower, geothermal, solar, wind, tidal, biofuels, and the renewable fraction of municipal waste—are now the generation technologies of choice, accounting for 82 percent of new capacity installed in 2020. Hydropower still accounts for the largest share of electricity generation from renewables, at just over 40 percent (IRENA 2021a). However, driven by rapid declines in price, the market share of wind, solar, and other[12] new renewables has grown significantly in recent years. In 2020 alone, wind and solar made up 90 percent of new renewable capacity deployed (IRENA 2021a), and installing these variable renewables is now more cost-effective than generating electricity from existing coal-fired power plants in most places (IRENA 2021b). While the percentage of new capacity does not translate directly to percentage of generation (as renewables have a lower capacity factor, or typical level of generation compared to their total potential capacity, than fossil fuel power), it is a clear indication that the sector is decisively moving toward renewables.

The target for renewable energy generation in this report is set at the highest level of ambition technically achievable based on national energy transition studies. Other studies (e.g., IEA 2021c; IRENA 2019c) include higher amounts of fossil-fueled power generation with carbon capture and storage and nuclear in their 2050 scenarios. The target within this report assumes that renewable technologies can be increased beyond shares of 90 percent through more aggressive deployment of multiple technologies including long-term storage (e.g., chemical storage from renewable resources), coupling heat generation via heat pumps as a flexible source of electricity demand on a large scale and advanced grid balancing.[13]

It is worth looking more closely at solar and wind electricity since they have been the dynamic drivers of renewable electricity growth in recent years. Solar and wind are already growing on a nonlinear path and reached 7 percent of global electricity generation in 2018 (Figure 6). The market share of solar and wind in electricity generation grew at a compound average annual growth rate (CAGR) of 15 percent from 2013 to 2018. If exponential growth continued at this rate, solar and wind would reach 45 percent of electricity generation by 2030 and 100 percent by 2033. This likely won't happen because we know technology adoption follows an S-curve. Technologies following an S-curve have a "top speed" for growth—a maximum growth rate that is achieved, lasts awhile, and then slows down long before reaching 100 percent. There have been some early attempts to determine what the top speed of growth for wind and solar is and what an S-curve could look like (Box 4). Overall, despite the promising signs, it does appear that growth in renewables must accelerate, though much uncertainty remains over how much acceleration is needed. This is a rapidly developing field, and there will likely be methodological improvements to S-curve evaluations in the future.

FIGURE 6. The historical global market share of solar and wind in electricity generation



Note: In the IEA 2020 historical data solar photovoltaic (PV) and wind are included under "new renewables," which is comprised almost entirely of solar PV and wind but has a negligible amount of tidal energy and heat pumps.
Source: IEA (2020n).

BOX 4. S-curve dynamics of solar and wind

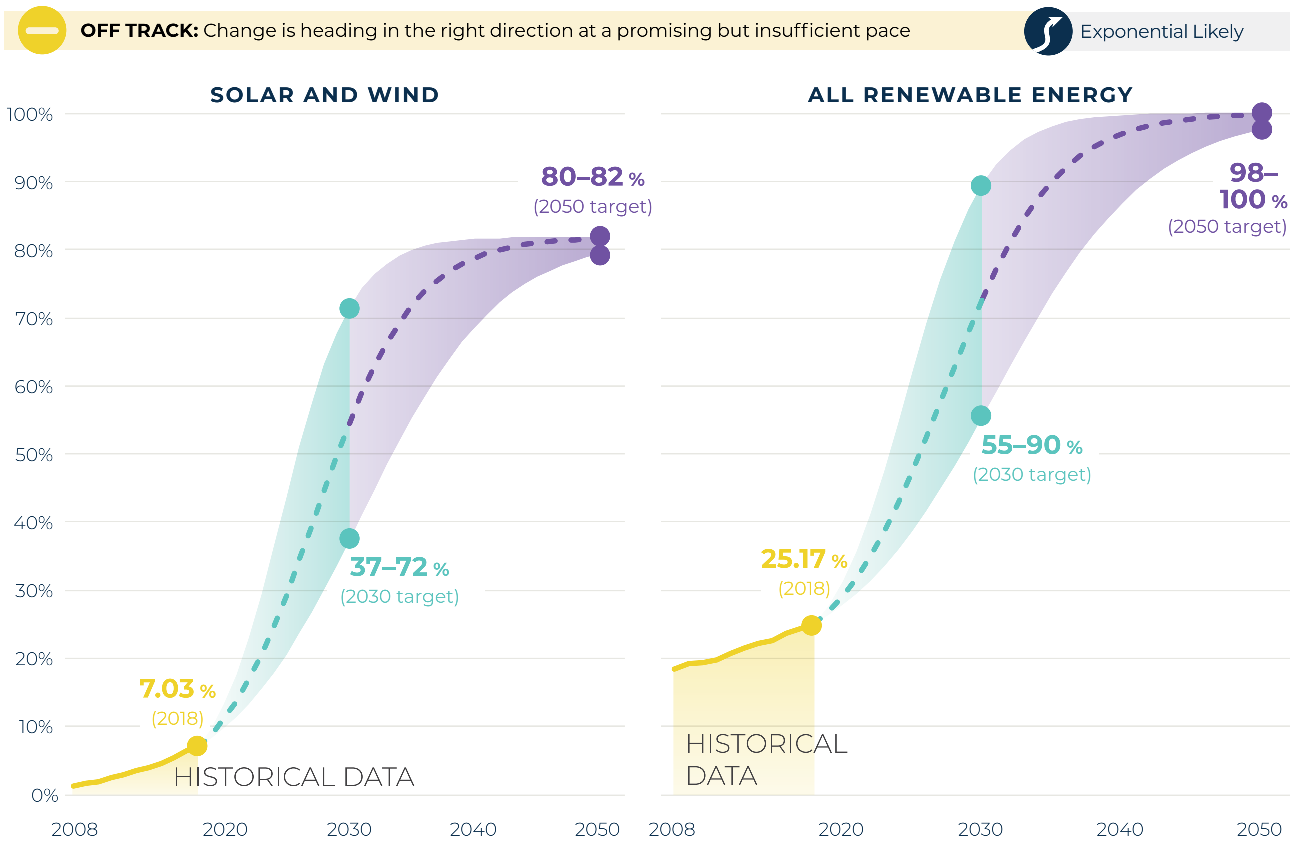
Solar and wind are growing quickly, but the question remains whether they are growing fast enough. Given the acceleration of growth of solar and wind in recent years, it doesn't make sense to make projections with linear extrapolation, as many mainstream assessments still do; this will underestimate the pace of change and risks leading to stranded assets and a less well-managed transition. Instead, the future trajectory of solar and wind will likely follow an S-curve, following the pattern of other instances of technology adoption.

There is limited literature evaluating solar and wind S-curves, and it does not agree as to whether they are "on track." It is impossible to project S-curves in the early stages of their growth with any level of certainty, and efforts to make such projections in the early stages have failed in the past (Kucharavy and De Guio 2011; Crozier 2020).

Therefore, Cherp et al. (2021) look to the countries where solar and wind are more advanced and have already reached the steepest part of the S-curve. They find that in these countries where solar growth has stabilized at a maximum rate, growth has been on average 0.6 percent of the total electricity supply per year, which is lower than the 1.4 percent maximum rate needed globally to meet one-half of 1.5°C-compatible scenarios. Onshore wind has grown at a 0.8 percent of the total electricity supply per year in the countries where growth has stabilized at a maximum rate, which is lower than the 1.3 percent maximum rate needed globally to meet one-half of 1.5°C-compatible scenarios. This means the entire world will need to increase its share of solar and onshore wind faster than the leading countries have ever achieved at the steepest point of their national S-curves. It could be that countries are able to achieve faster maximum growth rates in the future compared to today, but, historically, the maximum growth rates have not been higher for the countries that have reached the steepest part of the S-curve for renewables more recently compared to those that did several decades ago.

Despite extreme uncertainties in projecting S-curves at the early stages, Grubb et al. (2020) do project an S-curve by extrapolating the historical global growth rates of solar and wind share of generation. They assume that the shape of the S-curve will be symmetrical in that the acceleration in the first half is mirrored by the deceleration after the midpoint. They assume that the highest value that solar and wind will reach is 51 percent of total generation and use that to project the curve. They find that the growth of wind and solar generation are on track for the Paris-consistent trajectories they identify. However, our targets require higher levels of renewables than the benchmarks used by Grubb et al. (2020), so when we adjusted this method to our targets, solar and wind were not on track.

FIGURE 7. Historical progress and an illustrative S-curve of what's needed to reach 2030 and 2050 targets for the share of renewable energy in electricity generation



Note: In the IEA 2020 historical data solar photovoltaic (PV) and wind are included under "new renewables," which are comprised almost entirely of solar PV and wind but also include a negligible amount of tidal energy and heat pumps.

The targets in this report call for all renewables to make up 55–90 percent of electricity generation in 2030 and 98–100 percent in 2050, but for the first figure in this chart, we needed to adjust these to be focused solely on solar and wind. Using the simplification that other renewables like hydropower and bioenergy stay at 2018 levels (18.2 percent) allows us to estimate targets for solar and wind to be 36.8–71.8 percent in 2030 and 81.8 percent in 2050. The renewables target was derived using sustainability criteria regarding the use of biomass, nuclear, and carbon capture and storage for power generation (see Appendix C and the original publication [CAT 2020b]). The IEA net-zero-by-2050 study (IEA 2021c) derived slightly lower required shares of renewables applying different assumptions.

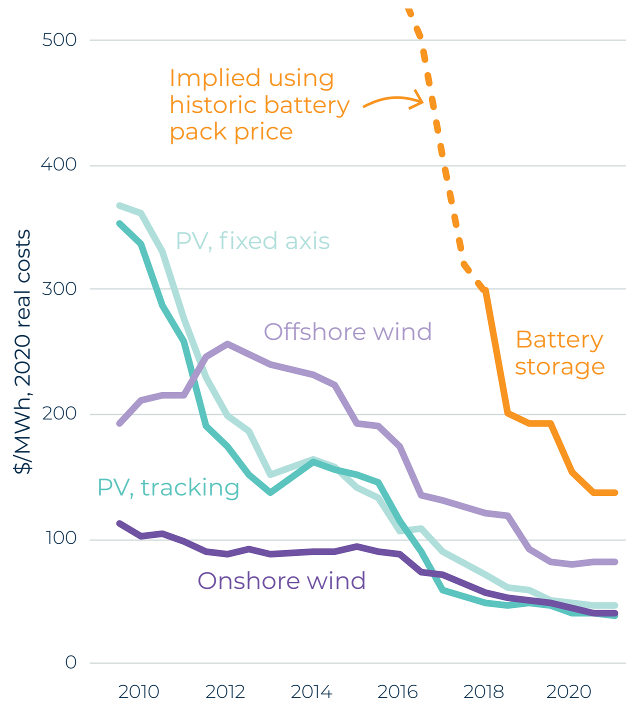
Sources: For data, IEA (2020n); for targets, CAT (2020b).

Accordingly, Figure 7 shows the shape of historical growth in solar and wind compared to a hypothetical S-curve to illustrate what's needed to meet our targets. The figure is based on a simple formula, and an S-curve could take other shapes to meet the targets. It is also a simplification to treat solar, onshore wind, and offshore wind as one entity, as they may follow different growth paths. But this gives a general sense of where the market share needs to be compared to where it is.

Enablers of climate action

Global renewables deployment is accelerating and is more cost-effective than fossil fuel-based power generation in most places (Hutchinson et al. 2021). This change is driven by declining prices, policy support, and improved performance of wind and solar electricity generation. In the last decade, the cost of solar PV fell by over 85 percent to $38 per megawatt-hour (MWh) (BloombergNEF 2021b) and the cost of onshore wind power dropped by 55 percent to $20 per MWh in some locations (ETC 2020). Costs for solar, in particular, have continued to fall more rapidly than projected, causing a reinforcing effect and leading to a higher uptake than expected (Figure 8).

FIGURE 8. Levelized cost of electricity for solar photovoltaic and wind



Note: PV = photovoltaic; MWh = megawatt-hour. The global benchmark is a country-weighted average using the latest annual capacity additions. The storage levelized cost of electricity reflects utility-scale projects with four-hour duration; it includes charging costs.
Source: BloombergNEF (2020f).

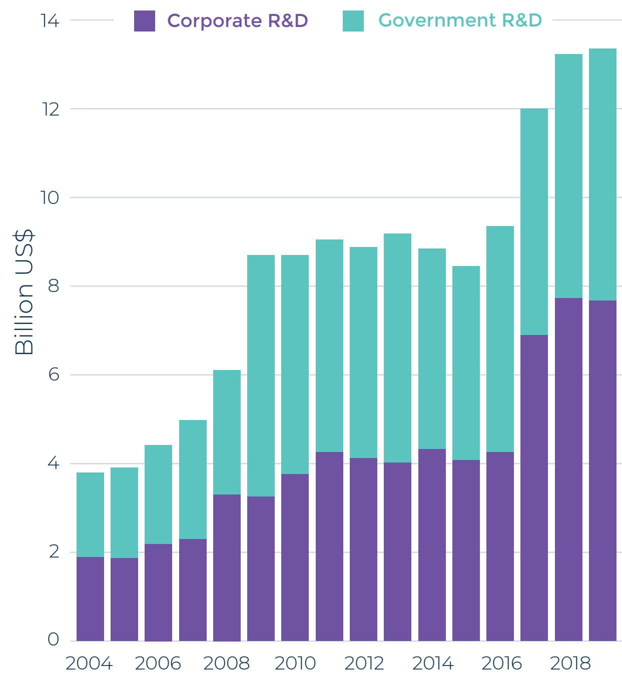
Several factors working in tandem have catalyzed and sustained these rapid decreases in cost, including technological gains that have improved the price and performance of renewables and supportive policies. Over the period 2010 to 2020, the weighted-average total installed cost of utility-scale solar PV fell by 34 percent for every doubling of cumulative installed capacity—this is referred to as the learning rate. Over the same period, onshore wind had a learning rate of 17 percent and offshore wind had a learning rate of 9 percent (IRENA 2021b). Sustaining the remarkable growth in solar and wind to meet the 2030 and 2050 targets will depend on continued gains made across this broad enabling environment.

Scaling up R&D investments in solar, wind, and a variety of tailored storage technologies

Investments in research and development from corporations and government have supported the technological innovations that have been instrumental in reducing the cost of renewable power (Figure 9). The average module efficiency for solar PV, for example, has increased 30 percent since 2010, reaching 19.2 percent in 2019 (IRENA 2020d). These efficiency improvements have allowed smaller areas to produce the same amount of electricity, thus reducing overall costs (IRENA 2020d),[14] and the next generation of solar panels are likely to be even more efficient (Leurent 2021). Technological advances have also made it possible to manufacture larger wind turbines with longer blades and larger heights, effectively reducing costs on a per megawatt basis for both onshore and offshore wind. A range of technological developments in offshore wind, in particular, are expected to fuel an estimated 10-fold increase in installed capacity by 2030 (IRENA 2019d). More sophisticated operation and maintenance activities have also driven down the price of wind power.

The real costs of renewables increasingly depend on the costs of their integration into the grid and

FIGURE 9. Corporate and government renewable energy research and development



Note: R&D = research and development.
Source: Frankfurt School–UNEP Centre/BNEF (2020).

balancing power generation with user consumption. Sustaining growth in renewable electricity generation will depend on technological advancements across a range of energy storage solutions, including pumped hydropower storage, behind-the-meter batteries with decentralized generation, utility-scale batteries often paired with renewable energy plants, long-duration storage technologies that can potentially operate for weeks at a time, and vehicle-to-grid services utilizing electric vehicle battery capacity. Stationary storage technologies, alone, will require investments of $662 billion over the next two decades (BloombergNEF 2019a). Utility-scale battery storage solutions are now being rolled out across many electricity networks (approximately 42 percent of total storage deployed in 2019) (IEA 2020e). Still in the early stages of development, storage solutions currently rely heavily on policy support, including mandates and incentives, and are present within just a few markets (IEA 2020e). Yet energy storage installations globally are forecast to increase 122-fold, from 9 GW in 2018 to 1,095 GW by 2040 (BloombergNEF 2019a). Cheaper battery prices and increasing demand for storage—coupled with changes in market design that enable a level playing field—will drive these projected gains.

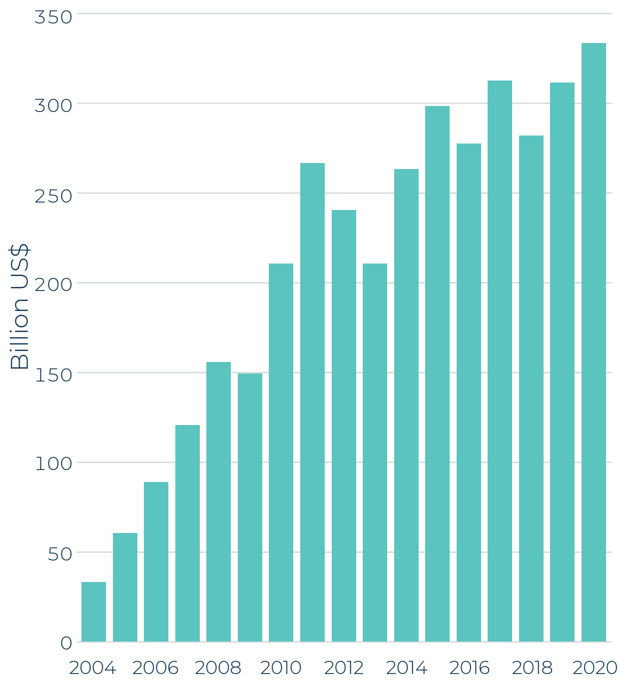
Improving integration of variable renewable energy sources into electricity grids

Integrating a large share of variable renewables requires a highly flexible grid—this will be critical to meeting 2030 and 2050 renewable electricity generation targets. Grids are made more flexible through new infrastructure (e.g., long-range transmission lines and energy storage), a strong portfolio of "clean firm power" that can be relied upon irrespective of weather and for as long as needed (e.g., geothermal power), technologies deployed at scale using, for example, bulk procurement, mass-scale retrofits, as well as through demand response (e.g., variable pricing) and efficiency measures to reduce peak demand (Baik et al. 2021; Hutchinson et al. 2021; IRENA 2019b). Enhanced system operations (e.g., advanced forecasting) also help ensure grid stability (IEA 2021h). Governments should plan for new transmission infrastructure to accommodate projected increases in renewables. For example, India and China are investing in building out their grids, particularly to absorb greater amounts of renewable energy in response to ambitious targets, and connecting their areas rich in wind and solar resources to demand centers (Hutchinson et al. 2021).

Adopting policies to increase renewable electricity generation and improve energy efficiency

Strong policy support has been central to the global deployment of renewables and driving renewable energy investments (Figure 10). By 2021, 165 countries had set national renewable capacity and/or generation targets, and 161 countries had adopted policies to achieve these goals, including regulatory and pricing instruments, such as feed-in tariffs, premium payments, renewable portfolio standards for utilities, net metering and billing, and renewable power tenders and auctions (REN21 2020). As more renewable energy projects come online, economies of scale are reached, which further improves performance, reduces costs, and enables solar and wind to compete with conventional power sources. Policies have kept pace with the evolving landscape of renewable energy, as regions enjoying significant renewable capacity have shifted their emphasis from measures that support technical and market integration of renewables toward those that help determine competitive prices through auctions for

FIGURE 10. Global new investment in renewable energy



Note: Renewable energy refers to onshore and offshore wind, large and small-scale solar, biofuels, biomass and waste, marine, geothermal, and small hydro.

Source: BloombergNEF (2021c).

large-scale renewable energy projects (REN21 2020). Overall, a predictable, transparent policy landscape that promotes investors' confidence that they will recover their investments is needed to continue to make strides in renewable power generation.

POWER INDICATOR 3:

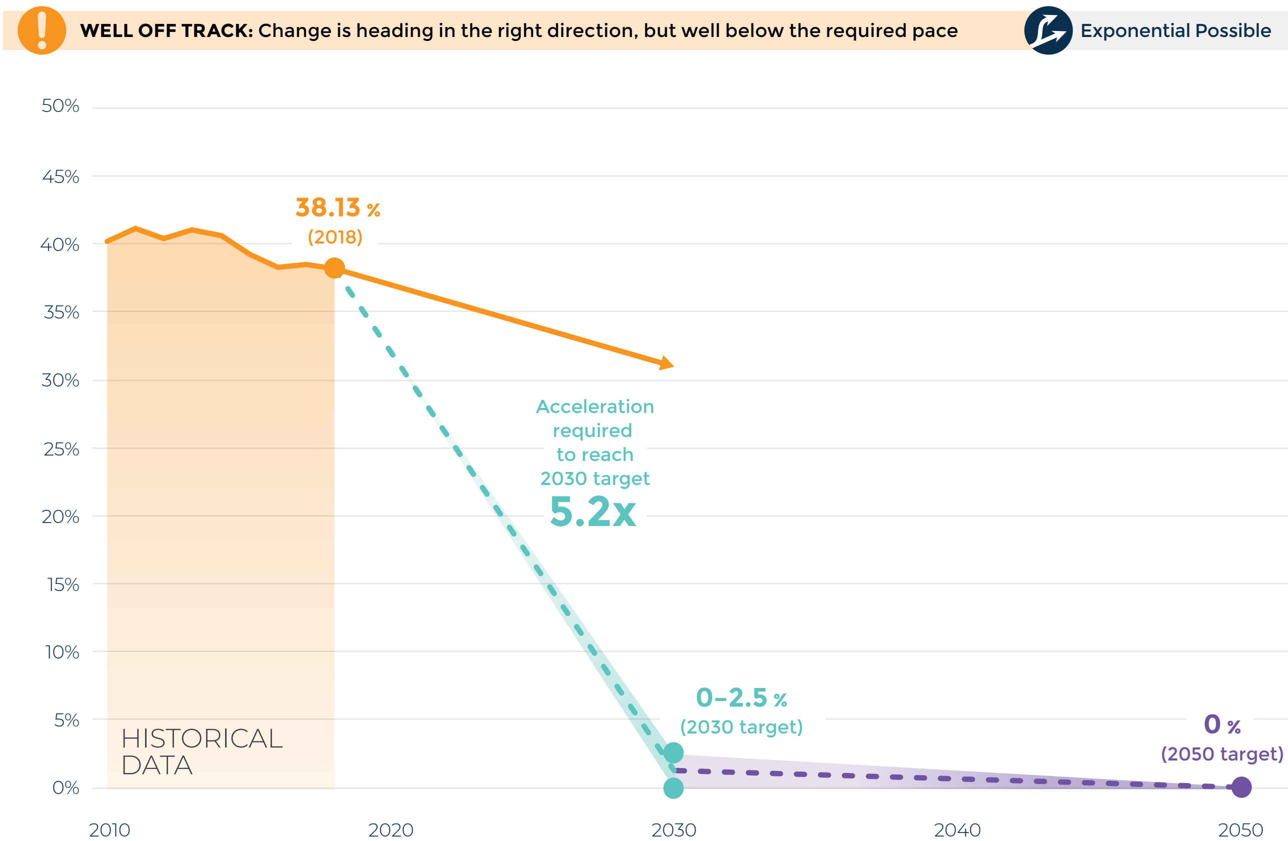
Share of unabated coal in electricity generation

Targets: The share of unabated[15] coal in electricity generation falls to 0–2.5 percent in 2030 and then to 0 percent in 2050.

Coal power plants are by far the largest source of carbon emissions in the power sector, producing on average around 800 gCO_2 per kWh generated (IPCC 2018). Globally, coal accounts for 38 percent of power generation (see Figure 11) and 74 percent of CO_2 emissions from the sector (IEA 2021c). Retiring coal generation capacity, therefore, is one of the most important short-term measures that could limit future warming. Because the average life cycle of a coal-fired power plant is 45 years (Erickson et al. 2015), recently installed power plants must retire early or be repurposed as energy storage facilities, while new construction must cease altogether to achieve the Paris Agreement's long-term temperature goal (IEA 2021c). To limit warming to 1.5°C, only a very small residual amount of power—0 to 2.5 percent—can be generated from coal in 2030 globally, with regional coal phaseout dates varying due to regional differences (Yanguas Parra et al. 2019).

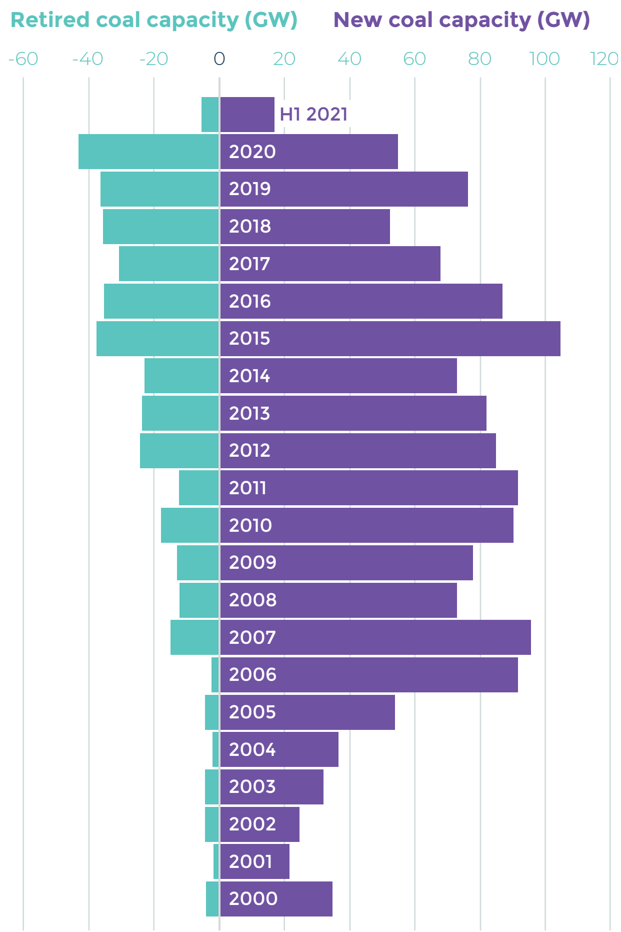
Most advanced economies have already experienced structural declines in coal power generation, including in the United States and many member states of the European Union. In 2019, for example, the share of coal in electricity generation was only about 20 percent for the European Union (IEA 2020g). But despite these gains in some developed countries and commitments to reduce coal capacity, worldwide coal buildout has not slowed sufficiently in recent years (Figure 12). In 2020, for example, newly installed coal capacity (54 GW) was still higher than retirements (43 GW) (Global Energy Monitor 2021a). More worryingly, new coal plants with

FIGURE 11. Historical progress toward 2030 and 2050 targets for the share of unabated coal in electricity generation



Source: For data, IEA (2020n); for targets, CAT (2020b).

FIGURE 12. **New coal capacity and retirements**



Note: H1 indicates the first half of 2021; GW = gigawatts
Source: Global Energy Monitor (2021a).

180 GW of installed capacity are under construction, and another 320 GW in new coal-fired capacity has been announced, received a prepermit or a permit, for a total of 500 GW in development globally. While this is down 66 percent from 2015 levels, it is still untenably high (Global Energy Monitor et al. 2021a).

Carbon capture and storage (CCS) could reduce emissions from remaining fossil power plants, particularly beyond 2030; however, widespread use of CCS faces a highly uncertain future. There are currently no large-scale, commercially viable examples of this technology, and it is not clear what the costs will be when deployed at scale. Further, CCS reduces efficiency, and fossil power plants with CCS still emit nontrivial amounts of CO_2, depending on the technology's efficiency. These emissions, in turn, would need to be offset by other net-negative technologies in a net-zero future.

Enablers of climate action

Even as governments, businesses, and banks are committing to accelerating the transition to clean energy, coal plants continue to receive finance—to the tune of $332 billion since the Paris Agreement was adopted in 2015 (BankTrack 2021). Successfully phasing out coal power by 2050 will require a combination of strategies aimed at the coal industry, including measurable, time-bound targets to reduce coal capacity and reform coal subsidies, along with just transition policies to minimize the adverse impacts of reducing coal on communities.

Setting ambitious coal phaseout targets

Establishing national targets to phase out coal sends a strong signal to the industry and helps avoid lock-in through new coal plants. Actors such as coal companies, unions, and civil society, as well as competitors of coal and financial institutions, play key roles in navigating the policy shift away from this fossil fuel (Brauers et al. 2020). Countries are likely to phase out their coal use at different rates, with advanced economies expected to do it sooner than the rest of the world. A wide range is seen among the few Group of 20 (G20) countries that have already set target dates with some (e.g., the United Kingdom) on a faster timeline and others (e.g., Germany) on a slower path that is not aligned with the Paris Agreement (Table 6) (Climate Transparency 2019; Brauers et al. 2020). Several other G20 countries with significant coal use are lagging

TABLE 6. **Coal phaseout targets of G20 countries**

Coal phaseout target year	2021	2024	2025	2030	2038	No target
G20 countries[a]	France	United Kingdom	Italy	Canada	Germany	Australia, Brazil, China, European Union, India, Indonesia, Japan, Mexico, Russia, South Africa, South Korea, Turkey, United States

a Argentina and Saudi Arabia have little to no coal being used for electricity generation and are not listed here.
Source: Climate Transparency (2019).

behind, building new capacity, and have no target dates or long-term vision for phaseout.

Beyond the G20, groups such as the Powering Past Coal Alliance (PPCA) are helping build support for complete phaseout of coal among national and subnational governments. By May 2021, 41 national governments had joined PPCA (PPCA 2021). While this signals progress, there is a need to expand membership to major coal consumers with higher costs of coal phaseout (Jewell et al. 2019). Further, initiatives like RE100 and Science Based Targets initiative (SBTi) are providing companies and financial institutions with a platform to make phaseout commitments.

Domestic efforts to phase out coal are often aided by considerable co-benefits from reducing coal power generation, such as improved local air quality (IRENA 2018). For example, in China, air pollution policies have helped reduce coal use, and in the United Kingdom, European Union pollution laws have contributed to the closure of old plants (Climate Transparency 2019).

Reforming fossil fuel subsidies

Around the world, coal prices are typically well below half of what they would be if there were no subsidies (Coady et al. 2019). Coal receives the largest share (44 percent) of all fossil fuel subsidies, with China, the United States, Russia, the European Union, and India among the countries providing the highest amount of energy subsidies (Coady et al. 2019). Although the practice of underpricing fossil fuels is pervasive, governments are beginning to implement energy pricing reform, which is often a slow and politically sensitive process (OECD and IEA 2019). From 2015 to 2020, at least 53 countries had implemented consumer subsidy reforms, raised taxes on fossil fuels, or implemented both measures (Table 7) (Sánchez et al. 2020). In 2021, the Group of 7 (G7) countries also agreed to stop international financing of unabated coal (Piper and Wacket 2021). Governments have also adopted producer subsidy reforms, though producers and utilities continue to receive a significant share of subsidies (IISD 2021b). The European Union, for example, will end government support of coal plants by 2025 (OECD and IEA 2019).

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

Shifts in jobs, changes in the quality of jobs, and individual job losses are expected as the world transitions away from coal. The coal mining industry alone employs about 8 million people globally (Jakob et al. 2020). While the transformation to clean energy will be accompanied by new jobs, these will not all provide similar remuneration as lost jobs, require comparable skill sets, or be located in the affected areas. For example, in China only 29 percent and 5 percent of coal mining areas are suitable for solar and wind power generation, respectively (Pai et al. 2020b). Strong measures (e.g., retraining programs, relocation measures, economic diversification strategies, etc.) to minimize the negative impacts on affected populations must accompany plans to phase out coal and reform subsidies. This will help ensure fairness, cultivate the political will for these actions, and enhance the likelihood that the policy-driven changes are long-lasting (Levin et al. 2012).

Just transition policies that are already underway include targeted income support programs, cash transfers, education funds, and health insurance schemes to provide a safety net (Sánchez et al. 2020). Egypt, for instance, has redirected revenues from fossil fuel subsidies to support other critical sectors, such as health and education (Sánchez et al. 2020). The government also implemented a campaign to raise public awareness of the benefits that these reforms can bring to communities. Similarly, governments can package these fossil fuel subsidy phaseouts as part of a broader energy transformation by reassigning resources to cleaner energy sources. Such examples of "subsidy swaps" exist in Zambia, Morocco, and India (Sánchez et al. 2020).

TABLE 7. Number of countries with fossil fuel subsidy reform

	2015	2016	2017	2018	2019	2020
Subsidy reform	14	26	29	33	27	30
Taxation reform	8	8	9	12	12	13
Subsidy and taxation reform	2	5	4	3	4	5

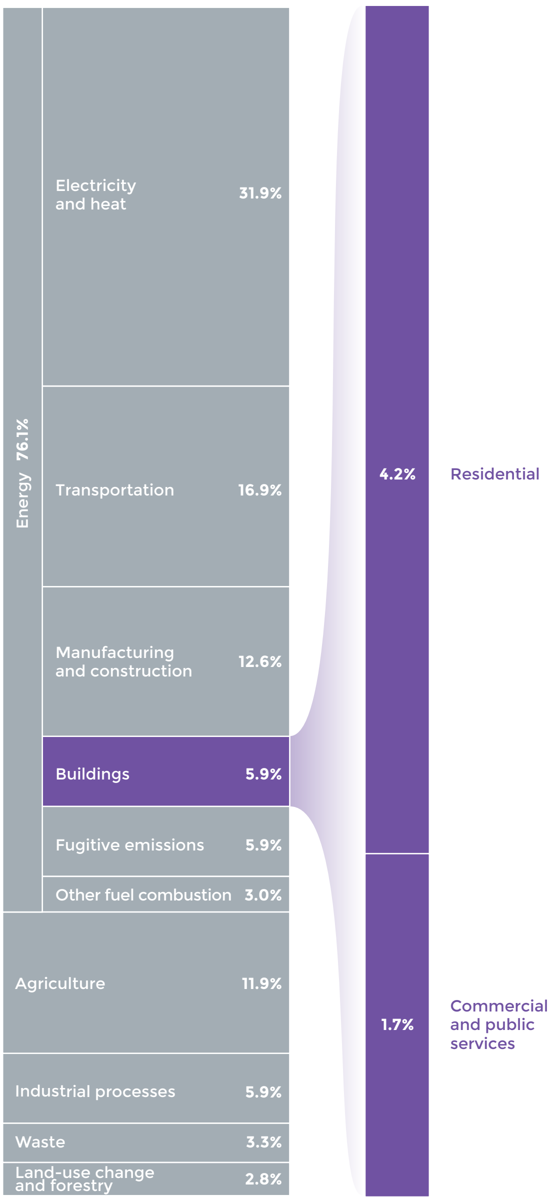
Note: Argentina and Saudi Arabia have little to no coal being used for electricity generation and are not listed here.
Source: Climate Transparency (2019).

4 BUILDINGS

Buildings are responsible for 5.9 percent of direct global GHG emissions (Figure 13) (ClimateWatch 2021), a figure that increases about threefold when including the indirect emissions from electricity and heat consumption (IPCC 2014).[16]

GROWTH IN ELECTRICITY CONSUMPTION in buildings has been mainly driven by population and economic growth. Increasing living standards, particularly in developing countries, have also improved electricity access and spurred higher use of electrical appliances and space cooling (IPCC 2018).

FIGURE 13. Role of the buildings sector in global greenhouse gas emissions



Source: ClimateWatch (2021).

Energy use and the carbon content of energy determine the level of emissions of the sector as defined by this indicator. As such, energy efficiency to reduce demand and electrification to shift away from carbon-intensive forms of energy are the two main drivers of decarbonization in buildings. These transformations rely primarily on technologies that are already available, including smart energy controls to avoid wasteful user behavior, heat pumps, energy-efficient appliances, and climatic and material-efficient building design (IEA 2021c).

In this chapter, we examine the transition in the buildings sector through three indicators: carbon intensity of residential and commercial buildings, energy intensity of residential and commercial buildings, and the rate of retrofitting. The three indicators in this section are closely linked. The carbon intensity per floor area reflects the share of low-carbon fuels used on-site and in the electricity grid, as well as the design and level of insulation of the building and its appliances. Energy intensity is similar but omits the fuel mix. Reducing energy consumption makes the transition to 1.5°C pathways easier and less costly than relying primarily on zero-carbon energy sources, as it decreases required investments in energy supply and distribution. The retrofitting rate describes the speed of one area of improvement that helps improve energy intensity and—as a result—emissions intensity.

Positive trends in the retrofitting rate will decrease the energy and carbon intensity levels. Improvements in the carbon intensity, however, may be the result of a cleaner fuel mix, meaning that the energy intensity can follow different trends. The sections describing the enablers of climate action for the indicators try to separate these overlaps: the carbon intensity indicator focuses on low-carbon energy solutions for buildings, the energy intensity indicator focuses on new builds, and the third indicator keeps its narrow focus on the retrofitting rate. For the indicator with available data (energy intensity), historical rates of change are headed in the right direction but are well below levels required

TABLE 8. Summary of progress toward 2030 buildings targets

Indicator	Most recent historical data point (year)	2030 target	2050 target	Trajectory of change	Status	Acceleration factor
Carbon intensity of building operations ($kgCO_2/m^2$)	60.70 commercial (2017)	15.17-21.24 (commercial)	0	Exponential change possible	?	Insufficient data[a]
	29.79 residential (2017)	10.40-16.38 (residential)				
Energy intensity of building operations (% change indexed to 2015 for which 2015 equals 100)[b]	98.14 (2019)	70-90 (commercial)	50-85 (commercial)	Exponential change unlikely	!	2.7x[c]
		70-80 (residential)	40-80 (residential)			
Retrofitting rate of buildings (%/yr)	1-2 (2019)	2.50-3.50	3.50 (by 2040)	Exponential change unlikely	?	Insufficient data[a]

Note: $kgCO_2/m^2$ = kilograms of carbon dioxide per square meter.

a This indicator has one historical data point and that, together with qualitative research, clearly shows it is not on track and must accelerate action, but we do not have enough information to assess how much it must accelerate (so we cannot categorize it into the yellow or orange). Thus it is in the "insufficient data" category.

b Energy intensity of building operations is indexed to 2015, because no separate historical data are available for residential and commercial buildings.

c The acceleration factor refers to the full range of targets across commercial and residential buildings, because historical data are not available for the two building types separately.

Sources: For data, IEA (2020a; 2020c; 2020k; 2019a); for targets, CAT (2020b).

for 2030 (Table 8). For the other indicators—carbon intensity and the retrofitting rate—one historical data point indicates they are not on track and must accelerate action. Qualitative insights support this judgment. We do not have enough quantitative information to assess how much they must accelerate, so we cannot categorize them. Openly accessible data at the global level are very limited for the buildings sector in general.

While a dynamic, S-curve growth is possible for the uptake of individual technologies in buildings, the energy and carbon intensity over time will likely not reflect such a curve, as it lumps together many different technologies and other factors, such as user behavior. For energy intensity, the required changes are not as drastic as for other indicators, making it possible to achieve them with less dynamic growth. For retrofits and the carbon intensity, one could assume an S-curve-type development in the future, which, rather than reflecting the progress of individual technologies, illustrates a shift to a different overall system, where retrofitted buildings and a high share of nonfossil fuels become the new normal.

The building sector is highly diverse; decarbonization trends vary greatly and so do the required actions to get the sector to decarbonize. Examples of extreme building diversity include Europe and North America with a relatively old building stock, and developing countries where fast-growing populations and economies are expected to nearly double the urban population by 2050 (UN DESA 2018). 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). Different climatic zones also require different approaches. Another extreme in terms of the structure in the energy demand in buildings is sub-Saharan Africa, where many people today rely on traditional biomass for cooking and heating, implying a huge suppressed demand for electricity.

Benefits of improving the energy and carbon intensity of buildings beyond mitigation of climate change include health benefits through improved indoor air quality, more comfortable living and working spaces, and avoiding or decreasing energy poverty. But building retrofits can be disruptive, often with complicated permitting processes and high upfront costs despite generally good payback periods, which may be discouraging. These issues are the biggest challenge the buildings sector faces in trying to achieve the required pace and depth of retrofits in the coming years (IEA 2021c).

This report focuses on the reduction of energy-related emissions of buildings, where we had a consistent set of Paris-compatible targets available at the time of writing the report. Additional areas of critical action related to buildings are material efficiency to avoid embodied emissions, reducing emissions of fluorinated gases from cooling in buildings, and waste avoidance and management. This report omits the analysis of floor area, an indicator of the activity level in the building sector, where Paris-aligned benchmarks are not available. The IEA expects the floor area worldwide to increase 75 percent between 2020 and 2050, of which 80 percent is expected to be in emerging markets and developing economies (IEA 2021c).

BUILDINGS INDICATOR 1: Carbon intensity of building operations

Targets: The carbon intensity of building operations for residential buildings is 45-65 percent lower than 2015 levels for select regions and 65-75 percent lower than 2015 levels for select regions for commercial buildings by 2030. All buildings reach near zero carbon intensity globally by 2050.

Through a transition to zero-carbon energy sources and highly efficient building envelopes, the carbon intensity of residential and commercial building operations in select regions[17] needs to decrease quickly by 2030 to be aligned with a 1.5°C-compatible pathway. By 2050, all buildings globally need to reach an emissions intensity near zero. A fast reduction of the intensity of the building stock is even more important given the expected growth in floor area.

Data limitations prohibit a clear quantitative assessment of progress in the global average emissions intensity of commercial and residential buildings. Total emissions from buildings have continued to increase by an average of 1 percent per year over the last decade (IEA 2020b), as total floor area has increased at around 2.5 percent per year over the same period (IEA 2019b). Although emissions intensities have decreased when averaged across the world, the pace of this improvement is insufficient to counteract increases in floor area and, therefore, reduce total emissions to reach the targets for this indicator (see Figures 14 and 15). Mitigation efforts in the building sector in most regions of the world need to significantly accelerate to bring emissions into line with Paris Agreement goals.

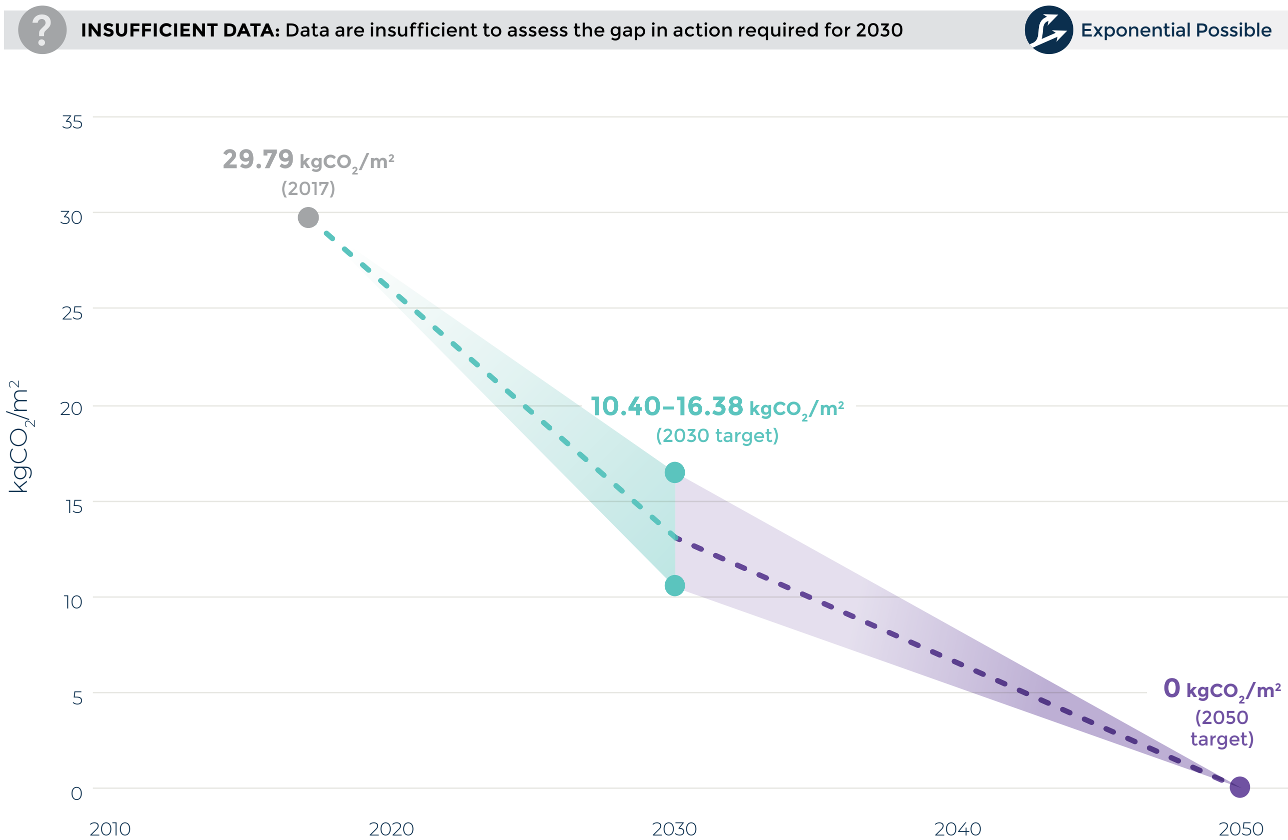
Two main technology options exist for decarbonizing the thermal energy demand of the building sector:

- The electrification of heating and cooling demand, which can be met through heat pumps[18] and electrification of cooking. For full decarbonization, the electricity used must be zero-carbon as well (see Power Targets 1–3).
- The use of renewable energy (e.g., biogas, woodchips, solar thermal energy, or recovered heat) for the supply of heating and warm water. In select cases, green hydrogen may also be an option (see Industry Indicator 5).[19]

The optimal path will vary by climate and other national or local circumstances. Given the seasonality of solar and sustainability concerns for the large-scale use of biomass (e.g., land use, biodiversity, and local air pollution); electrification is of utmost importance and can have a lasting, transformative effect on the sector. Given that this indicator is dependent on multiple types of technology adoption, there is a possibility for nonlinear change in its future trajectory.

This indicator focuses on energy-related emissions from buildings. Embodied emissions (i.e., the emissions resulting from the production and transport of construction materials) play an important role. The UN Climate Action Pathway for Human Settlements suggests that such emissions need to be reduced by at least 40 percent by 2030, and to zero by 2050 (Marrakech Partnership 2021).

FIGURE 14. Historical progress toward 2030 and 2050 targets for carbon intensity of residential building operations

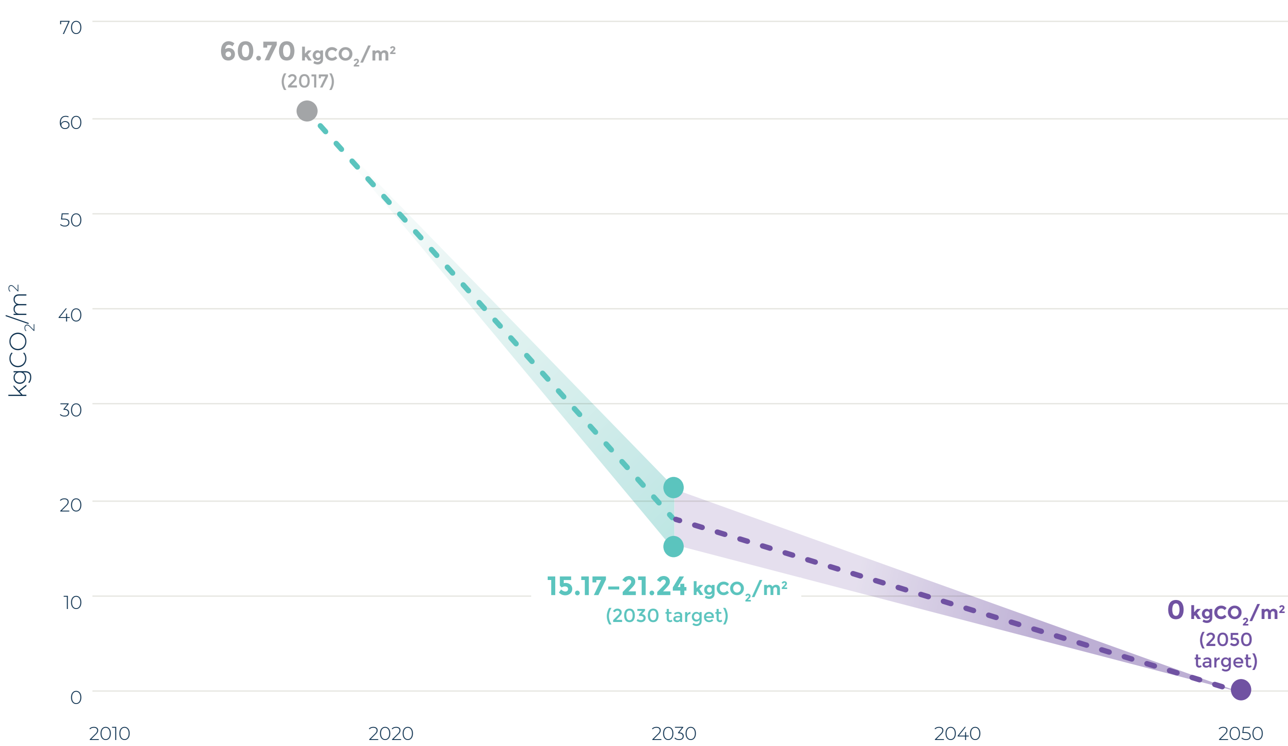


Note: $kgCO_2/m^2$ = kilograms of carbon dioxide per square meter. Data are insufficient to calculate an acceleration factor, given only one historical data point.

Sources: 2030 and 2050 targets taken from CAT (2020b). Historical data calculated based on IEA (2020c, 2019a).

FIGURE 15. Historical progress 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. Data are insufficient to calculate an acceleration factor, given only one historical data point.
Sources: 2030 and 2050 targets taken from CAT (2020b). Historical data calculated based on IEA (2020c, 2019a).

Enablers of climate action

To avoid overlaps in the text across the three indicators in the buildings sector, this section looks only at enablers of improving carbon intensity through low-carbon energy solutions in buildings. The text focuses on the supply of thermal energy (heating and cooling). The decarbonization of electricity is covered under the indicators in the power sector.

The widespread implementation of zero-carbon technologies in buildings faces two main challenges:

- Higher costs to the consumer for many renewable solutions. Unlike renewable electricity, renewable heat (e.g., solar thermal) is often not yet available at competitive prices, and while heat pumps have improved over the last years and are becoming cost-competitive, refurbishing homes with heat pumps has high upfront costs (IEA 2019b; D'Aprile et al. 2020).
- The large number of actors with differing levels of abilities to purchase energy, let alone new equipment required for a fuel switch (IEA et al. 2021).

This calls for a comprehensive package of financial support and leadership from key players to make low-carbon technologies the new normal in the buildings sector. At the same time, locking in carbon-intensive technologies must be avoided, this is where the role of district heating needs to be regarded carefully, although it can contribute to managing the multiactor challenge and support decarbonization at scale.

Increasing financial and regulatory support to increase adoption of heat pumps

Heat pumps provide thermal energy most efficiently at a relatively low temperature level and are thus very well suited for heating and cooling well-insulated houses, both new and renovated. However, technology improvements in recent years make heat pumps more and more attractive to also generate higher-temperature heat for households (McKenna et al. 2020). The number of heat pumps installed has increased in recent years, particularly in new buildings in Europe, North America, and Northern Asia. Financial incentives to cover a part of the upfront costs, as well as labeling and efficiency standards, have supported adoption of this technology in recent years (IEA 2020m). Continued technology improvements for heat pumps have also supported this positive trend. These two drivers reinforce each other: regulations, standards, and labeling create transparency regarding the performance of heat pumps and set best practice standards or mandatory requirements. Financial support increases the market for the technology. As awareness and acceptance of the technology increase, so does the market volume, and costs decrease through economies of scale. Less need for financial incentives and the possibility of increasing the stringency of regulations and standards are the result.

Even the IEA's more conservative Sustainable Development Scenario projects that the contribution of heat pumps today—5 percent share of global residential heating demand[20]—will triple by 2030 (IEA 2020m). More countries need to implement financial and regulatory policies for heat pumps as a main means of electrification of thermal energy supply in buildings globally. Besides targeting heat pumps directly, particularly in regions with a high share of old buildings, there is also a need to increase the retrofitting rate and level of insulation when renovating, so that heat pumps become even more attractive beyond new construction. In parallel, planning for grid infrastructure and electricity generation needs to consider the changes in demand patterns from buildings.

Planning for district heating systems to avoid unintended consequences

District heating (a central form of energy conversion combined with a network to distribute the heat) can supply multiple buildings with heat, saving space and efforts for building owners. If the central heat supply is decarbonized, so is the heat supply of the whole network. Besides renewable energy sources, heat recovery from wastewater, data centers, and industrial processes can be sources of heat. Economies of scale can also make options such as geothermal energy more attractive than they would be on a smaller scale (IEA 2020m). However, the availability of district heating requires a minimum level of heat demand from the buildings for the network to be economically feasible, and thus risks creating disincentives for near-zero-energy buildings. Municipalities and energy companies involved in planning district heating thus need to carefully consider the construction, maintenance, or expansion of heat networks.

Only a few countries have transitioned to a large share of low-carbon fuel supply in buildings. Where these trends are observed, they have thus far occurred in a combination of district heating systems with biomass (e.g., Sweden) (IEA 2019b; Ericsson and Werner 2016). These countries have high biomass potential, and it is not possible to transfer this setup to most other countries sustainably. District heating systems today mostly use fossil fuels, with a large amount of coal consumed in such systems in China and Russia (IEA 2019b).

In a low-carbon future, district heating can play a role in dense areas with a large share of old buildings, such as the city centers of historically grown cities. However, the use of district heating should not be an excuse for relaxing building codes. New builds need to be near-zero energy, and retrofits should go to the highest level of efficiency possible.

The planning for district heating needs to account for the required retrofitting activities to avoid the construction of heating grids that would become stranded assets under a Paris-compatible buildings sector. Biomass as a source of energy for district heating is only a Paris-compatible option where its sustainability is assured and life-cycle emissions are near zero.

Establishing subnational and nonstate actor commitments and roadmaps to decarbonizing buildings

In addition to national governments, several other actors shape the future of the buildings sector, including companies and municipalities that own buildings and industry associations in the sector. Their commitment to a zero-carbon future can give the sector a sense of direction, facilitate action on the ground, and support knowledge sharing. The development of roadmaps links the commitments to reality and spurs implementation. A number of initiatives have been targeted at the local level:

- The "Net Zero Buildings Carbon Commitment" of the World Green Building Council (WGBC), with about 140 signatories,[21] including business and organizations, cities, states, and regions (World Green Building Council 2021).

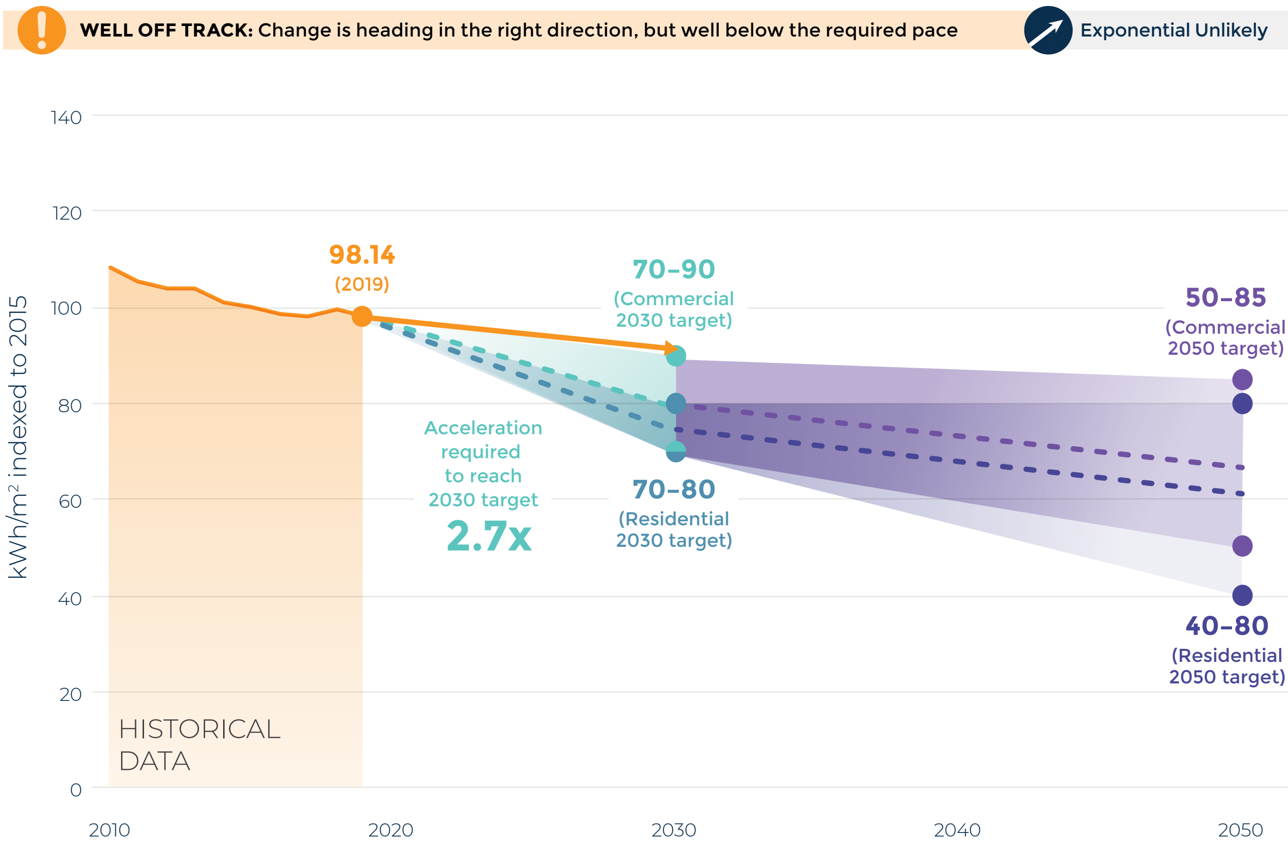
- The C40 Net Zero Carbon Buildings Declaration (C40 Cities 2018). Cities that sign the declaration commit to establishing regulations and planning policy so that by 2030, all new buildings operate at net-zero carbon, and by 2050 all buildings do. Some of the signatory cities additionally promise to get to zero carbon for all of their own buildings by 2030.
- The Zero Carbon Buildings for All initiative (WRI 2019b, 2021k). Under this initiative, national and local leaders from all over the globe commit to developing and implementing policies to drive decarbonization of all new buildings by 2030 and all existing buildings by 2050. Financial and industry partners are also part of the initiative and commit to providing expert input and $1 trillion in market action by 2030.
- The Zero Carbon Building Accelerator (WRI 2021j). This project fosters outreach, dialogue, planning, and policy adoption for zero-carbon buildings.

BUILDINGS INDICATOR 2: Energy intensity of building operations

Targets: 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.[22] 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.[23]

Globally, energy intensity decreased by 19 percent from 2000 to 2015 and another 2 percent by 2019 (IEA 2020a). While the decrease was faster in the 2000s and early 2010s, it has slowed in recent years and needs to accelerate again to fully meet the targets (see Figure 16). The historical trend between 2014 and 2019 will need to accelerate by 2.7 times to meet the midpoint of the target for the commercial sector in 2030 and by 3.4 times for the residential sector.[24] To fully decarbonize buildings in

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



Note: The source of the historical data (IEA 2020a) does not specify the building types included; we used the same data set for commercial and residential buildings.

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

the future, the sector requires a clear shift to best available technologies: near-zero energy levels for new constructions and retrofits, as well as the most efficient appliances. Near-zero energy means that the energy demand of the building is very low. For example, the thermal energy demand is limited because of a high degree of insulation, passive design and solar heating, and net-electricity demand is small because the building integrates rooftop solar energy to generate electricity and adopts efficient appliances. Further, new constructions need to minimize their embodied carbon, to decrease the demand for high-emitting materials.[25]

Heating and cooling are major drivers of energy demand. Cooling needs will become especially important as climate change causes higher average temperatures, with impacts on health and ability to work. IEA data show that sales of air conditioners have grown quickly in recent years, with India showing the fastest growth rate, at about 15 percent per year between 2010 and 2019 (IEA 2020l). Cooling requirements can also be reduced through passive cooling measures, including insulation, reflective surfaces, shading, green infrastructure and natural ventilation.

Enablers of climate action

To avoid overlaps in the text across the three indicators in the buildings sector, this section looks only at enablers of improving energy intensity of appliances and new buildings. Improvements to existing buildings are covered under Buildings Indicator 3, "Retrofitting rate."

The energy demand of new buildings can be decreased by improving the efficiency of appliances and equipment (e.g., cooking stoves, electrical equipment, lighting, and equipment for heating and cooling) and by reducing the heating and cooling demand of buildings through improvements in the building design and envelope. Smart controls further limit energy demand and alleviate the risk of wasteful user behavior.

The widespread implementation of those measures faces several challenges:

- The lack of or weak efficiency requirements in building codes for new construction and/or loose enforcement of existing codes (IEA and UNDP 2013)
- The perception that investing in energy efficiency is risky, heightened by the difficulty of accurately predicting energy savings (Bertoldi et al. 2019)
- The higher upfront costs of construction for above-code energy performance

A clear regulatory framework and financial incentives can increase the efficiency of new buildings and appliances. Analysis of and education on building codes can help inform building owners and developers about typical cost and savings impacts. Education can also help address the "rebound effect," where users increase consumption due to reduced energy costs. Outcome-based building codes, which are tied to building operational performance, can address both technical capabilities and occupant behavior.

Strengthening efficiency codes for new constructions

Building codes and standards that mandate greater efficiency of buildings already play a key role in improving efficiency in many countries. Under a decarbonization pathway, new buildings will need to embrace the least energy-intensive technology possible and strive for near-zero energy consumption. In some regions policymaking sets these regulations as the default already. For example, since 2020, the European Union's Energy Performance of Buildings Directive requires member states to ensure that all new buildings are near-zero energy (European Commission 2019). Standards of this ambition are even more important in regions where new constructions are dominant, such as in countries with high urbanization rates. In addition to high stringency, codes should cover all newly constructed buildings, both commercial and residential, in both urban and rural areas.

Compliance mechanisms will be necessary to ensure that codes are enforced. Despite the sector's diversity, knowledge sharing between policymakers and the entire construction value chain can drive the adoption of mandatory and stretch building codes. One initiative that supports the global adoption of zero-emissions building codes is the "Zero Code." The Zero Code provides a framework for near-zero-carbon building codes, including language that policymakers can use in their legislation and software to support calculations about, for example, the feasibility of solar energy on the roof of the building (Architecture 2030 2021b). The Zero Code also includes embodied carbon.

Setting standards for, as well as incentivizing, highly efficient appliances

Minimum energy performance standards are a key policy instrument to improve the energy performance of equipment. Indirect emissions of the buildings sector have increased in recent decades (IEA 2020b), likely also as a result of the increased number and use of appliances, including air conditioning.[26] Most household appliances have a technical lifetime of less than a decade, while commercial building equipment can last 15–25 years or more. The standards should also consider recycling and, where appropriate, repairing of appliances to ensure minimal life-cycle energy needs and associated emissions, also of fluorinated gases from refrigerants. Minimizing the negative impacts of the appliances over their full life cycle—including production, use, and disposal—will not change the efficiency of the buildings sector, but it will generate savings elsewhere.

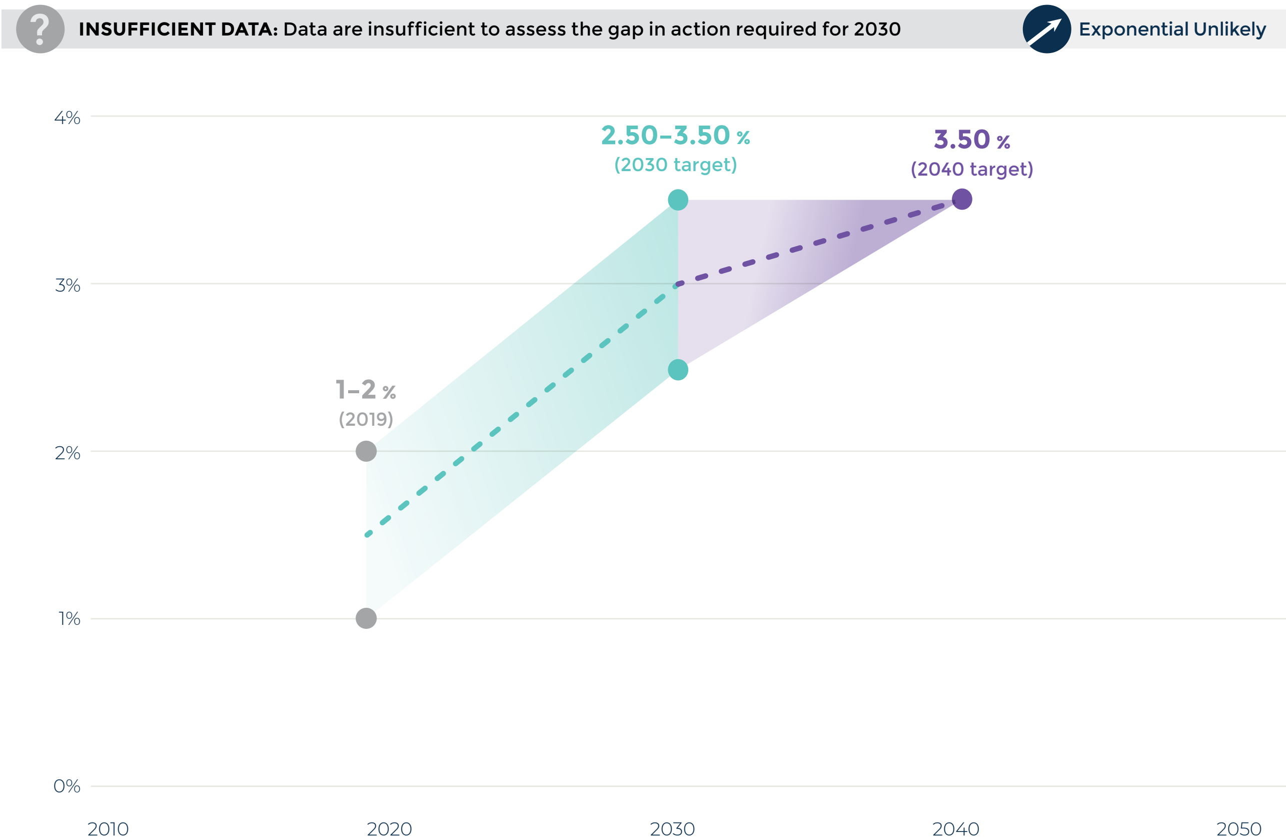
The standards for appliances should consider the climate impact of refrigerants, to support the phaseout schedule under the Kigali Amendment to the Montreal Protocol for substances with a high global warming potential.

BUILDINGS INDICATOR 3: Retrofitting rate of buildings

Targets: Globally, the annual retrofitting rate of buildings reaches 2.5–3.5 percent by 2030 and 3.5 percent by 2040; all buildings should be well insulated and fitted with zero-carbon technologies by 2050.

Retrofitting the building stock is a major requirement to enable the building sector to get on a 1.5°C-compatible pathway. By 2050, all buildings should be energy efficient and designed to meet zero-carbon standards. To that end, the retrofitting rate needs to increase to 2.5 to 3.5 percent per year in 2030, and 3.5 percent in 2040 (see Figure 17). These retrofitting rates refer to deep retrofitting, which goes significantly beyond current conventional practice.[27] To limit the number

FIGURE 17. Historical progress toward 2030 and 2040 targets for the retrofitting rate of buildings



Note: The data are very uncertain, and there is no clear definition of a deep retrofit. Data are insufficient to calculate the acceleration rate needed to reach the 2030 target. Only data available are for shallow retrofitting rates; deeper retrofitting is needed to meet the targets.
Sources: Historical data based on IEA (2020k); targets from CAT (2020b).

of retrofitting rounds by 2050, it is recommended that the retrofit result in as close as possible to a zero-carbon building. The retrofitting rates refer to improved insulation and design of buildings, as well as shifts to efficient and zero-carbon technologies for heating, cooling, cooking and other appliances, and the implementation of plug-load management and occupancy-based controls. Depending on the type of building (e.g., commercial or residential), different elements may be more important than others. The exact combination of them and the economic feasibility is very much case-dependent.

Data on retrofitting rates are difficult to obtain and therefore difficult to track. The IEA states that shallow[28] retrofitting rates are on the order of 1–2 percent per year (IEA 2020k), and less than 1 percent per year in advanced economies (IEA 2021c). Architecture 2030 mentions a retrofit rate of 0.5 to 1 percent (Architecture 2030 2021a). While limited historical values of retrofitting rate data are available to calculate the historical rate of change and the rate of change needed to achieve the targets, the current rate of energy retrofitting is clearly not sufficient for the deep retrofitting target set for 2030 and 2040. Both the depth and pace of retrofitting needs to increase drastically. Retrofitting is more important where most of the building stock that will exist in 2050 has already been built; this includes most European countries, the United States, Canada, Japan, and Australia, but also and increasingly China (Liu et al. 2020).

Enablers of climate action

Increased retrofitting rates with strong efficiency improvements face two principal challenges:

- The multitude of different actors required for this shift (i.e., homeowners) and the insufficient coordination of them (Brown et al. 2018).
- The disruption and affordability of retrofits, including the need for investments along renovation cycles independent of the building owner's liquidity (Kruit et al. 2020; BPIE 2017).

The conflict between deep and fast retrofitting: the stronger the retrofit is, the fewer building owners will sign up for it; but a retrofit that is too shallow locks in an insufficient level of efficiency.

To overcome these challenges, strong leadership is needed that supports coordination and translates into a comprehensive set of incentives and regulations. Such leadership should embrace the need for strong and deep retrofits simultaneously.

Supporting multistakeholder coordination to increase demand for deep retrofits

Speeding up the retrofitting of buildings will require the conjoined efforts of multiple actors, all of whom have their own motivation for (or aversion to) retrofitting. It is particularly challenging to motivate millions of building owners to initiate a retrofit that takes the building close to zero energy. More insights on this topic can be found in Carmichael and Petersen (2018); Killip et al. (2020); Guzowski (2014); Miu and Hawkes (2020); and Melvin (2018).

The knowledge by architects, designers, and contractors of low-carbon retrofit options heavily influences a client's evaluation of these solutions' feasibility (Simpson et al. 2020). Training and educating these actors well, and creating awareness of zero-carbon retrofits, is essential. Increased requests from clients can also make architects, designers, and contractors more interested in these options. Clients that could make such requests include the public sector, which should set benchmarks through its own buildings for retrofit depth and speed, in addition to seeking the most cost-efficient solutions.

The "Energiesprong" initiative connects different actors, serving as an intermediary between building owners, construction companies, and policymakers, with the aim of making net-zero energy building materials affordable and the retrofitting as undisruptive as possible. The program started in the Netherlands in 2010 and is gaining traction across Europe (Energiesprong Foundation 2021). International initiatives, such as the Race to Zero Built Environment System Map or the Building System Carbon Framework of the World Business Council for Sustainable Development, also support interactions among different players (World Green Building Council 2020; Race to Zero 2021c). An example for a local initiative in this area is Washington, DC's high-performance building hub (Department of Energy & Environment [District of Columbia] 2019).

Creating low-cost loans and grants, and fostering contract financing models to boost the affordability of retrofitting

Affordability is a key driver of retrofitting, and low-interest loans and grants for retrofits, or contract financing models, can support it. In contract financing models, contractors take on the upfront payment and administrative burden and guarantee a particular energy service, and the investor, often the building owner, pays a monthly fee. Examples include energy service companies or the Property Assessed Clean Energy program in the United States (Office of Energy Efficiency and Renewable Energy 2021).

Deep retrofits often require tailor-made solutions, making them sometimes difficult to plan and more expensive than ensuring the energy efficiency of a new building. To avoid disruption, owners can implement energy retrofit measures when other refurbishments take place, when a piece of equipment, such as a gas boiler, is replaced, or when all or part of the building is not being used for other reasons. To increase the retrofitting rate, it will be necessary to start energy-related retrofits even if other renovations (for example, painting a building or fixing a roof) are not yet necessary. The timing may not coincide with the availability of savings to cover additional upfront costs, which makes the wide availability of finance options essential. Green mortgages can come in, for example, at the point of refinancing. National and local governments are best placed to decide whether loans are sufficient to overcome the burden of upfront costs, or whether grants are needed to make the additional effort cost-neutral, based on circumstances on the ground.

Risks resulting from lower costs to consumers include increased demand, which leads to higher prices for construction in the largely liberalized construction sector, and "free riding" by actors who would have been able to afford the costs without the policy incentive (Artola et al. 2016).

Several governments are incorporating green energy considerations into their COVID recovery plans, including funding for buildings. Germany, for example, has provided extra funding for a CO_2-focused building-retrofit program (Artola et al. 2016), and South Korea plans to retrofit part of its public buildings stock (Ministry of Economy and Finance 2020).

Establishing clear governmental targets to guide deep retrofitting

Clear targets and national strategies for the sector can guide the thinking of local policymakers and other actors, simultaneously coordinating their efforts and setting a priority for deep and fast retrofitting. The European Union has called for a "renovation wave," with the aim of doubling the retrofitting rate in its member states, and providing a stimulus to the construction sector. The strategy document suggests various areas of intervention, including information and regulatory measures, funding, addressing energy poverty, and technical assistance (European Commission 2020b). Various cities incentivize retrofits through local legislation; successful examples are Tokyo's cap-and-trade policy (Bureau of Environment, Tokyo Metropolitan Government 2020) and New York City's Local Law 97, which requires large buildings to reduce their emissions by 40 percent by 2030 and 80 percent by 2050 (New York City 2019).

The BUILD UPON2 project, supported by the WGBC, works with eight pilot cities to develop an impact framework for cities to measure the benefits of renovation projects across environmental, social, and economic factors, and to identify which of these can be scaled up to the regional and national level.

In combination with other support, policymakers can also set highly efficient standards for retrofits, increasing their depth to get close to near-zero energy. For example, one clear signal for a transition to a decarbonized buildings sector would be banning new natural gas installations in buildings. The IEA suggests no sales of gas boilers as of 2025, globally (IEA 2021c). The United Kingdom is also discussing such a measure (IEA 2020r; Howell 2020).

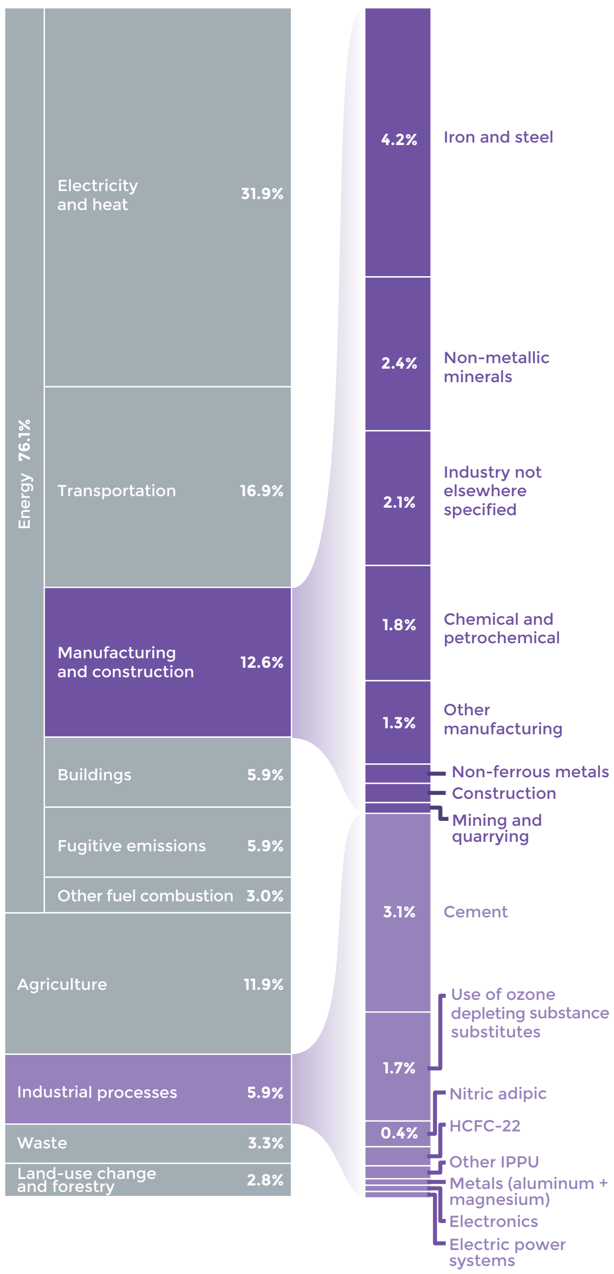
5

INDUSTRY

Industry has a critical role to play in limiting warming to 1.5°C. Emissions from industry have grown the fastest of any sector since 1990 (Ge and Friedrich 2020), and now account for 18.5 percent of direct global GHG emissions (Figure 18) (ClimateWatch 2021).

MITIGATING EMISSIONS IN INDUSTRY WILL require a range of new and existing technologies and practices. Improved product design, such as in buildings and automobiles, can reduce waste from overbuilding and enhance recyclability. Technologies include hydrogen, sustainable bio-based feedstocks, alternative materials, and carbon capture, utilization, and storage (CCUS), which are all technically proven at different scales (IPCC 2018). Improved energy and process efficiency, coupled with end-use electrification where possible, are also part of the solution set.

FIGURE 18. Role of the industry sector in global greenhouse gas emissions



Note: HCFC-22 = chlorodifluoromethane, a common refrigerant; IPPU = industrial processes and product use
Source: ClimateWatch (2021).

In this chapter we examine the industry transition through five indicators (Table 9), focused on two heavy industries—steel and cement—that account for more than half of CO_2 emissions from the industry sector (IEA 2020b).[29] For one of the five indicators, historical rates of change are headed in the right direction at a promising but insufficient pace, while for another two, historical rates of change are headed in the right direction but are well below levels required for 2030. The remaining two have experienced stagnant historical rates of change, and a step change in action is needed to achieve the 2030 targets (Table 9).

Heavy industry is often characterized as "hard-to-abate," but some solutions are readily available and can lead to cost savings. For example, energy- and process-efficiency practices can be economically feasible and help drive industrial system transitions. But these technologies on their own are insufficient to align the heavy industry sector with a 1.5°C pathway and must be complemented with carbon removal or replaced with GHG-neutral technologies (IPCC 2018).

To illustrate the scale of the challenge, more than 60 percent of the mitigation needed to significantly reduce emissions in industry relies on technologies that are only under development today, not yet commercially available (IEA 2021c). An overarching complicating factor for reducing emissions in industry is the long-lived nature of the equipment. Average lifetimes of emissions-intensive assets such as blast furnaces and cement kilns, for example, are around 40 years (IEA 2021c). This underscores the importance of getting demonstration and pilot projects to the market very quickly, so as to inform the next investment cycle.

TABLE 9. Summary of progress toward 2030 buildings targets

Indicator	Most recent historical data point (year)	2030 target	2050 target	Trajectory of change	Status	Acceleration factor
Share of electricity in the industry sector's final energy demand (%)	28.35 (2018)	35	50–55	Exponential change possible	—	1.1x
Carbon intensity of global cement production (kgCO_2/t cement)	635.47 (2018)	360–70	55–90	Exponential change possible	✕	n/a; historical data flat
Carbon intensity of global steel production (kgCO_2/t steel)	1,830 (2019)	1,335–50	0–130	Exponential change possible	✕	n/a; historical data flat
Low-carbon steel facilities in operation (# of facilities)	0 (2019)	20	All facilities	Exponential change possible	!	Insufficient data[a]
Green hydrogen production (Mt)	0.07 (2018)	0.23–3.50 by 2026	500–800	Exponential change likely	!	n/a; in emergence stage of S-curve

Note: n/a = not applicable; kgCO_2/t = kilograms of carbon dioxide per tonne; Mt = million tonnes.

a This indicator has only one historical data point, so historical rate of change cannot be calculated, but the number of planned projects gives an indication of the expected future growth, which suggests that a step change in acceleration is required.

Sources: For data, IEA (2020n); GCCA (2019); Andrew (2019); IEA (2020n); USGS (2021); World Steel Association (2020b); Leadit (2021); Global Energy Monitor (2021b); and IEA (2019c). For targets, CAT (2020a; 2020b) and Race to Zero (2021a).

INDUSTRY INDICATOR 1:

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

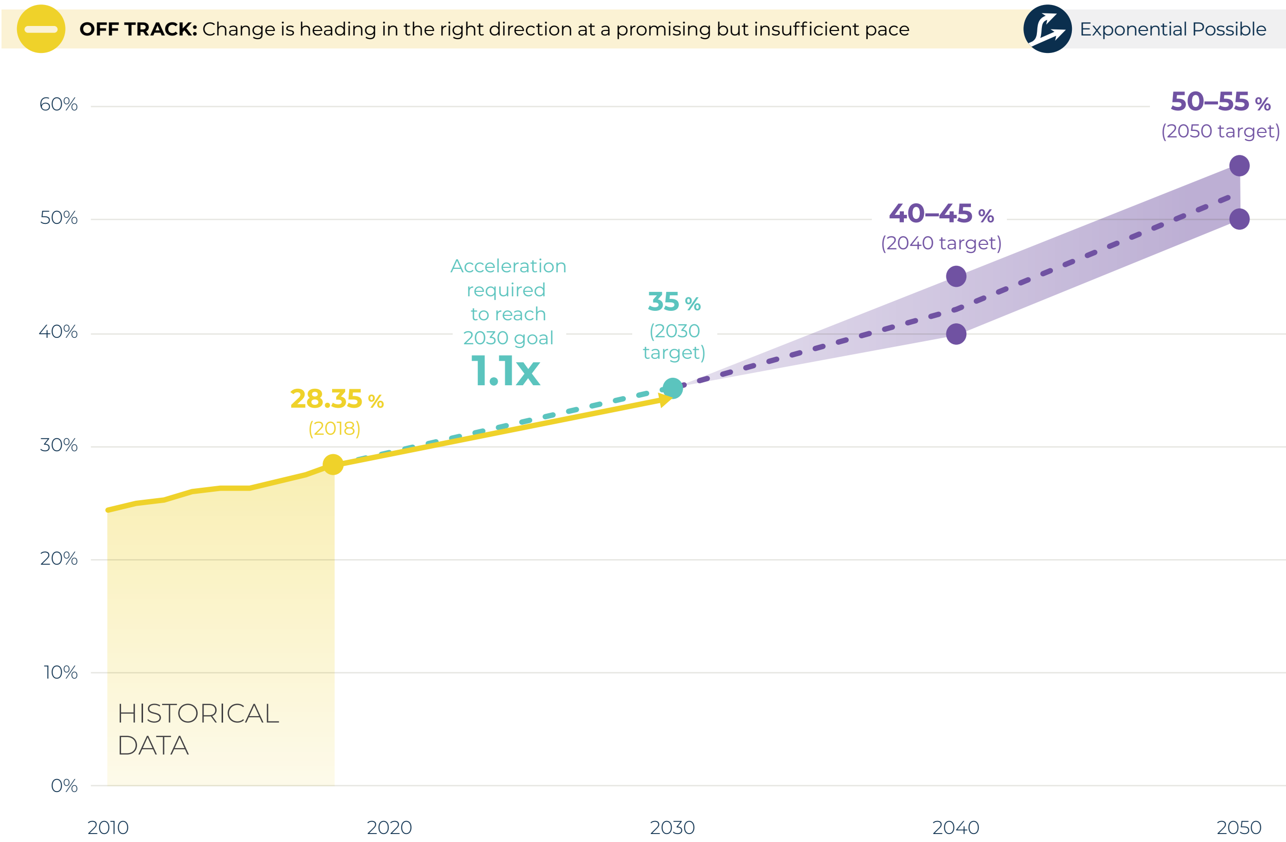
Targets: The share of electricity in the industry sector's final energy demand increases to 35 percent in 2030, 40–45 percent in 2040, and 50–55 percent in 2050.

As the sector that consumes the most energy, requiring high temperatures for many of its processes, industry is highly dependent on fossil fuels for its energy consumption, much of which can be reduced through a shift to electric technologies. Past electrification efforts have focused primarily on nonheating industrial operations, and today machinery such as pumps, robotic arms, and conveyor belts consume most of the sector's electricity. But looking ahead, decarbonization of industry will require the electrification of heat supply as well as indirect electrification, including the use of hydrogen as an energy carrier and industrial feedstock—a shift that will depend on the deployment of both existing and innovative technologies.

According to Roelofsen et al. (2020), about 50 percent of fuel consumed for energy in the industry sector could be electrified through the adoption of existing technologies. This includes all generation of heat up to 1,000°C (Roelofsen et al. 2020). Nevertheless, a substantial share (about 30 percent) of energy consumption in the industry sector is for processes requiring heat above 1,000°C, such as cement-making and ceramics production. Even though electrification technologies are under development for these purposes, they are not yet mature (ETC 2019a; Roelofsen et al. 2020). Beyond heat, indirect electrification can replace fossil fuels through the use of hydrogen, which can serve as an industrial feedstock.

Over the last five decades, the share of electricity in the industry sector's final energy demand has slowly increased through the introduction of electricity-dependent technologies, including digitalization, automation, and machine drive (McMillan 2018; IEA 2017b). Electricity demand rose from 15 percent of industry's energy demand in 1971 to about 28 percent in 2018 (Figure 19). To follow a 1.5°C-compatible pathway, this share needs to reach 35 percent in 2030, 40–45 percent in 2040, and 50–55 percent in 2050 through the adoption of electric technologies. Such a trajectory suggests an average annual growth rate of 0.6 percentage points between 2018 and 2030, and 0.9 percent between 2030 and 2050, compared to a historical average growth rate of 0.5 percent. The corresponding acceleration factors are 1.2 and 1.7,

FIGURE 19. Historical progress toward 2030, 2040, and 2050 targets for the share of electricity in the industry sector's final energy demand



Sources: For historical data, IEA (2020n); for targets, CAT (2020a; 2020b).

respectively. As this indicator relies on the introduction of new technologies, the growth could be expected to have nonlinear elements, and the acceleration factors should be considered as a floor.

Although the historical growth rate is relatively close to what is needed in the medium term, the indicator is not fully headed in the right direction. Additional electrification of the industry sector will require electrifying heat supply and adopting new technologies, which will prove more challenging than electrifying nonheating processes and may not occur at the same rate as past electrification. Thus, the historical pace of change alone may not provide the most useful indication of future progress.

Enablers of climate action

Key challenges for an increased share of electricity in the industry sector are the costs of power (Roelofsen et al. 2020) and the adoption of policies and regulations incentivizing the adoption of commercialized electric technologies for low- and medium-heat processes. Further, the commercialization of high heat and other indirect electrification technologies needs to be promoted and accelerated. Measures that can help heavy industry overcome these barriers include the following enablers.

Adopting policies to reduce electricity costs

The cost of electricity is a key driver of electrifying industrial processes, and policies should aim to reduce the relative price of electricity by increasing fossil fuel prices or reducing electricity prices. Other policy measures such as subsidizing electricity consumption in the industrial sectors could also be considered. Unlike other sectors, such as transport, the shift to electric technologies in most industrial applications does not come with significant efficiency gains (Roelofsen et al. 2020). Thus, replacing traditional technologies with electric technologies fed by dirty electricity, alone, will not lead to any emissions reductions, nor will these transitions enable companies to save money through efficiency improvements. Moreover, the level of capital investments in new electric heat technology (in terms of low and medium heat) is similar to that for new heating technologies running on fossil fuels (Roelofsen et al. 2020). Electrification of heat, then, will only be financially sensible when electricity prices are lower per unit of energy than those of fossil fuels. Similarly, indirect electrification through the use of green hydrogen will also be highly reliant on renewable electricity prices. Focusing on the reduction of electricity costs will therefore be essential in making electrification more attractive. Despite falling prices of renewable electricity generation (see Power Indicator 2), the deployment of renewables is associated with additional costs such as grid upgrades, expansion, and storage. To make electrification more attractive for industrial processes while promoting renewable energy deployment, several measures could be considered. For instance, new revenue streams could be created by collecting financial rewards from power producers for providing grid-balancing services—during periods of excess power supply, industries use the additional electricity generated from renewables, and in doing so help balance power supply and demand (Roelofsen et al. 2020).

Promoting a shift to electric technologies in the near term

Even so, there are reasons to argue that an introduction of electric technology in industry should be promoted even before the power mix is nearly or fully decarbonized. As the lifetime and investment cycle of most industrial plants are long, retrofitting old plants with electric technologies where available now would avoid the risk of stranding assets in the medium to long term (IEA 2021c). Policies and regulation can play an important role in promoting the deployment of electric technologies throughout the industry sector by providing financial incentives that reduce capital costs for actors in the industry, but also through campaigns to inform actors about their potential benefits of electrification. The early adoption of electric technologies should therefore be promoted. Even though the environmental benefit would be small in the case that the power supply is not yet decarbonized, making sure that the electric equipment is in place can have climate and economic benefits in the medium to long term. Nevertheless, there might be cases in which electrification today could lead to increased GHG emissions. That could occur, for instance, in industrial facilities that presently use natural gas. Replacing natural gas with coal-fired electricity would in such a case lead to increased emissions. The long-term benefit of promoting electric technologies at an early stage by making the industrial technology stock ready for decarbonization is important but needs to be followed by renewable energy growth in order to bring down emissions—particularly in order to justify electrification for companies concerned with meeting their own near-term emissions reduction targets.

Developing new deep decarbonization technologies for timely rollout

For technologies still under development, the major challenge will be to get low-emissions technologies currently in demonstration out on the market within the next decade and ahead of the next investment cycle. Although the lifetime of most equipment is long (around 40 years), plants commonly undergo a major refurbishment after 25 years of operation to extend their lifetimes (IEA 2021c). To avoid technological lock-in effects, it is therefore vital that novel technologies be ready by 2030, as a large share of existing plants will be 25 years old within the next decade (IEA 2021c). To support this need, policies should promote R&D through financial support packages and the establishment of public-private partnerships. An additional and related issue is the challenge of making novel electric technologies cost-competitive. Many industrial products are globally traded, creating a competitive market with low margins. This discourages companies from committing to more expensive production pathways, making efforts to reduce the costs of new technologies important (Wei et al. 2019).

Managing trade-offs and synergies with the power sector

Considering industry's significant energy demand, its electrification will have considerable implications for the power sector. Meeting industry's rising renewable electricity demand under a 1.5°C-compatible pathway will require not only replacing fossil fuel capacity but also substantially expanding total power capacity (de Pee et al. 2018). Electrification of industrial processes, then, could act as a key driver for the decarbonization and expansion of the power sector by increasing the demand for renewable electricity specifically, and, in doing so, attracting investments in renewable energy deployment.

Renewable electricity may also play an important role in decarbonizing the industry sector that goes beyond direct electrification. As green hydrogen is increasingly being considered a feasible option to decarbonize heavy industries, the demand for renewable electricity will rise further (see Industry Indicator 5). It is therefore vital for policymakers and energy planners to consider industry's impacts on the power sector and how synergies can be created. Governments thus need to take a leading role in managing trade-offs and maximizing synergies through combining top-down and bottom-up policymaking, including target-setting and creating incentives for electrification. In the meantime, industry companies should include electrification in their technological roadmaps at an early stage, with support from policy and regulation. Just as electric technologies should be promoted, the phaseout of old, fossil-driven technologies should be encouraged. In this regard, measures such as carbon taxation could be instrumental.

INDUSTRY INDICATOR 2:

Carbon intensity of global cement production

Targets: The carbon intensity of global cement production declines 40 percent by 2030 and 85–91 percent by 2050 relative to 2015, with an aspirational target to achieve a 100 percent reduction by 2050.

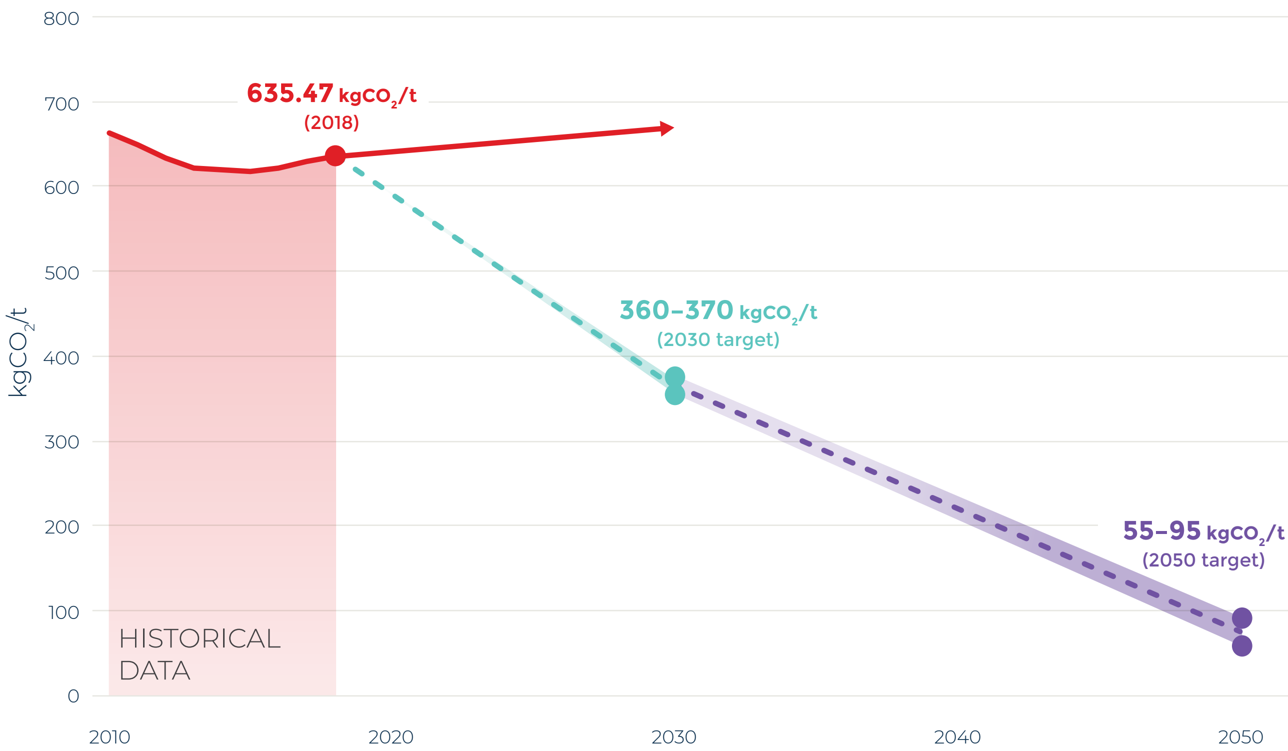
Decarbonizing the production of cement—one of the world's most energy-intensive, and in-demand, construction materials—poses a major challenge to the low-carbon transition. Cement is the key ingredient in concrete—it serves as the glue that holds the aggregate (sand and gravel) together and provides strength as it hardens. Although this industry has made improvements over time, namely in energy efficiency and increasing the share of supplementary cementitious materials (SCMs),[30] the carbon intensity of cement has declined very slowly over the last decade. Emissions intensity[31] fell just 4 percent from 664 kilograms of carbon dioxide per tonne ($kgCO_2/t$) of cement in 2010 to 635 $kgCO_2/t$ cement in 2018 but has actually increased in recent years (Figure 20). The main reason for the increase in recent years is increasing process emissions, caused by an increasing average clinker-to-cement ratio (Andrew 2019).

For this industry to follow a 1.5°C-compatible pathway, the carbon intensity of cement needs to decrease 40 percent below 2015 levels by 2030 and 85–91 percent, with an aspiration to reach 100 percent, by 2050 (CAT 2020a; CAT 2020b). This implies that average rates of decline should correspond to 24.6 $kgCO_2/t$ cement per year between 2018 and 2030, and 14.6 $kgCO_2/t$ cement per year between 2030 and 2050. Achieving such reductions will entail a steep reduction in emissions in the near term, requiring cement companies to go beyond traditional mitigation options such as improving energy efficiency and switching fuels. But alternative technologies such as carbon capture, utilization, and storage (CCUS) and novel cements are currently costly and immature. Decarbonization in the long term thus will depend on significant investments in research, development, and demonstration, alongside efforts to create a demand for low-carbon cements and policies

FIGURE 20. Historical progress toward 2030 and 2050 targets for the carbon intensity of global cement production

STAGNANT: Change has stagnated, and a step change is needed

Exponential Possible



Note: $kgCO_2/t$ = kilograms of carbon dioxide per tonne. Due to a change in the methodology, the historical data are slightly different in this year's report compared to Lebling et al. (2020), where data from the Getting the Numbers Right (GNR) project were used. The GNR data only represent parts of the global cement production. In this year's report, a different methodology was developed to estimate the global emissions intensity by using global data on process emissions from Andrews (2019), and energy data from IEA and GNR. Generally, the historical annual rate of change is calculated by using the most recent five years of data. However, for cement intensity, the five-year period of data selected greatly impacts the change in direction in which the indicator is heading. This year, the indicator is heading in the wrong direction, but in Lebling et al. (2020) it was heading in the opposite direction. Analysis over a longer period (e.g., 10 years) suggests that the changes in the indicator fluctuate up and down, so we categorize its progress as "stagnated."

Sources: Historical emissions data derived from GCCA (2019); Andrew (2019); IEA (2020n); and USGS (2021); for targets, CAT (2020a; 2020b).

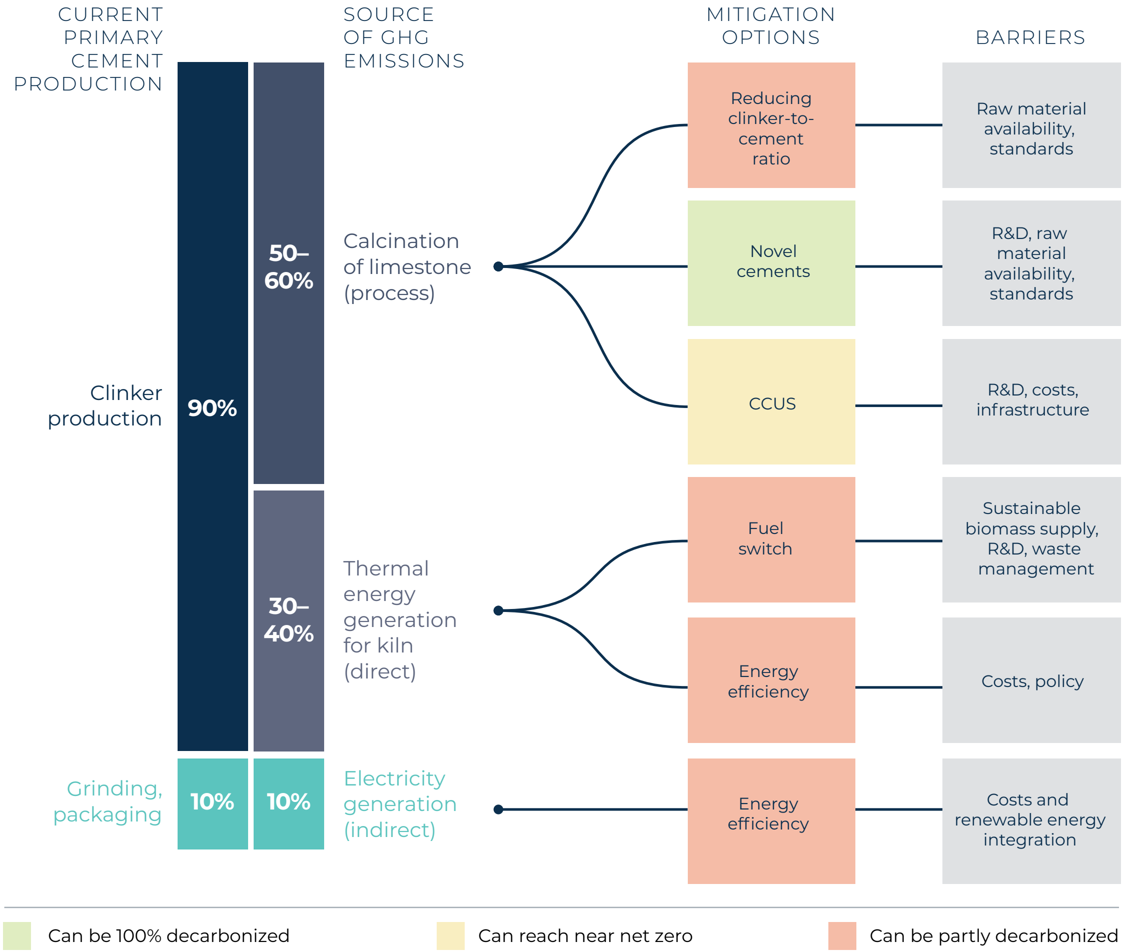
to support investment in decarbonization technologies. If these new technologies receive the appropriate support, there is a possibility for nonlinear change in this indicator's future trajectory.

Enablers of climate action

Traditional cement production generates energy-related and process emissions, with process emissions accounting for a significant proportion (about 50–60 percent) of GHGs released (Figure 21). As process emissions are the result of the chemical-based processes inherent in the production of cement, they cannot be reduced through decarbonization of the energy mix. There are two strategies to fully decarbonize cement:

- Limiting the release of process-related emissions through carbon capture and storage (CCS) and replacing fossil fuels with alternative fuels in the thermal energy mix. Alternative fuels include

FIGURE 21. Overview of cement emission sources, potential mitigation options, and their respective limitations



Note: CCUS = carbon capture, utilization, and storage; R&D = research and development.
Sources: CAT (2020a; 2020b).

biomass and wastes, electricity, and hydrogen.[32] Since decarbonizing the energy mix only targets energy-related emissions, the process needs to be complemented with CCS to mitigate process emissions. Various recent studies suggest that decarbonization of the cement industry will not be possible without substantial scaling of CCS (CAT 2020a; CAT 2020b; Napp et al. 2019; Material Economics 2019).

- Producing novel cements,[33] which use alternative binders that do not generate process emissions and require less heat.

Both strategies face technological challenges, as they are not yet fully mature in terms of technology development, costs, and scaling. As such, key barriers to the decarbonization of cement production include the development, piloting, and scaling of CCS, including required infrastructure, as well as the development and commercialization of low-carbon novel cements.

These two strategies also present two drastically different pathways for the cement industry. The first approach allows cement production to continue relatively unchanged with new technology and infrastructure requirements, while the latter entails a complete restructuring of the cement industry. Given the limitations and uncertainty attributed to each of these decarbonization pathways, both strategies will need to scale up in a net-zero future. The most suitable pathway will depend on context-specific aspects such as availability of raw materials and geographical potential to store CO_2. This might lead to cement companies producing cement for specific end-uses, based on raw material input and the development of new standards, which in turn might result in the restructuring of global supply chains. In parallel, the immediate adoption of existing emissions reduction measures is required to decrease emissions in the medium term. Such measures, including fuel switching and lowering the clinker-to-cement ratio, are commercially available and do not require much retrofitting to existing technology. Overcoming technical and innovative barriers will require the adoption of stricter regulations combined with the allocation of more resources for innovation and should be a joint effort by public and private actors. Critical enablers are discussed below.

Adopting stricter regulations

Regulations play an important role in driving action, both for moving the cement industry onto a long-term decarbonization pathway, and requiring emissions reductions where possible in the meantime. Stricter regulations, such as mandates to use waste fuels or energy efficiency standards, can reduce energy-related emissions in the near term; in the longer term, low-carbon product standards could drive development of new technologies and approaches (Fransen et al. 2021). At the same time, updated material standards for novel cements and supplementary cementing materials (SCMs) can enable new cements to enter the market and governments can update or develop new cement standards while these new materials are being developed. Putting a price on carbon and the implementation of measures such as carbon border adjustments can also play an important role in driving down emissions. From a more high-level perspective, governments' system-wide net-zero targets will send a clear signal to the private sector. The recent surge in governments' commitments to national, economy-wide net-zero targets is a positive development and can support this shift in the cement industry.

Increasing demand for low-carbon cement

In combination with supply-side policies, creating a market for low-carbon cements through the implementation of demand-side measures can incentivize cement producers to adopt new technologies. Responsible for a significant share of cement consumption, governments could have a substantial impact by enacting procurement mandates or incentives for low-carbon cement in large public infrastructure and building projects (Dell 2020). Further, regulations such as the inclusion of embodied emissions in building codes and large infrastructure projects can also help change cement companies' behavior and will likely prove critical in facilitating broader market uptake. Building codes should thus be viewed as an important driver of commercialization and be developed in parallel alongside technological development.

Investing in pilot projects and large-scale demonstrations of novel cements

A study by Chatham House found that while a high number of patents emerged from the cement sector, most of these have a strong focus on technologies that reduce emissions within the parameters of traditional production systems, rather than on technologies that transform existing manufacturing processes, such as novel cements (Lehne and Preston 2018).

Global demand for cement, mainly driven by increased use in developing countries, is outpacing innovation (Lehne and Preston 2018). These trends have led to the expansion of traditional technologies and could result in technological lock-in effects, further underscoring the need for research and development in the near term. Stronger incentives for emissions reductions will be needed to encourage cement producers to go beyond mitigation measures in traditional cement technology.

About nine types of novel cements are under development, with various emissions reduction potentials and limitations. Some could only marginally reduce carbon intensity, while others actively sequester carbon (Material Economics 2019; Lehne and Preston 2018). But without investments or large-scale demonstration projects, most novel cement technologies have yet to enter the market. Raw material availability at both regional and global levels has also limited the uptake of some novel cements (Lehne and Preston 2018; CAT 2020a; CAT 2020b). Moreover, in this already well-established industry, comprised of a few major companies, it is difficult for innovative entrepreneurs to enter the market. Producers tend to shy away from exploring novel approaches, which they perceive as risky investments (Lehne and Preston 2018). Further, without building code approval, consumers might consider the use of novel cements structurally risky. There is therefore a need for increased investments in pilot and large-scale demonstration projects, and a continuous standardization process to prove new technologies and to get them out on the market.

INDUSTRY INDICATOR 3:

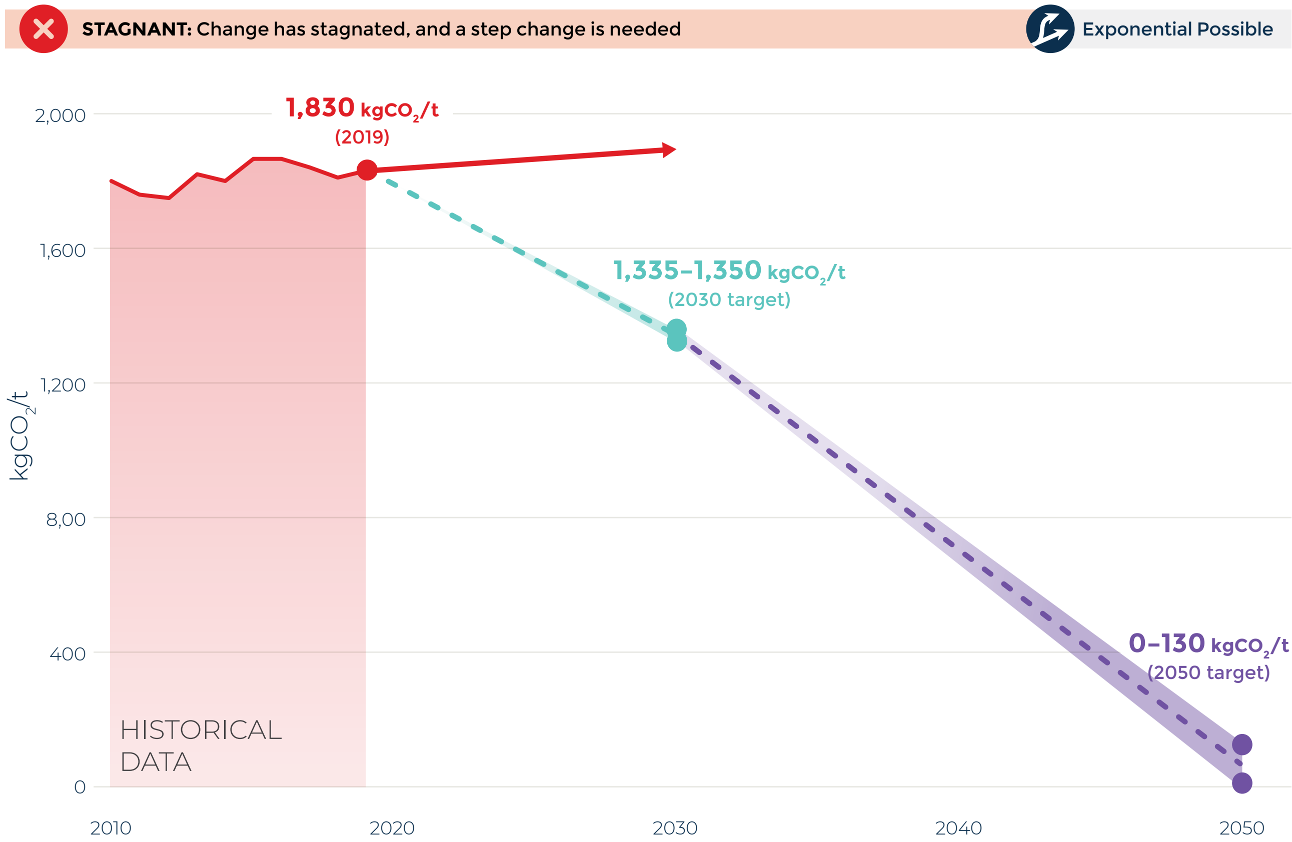
Carbon intensity of global steel production

Targets: The carbon intensity of global steel production declines 25–30 percent by 2030 and 93–100 percent by 2050, relative to 2015.

Worldwide, the carbon intensity of steel production has remained steady over the past decade at around 1800 kilograms of carbon dioxide per tonne ($kgCO_2/t$) of steel (Figure 22). Steel is a key material in buildings, cars, and transportation infrastructure, and, although demand is stabilizing or even decreasing in some developed countries, demand in developing countries is rising and will likely offset decreases in other regions (ETC 2019c).

For a 1.5°C-compatible pathway, the carbon intensity of steel will need to decline 25–30 percent below 2015 levels by 2030 and 93 to 100 percent by 2050. Achieving these targets will require a trend change in emissions intensity, requiring a steep drop in the coming years that corresponds to an average rate of decline of 35.2 $kgCO_2/t$ steel per year between the baseline year and 2030, and 63.9 $kgCO_2/t$ steel per year between 2030 and 2050. Historically, between 2010 and 2019, the carbon intensity of steel has increased by an average of 3 $kgCO_2/t$ steel annually. Such a reversal will depend on the introduction of novel technologies, such as zero-carbon fuels and carbon capture, utilization, and storage, as well as the optimal use of recycled scrap steel. In terms of technological shifts, exponential growth has been observed historically when open-hearth furnaces were replaced with blast furnaces (World Steel Association 2021). There is great technical potential to reduce emissions in the steel industry according to Hoffmann et al. (2020). If these novel technologies receive enough support, there is a possibility for nonlinear change in this indicator's future trajectory.

FIGURE 22. 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. The historical rate of change (calculated over the most recent five years of data) indicates that change has stagnated and requires a step change to meet the 2030 target. Generally, the historical annual rate of change is calculated by using the most recent five years of data. However, for steel intensity, the five-year period of data selected greatly impacts the change in direction in which the indicator is heading. Analysis over a longer period (e.g., 10 years) suggests that the changes in the indicator fluctuate up and down, and so, we categorize its progress as "stagnated."

Sources: For historical data, World Steel Association (2020b); for targets, CAT (2020a; 2020b).

INDUSTRY INDICATOR 4:

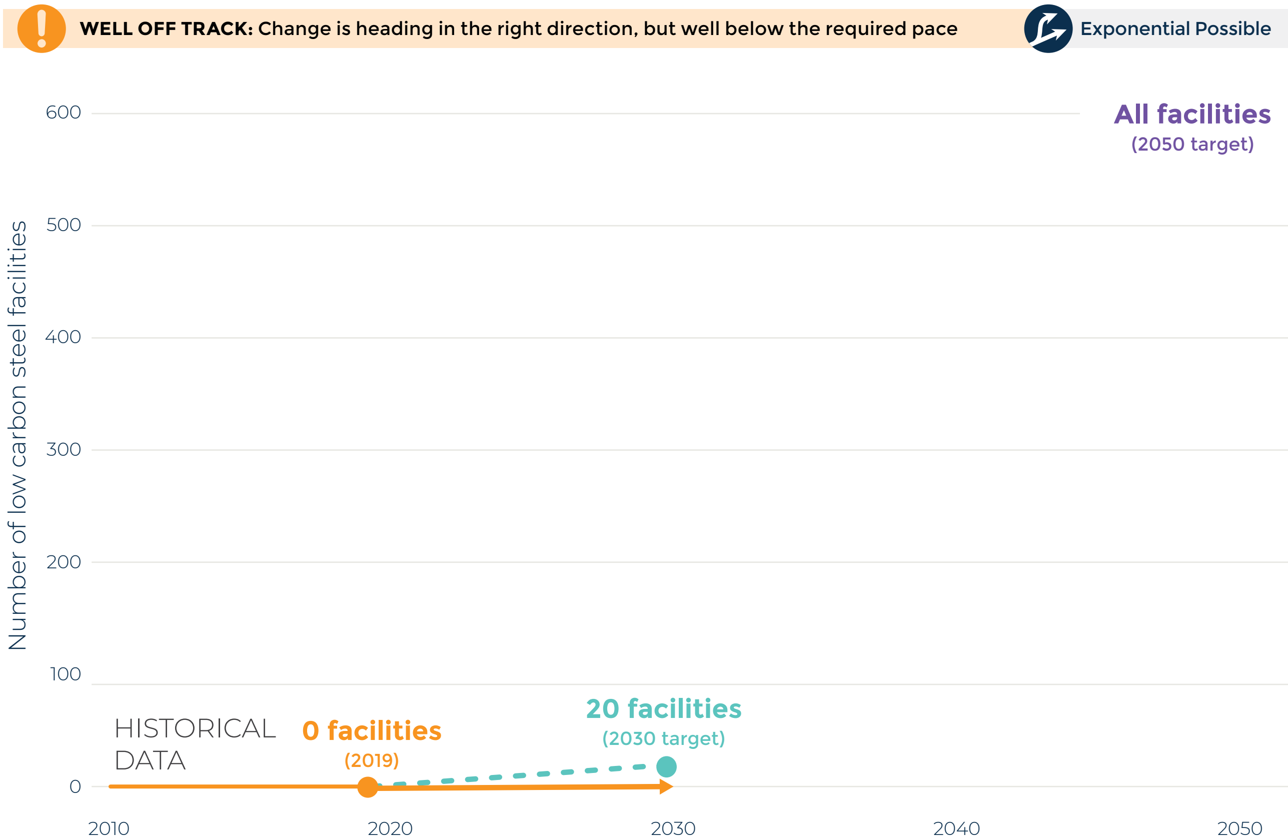
Low-carbon steel facilities in operation

Targets: 20 low-carbon steel facilities with a production capacity of at least 1 million tonnes (Mt) per year become operational[34] by 2030, and all steel facilities are net-zero GHG emissions by 2050.

To support the alignment of the steel industry with a 1.5°C pathway, at least 20 low-carbon steel facilities with at least 1 Mt production capacity should be operational by 2030, and all facilities should be net-zero GHG emissions by 2050 (Figure 23).[35] Recent years have seen some progress in terms of piloting and demonstration, but acceleration is needed. In the past three years, the number of announced low-carbon steel projects has increased rapidly, from 1 in 2016 to 23 in 2020 to 45 as of August 2021 (Figure 24). By 2030, 18 full-scale projects are planned to be operational (Figure 25). Although that is close to meeting the 2030 target in terms of the number of facilities, data are insufficient on the projects' production capacity; production capacity is only known for 4 of the projects, all of which meet the annual 1 Mt criteria. Although yet uncertain, a maintained pace in low-carbon steel announcements could indicate the emergence of a nonlinear trend. Data from the Green Steel Tracker suggest that the industry is relatively confident in these plants' technological potential and that it is rapidly reaching a technological tipping point, as many projects move from small-scale pilots to the demonstration phase (Watt and Hobley 2021).

The actual transition from a pilot to a full-scale plant, however, requires time. One of the early movers, the Swedish steel producer SSAB, initiated its project on green hydrogen-based steel production, Hybrit, in 2016. It aims to produce 1.3 Mt fossil-free steel by 2026 and reach full-scale production of 2.7 Mt in 2030 (SSAB 2021a, 2021b), a 14-year process from initiation to a full-scale facility. Judging from the announcements

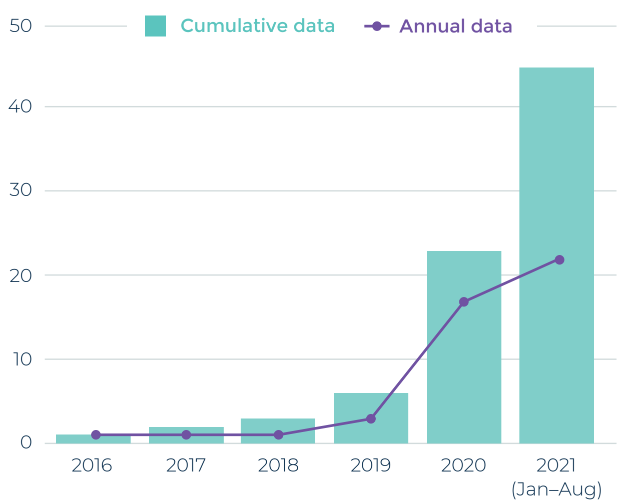
FIGURE 23. Historical progress toward 2030 and 2050 targets for low-carbon steel facilities in operation



Note: The indicator is marked as "well off track" because while no low-carbon steel facilities are currently in operation, 18 are expected to be operational by 2030. Of these 18 projects, data on production capacity are only available for 4, all of which meet the production criteria of at least 1 million tonnes annually.

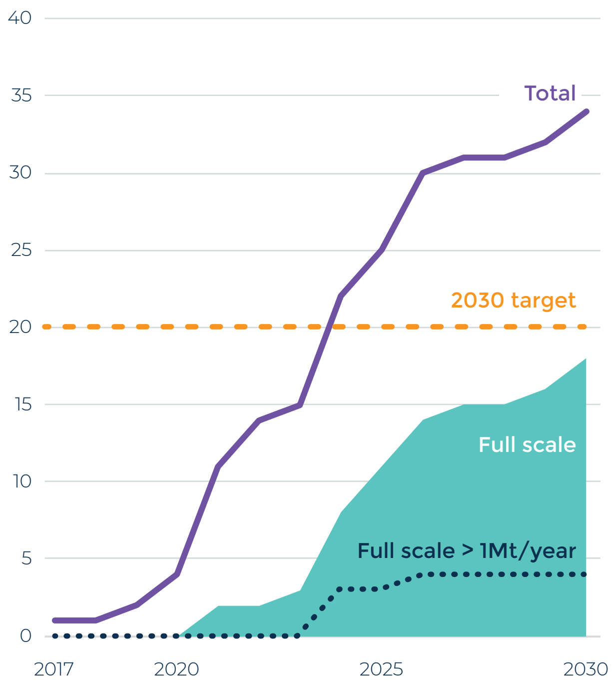
Sources: Historical data from Leadit (2021); targets from Race to Zero (2021a); total facilities number from Global Energy Monitor (2021b).

FIGURE 24. Number of announced low- and zero-carbon steel projects by year and aggregated



Source: Authors' analysis of data from Leadit (2021).

FIGURE 25. Number of low- and zero-carbon steel projects in the year they are planned to go online

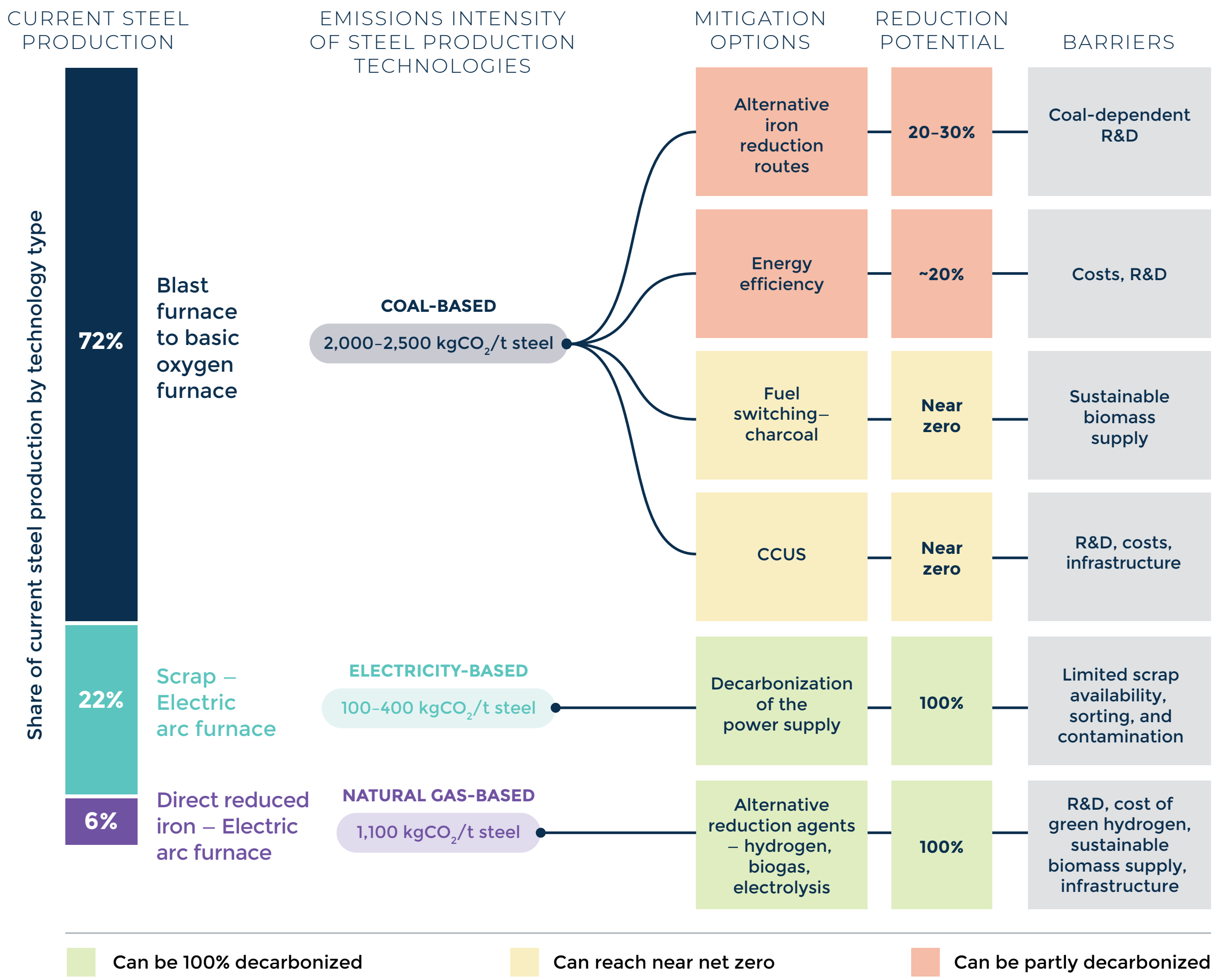


Note: R&D = research and development. The figure excludes 12 projects with no specified planned year to go online.
Source: Authors' analysis of data from Leadit (2021).

collected by the Green Steel Tracker, the 2030 target would not be reached on time (counting full-scale projects), assuming a similarly long process (Figure 24). In addition, another six demonstration projects and eight pilot projects are planned to be operational by 2030. Nevertheless, the actual progress of this indicator is uncertain, due to the lack of information on projects' production capacity, whether they will actually be implemented, and, if so, whether they will go online in the year planned.

Beyond individual projects, a rising ambition is emerging in terms of target-setting within the private sector. A total number of 14 steel companies and associations have committed to carbon neutrality by 2050, together accounting for about 24 percent of global primary production in 2019. When also considering the Chinese steel industry's commitment to carbon neutrality by 2060, that share increases to 68 percent (Lee 2021a). Although such numbers suggest a promising outlook, there is a general lack of technological roadmaps and short-term investment commitments, mirrored by the limited number of companies that have announced 2030 emissions reduction targets. Out of 17 companies and associations that have announced long-term decarbonization goals, only 8 have medium-term emissions reduction targets.

FIGURE 26. Overview of current steel production technologies and their corresponding decarbonization options



Note: BF-BOF = blast furnace to basic oxygen furnace; EAF = electric arc furnace; kgCO_2/t = kilograms of carbon dioxide per tonne [of steel]; CCUS = carbon capture, utilization, and storage; DRI = direct reduced iron; R&D = research and development. Reduction potentials given are for the emissions intensity of the steel production technologies (e.g., coal-based steel) and assume no other mitigation measures are taken.

Sources: CAT (2020a; 2020b).

Enablers of climate action

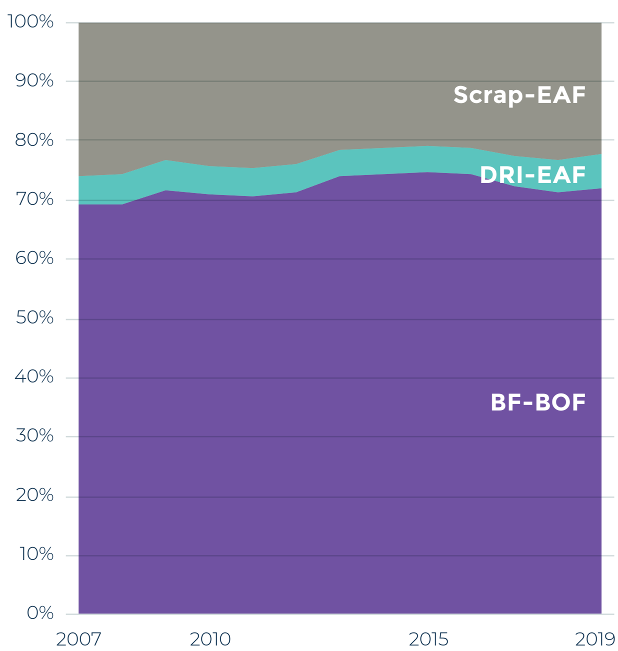
The number of low-carbon projects influences the indicator "carbon intensity of steel production." Given the interlinkages between these two indicators, this section identifies enablers for both.

Historically, steel is produced with three main technologies, which vary significantly in terms of energy, emissions intensity, and mitigation options (Figure 26).[36]

In terms of primary steel production, various decarbonization technologies are in development, each facing barriers such as renewable energy availability, carbon storage feasibility, or technical maturity. The optimal choice of decarbonization technology will depend on context-specific aspects, including the price and emissions intensity of electricity, and the ability to scale CCS (Bataille 2020; Hoffmann et al. 2020). A shift from primary to secondary steel production is the most energy-efficient technology option but will be limited by the regional availability and quality of scrap steel (ETC 2019c; Hoffmann et al. 2020; Bataille 2019). More broadly, the main barriers include the lack of strong leadership from governments in the form of target-setting and stronger regulation, and the lack of targeted incentives or broad measures to drive the shift to less carbon-intensive technologies. Pressure from governments through public procurement and from upstream companies could be another significant driver for the iron and steel industry to shift to less emissions-intensive pathways. More proactive engagement in development and innovation is also sought from governments and private actors.

Given economic and technical limitations to the widespread adoption of CCS on the most carbon-intensive technology—the blast furnace-basic oxygen furnace (BF-BOF)—the introduction of novel technologies and the ultimate replacement of BF-BOF plants will be imperative to reduce emissions. A shift from BF-BOF to the direct reduced iron-electric arc furnace (DRI-EAF) route will be key, given the energy efficiency gains and the possibility of replacing fossil fuels with clean fuels in the DRI-EAF route. Although DRI-EAF is more energy efficient, its share of global production has not increased in the last decade (see Figure 27). The main fossil fuel source in the DRI-EAF process historically and presently is natural gas, which is used to reduce the iron ore, so the shift to an alternative reduction agent eliminates the need for fossil fuels in the DRI-EAF process. The most promising option for this process is to use hydrogen as a reduction agent and energy source, leaving only water as a byproduct (Figure 26). For the steel to be considered carbon-free, the hydrogen used in the process must be green (i.e., produced from dedicated renewable electricity). As such, the DRI-EAF route has the technical potential to fully decarbonize steel production without the need for CCS, which gives it a clear advantage compared to the energy-intensive and fossil fuel-dependent BF-BOF route.

FIGURE 27. Share of global steel production by technology type



Note: BF-BOF = blast furnace to basic oxygen furnace; DRI-EAF = direct reduced iron to electric arc furnace.

Sources: Authors' analysis of data from the World Steel Association (2020a, 2019, 2018, 2016, 2015, 2014, 2013, 2011, 2010, 2009).

Increasing public finance for R&D

Although technologies are advancing, the required technological transformation to decarbonize the steel industry will not be achievable without meeting financial needs, including investments in new technology and the development of new infrastructure. To meet the 2030 targets, the shift from decarbonization pilot-phase projects into the demonstration and full-scale deployment phase needs to accelerate, which will require increased activities in R&D and public-private partnerships to manage risk for private actors.[37] At the same time, deep decarbonization with high-potential direct electrification technologies such as low- and high-temperature direct electrolysis of iron ore will require dedicated support to cross into the pilot stage (Bataille 2019).

Particular focus needs to be put on the further development of CCS technology to increase its efficiency and capture rates, and to drive down capital costs. A substantial part of the current technology stock, particularly in developing countries, is relatively new, and where steel producers have built BF-BOF plants, a fast shift to the DRI-EAF route could lead to stranded assets and might not be economically feasible in the short term (Hoffmann et al. 2020). In those cases, adding CCS technology to current BF-BOFs might be a more suitable option. Doing so could reduce emissions significantly, although not to zero, as current CCS technology does not allow for 100 percent capture rates (ETC 2019c). Considering that the CO_2 concentrations in the flue gas of a BF-BOF plant are relatively low (16–42 percent), retrofits of BF-BOF facilities would have trouble economically capturing more than 30–50 percent (Bains et al. 2017). However, new technologies producing higher concentrations of CO_2 are in development (Bataille 2019). Given such technological and economic challenges, and the fact that there likely will be a need for CCS to decarbonize the steel industry, more support needs to be directed to research and development for CCS to go beyond the pilot stage (Chan et al. 2019; ETC 2019c).

With regard to hydrogen-based steel production, which is closer to commercialization, more investments are needed to support its deployment and achieve economies of scale, and particularly to drive down the cost of green hydrogen. Public-private partnerships can be a helpful mechanism to manage risks for companies and to reward early movers.

The initial need for policy commitments to net-zero GHG emissions and the development of technology roadmaps to send a clear signal to steel producers

In addition to the promotion of new technology development, financial support measures need to be complemented with top-down policies aiming to reduce emissions in steel production. The dynamic of interactions across steel producers is an important driver for the decarbonization of the industry, as producers are encouraged by the increased activities and commitments, making new technologies more mainstream. To further encourage companies to take bolder steps toward decarbonizing their processes, national targets, such as countries' economy-wide net-zero GHG emissions targets, play an important role, as they can send clear signals to industry.

Targets need to be followed by thorough strategies, setting relevant interim targets, allowing for logical stock turnover and investment cycles (Bataille 2019). The development of technology roadmaps is particularly important in planning for infrastructure development. It is therefore critical for companies and governments to assess various decarbonization technologies at an early stage and develop technology roadmaps. Such assessments should evaluate the feasibility of various decarbonization technologies and identify the future need for new infrastructure, storage, and transportation, as well as ensuring buy-in from surrounding communities. These plans will, in turn, inform policymaking, allow decision-makers to assess infrastructure needs and develop supportive financial mechanisms.

Driving down the cost of green hydrogen

Green hydrogen produced using renewable electricity to split water through electrolysis will be a key component of the decarbonization of the steel industry (see Box 5).

BOX 5. The role of a green hydrogen economy in the decarbonization of the steel industry

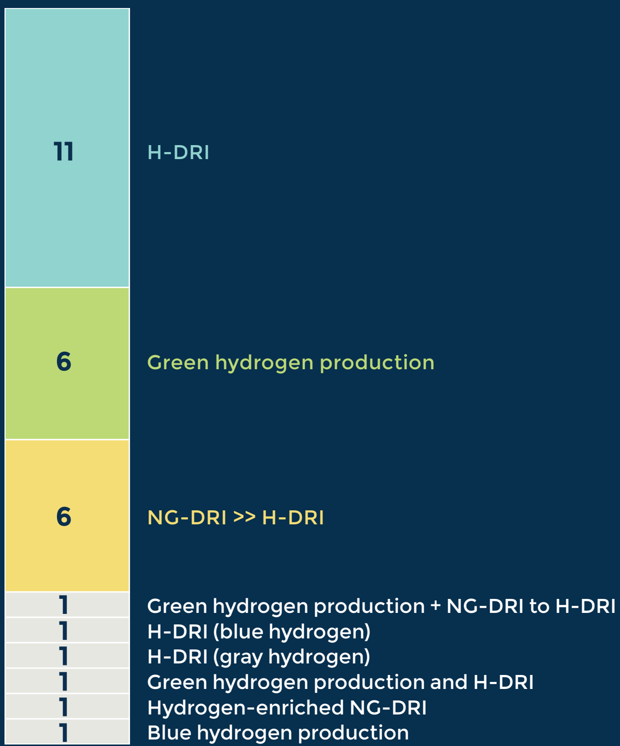
Among hydrogen-related steel projects, the majority currently focus on the green hydrogen-based DRI route or solely on green hydrogen supply for the steel industry (Figure B5.1). However, about 15 percent of hydrogen-related projects currently focus on the shift to, or new installation of, natural gas-based direct reduced iron (DRI)—aiming to shift to green hydrogen depending on its future availability and cost. These data illustrate an emerging and accelerating interest in hydrogen-based steel production, and identify the cost and availability of green hydrogen as a limiting factor. As such, a precondition to further accelerate the rising interest in hydrogen-based steel is developing a green hydrogen economy and closing the price gap between green hydrogen and incumbent fuels. None of current green hydrogen-based steel projects have yet reached full scale. This indicates that there is still a long way to go before a substantial shift to green hydrogen-based steel production can be achieved.

The moment when green hydrogen reaches cost parity with natural gas is likely to be the key positive tipping point. The regional price of green hydrogen will be highly dependent on the renewable power production potential as well as the geological storage potential. Given high sensitivity to electricity prices in green hydrogen production costs, the timing will vary greatly across regions, which could lead to a shift in material flows. This poses an opportunity for countries endowed with rich renewable energy resources and those with rich iron ore reserves, as well as for major steel-producing countries suffering from high levels of air pollution and greenhouse gas emissions. Steel-producing countries with limited renewable energy resources could avoid the most polluting part of their steel production—the reduction of iron ore. Instead of importing iron ore, they could import reduced iron, which is then further processed into steel in electric arc furnaces in the importing country. In addition, green hydrogen could be used to produce carbon neutral fuel for shipping of the iron ore. Countries endowed with rich renewable energy and iron ore resources could in that way add value to the otherwise limited added value from exporting iron ore, while utilizing renewable energy resources in remote locations (Bataille 2020; Gielen et al. 2020). This approach would limit the polluting and expensive transportation of hydrogen. International partnerships and policies promoting green hydrogen production will be an important driver to make global trade flows as efficient as possible.

As such, a shift to a hydrogen-based steel industry could be an opportunity to accelerate the emergence of a global green hydrogen economy. The emergence of a green hydrogen economy brings important synergies with the transition of the power sector, as green hydrogen production benefits from high shares of renewables in the power mix (Liebreich 2020). In addition, as the hydrogen DRI route could be operated in periods of low electricity demand, it could be used to smooth the electricity load curve and to balance electricity prices by taking advantage of off-peak variable renewable energy generation (Bataille et al. 2018). In developing a green hydrogen sector, however, proper planning and infrastructure development are required to ensure buy-in from surrounding communities. It also will be important to assess potential impacts on land and water related to renewable energy deployment and electrolysis, as well as associated social and cultural impacts.

The potential of using blue hydrogen—hydrogen produced from fossil fuels and with carbon capture and storage—could become an option for some countries where the production of green hydrogen is too costly and importing it is not feasible today or in the near future. Production of blue hydrogen could co-locate with steel facilities using methane as a reduction agent to take advantage of the shared pipelines. Direct import of green iron and steel produced in regions rich in renewables and iron ore is another solution. Otherwise, once green hydrogen becomes feasible, DRI facilities can shift to that resource without the need for adjustments in the steel-producing process. To ensure the sustainability of DRI-produced steel, it will therefore be important to develop guarantees of origin, such as international standards that account for the life-cycle emissions of the hydrogen used in the production. In that way, green hydrogen could be promoted, while avoiding steel producers' continued use of gray hydrogen.

FIGURE B5.1. Distribution of hydrogen-related ongoing and announced low- and zero-carbon steel projects by type

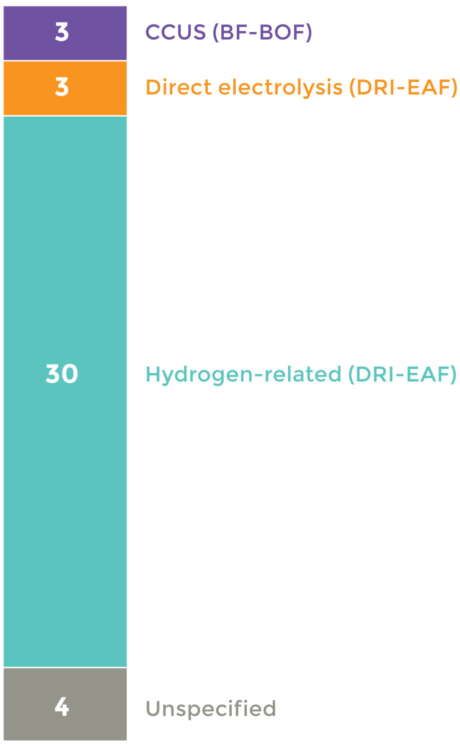


Note: H-DRI = hydrogen-based direct reduced iron; NG-DRI = natural gas to direct reduced iron.
Source: Authors' analysis of data from Leadit (2021).

Among announced green steel projects, there seems to be a clear preference for the hydrogen-based DRI route (Figure 28). This suggests that hydrogen is currently viewed as the most feasible decarbonization technology by the majority of steel producers. This sends a clear message to the green hydrogen sector. Considering that the green hydrogen-based DRI-EAF route is highly electrified (for the production of green hydrogen as well as for the EAF), the cost-competitiveness of this technology will depend heavily on the price of electricity as well as on driving down the costs of electrolyzers (see Industry Indicator 5). Renewable energy costs have decreased rapidly in the past decade and are projected to decrease further, while electrolyzers are still at an emerging stage, with costs expected to fall in the coming decade (IRENA 2020d). As a result, the price of green hydrogen is projected to reach near cost parity with natural gas by 2030 in regions with abundant renewable energy resources and storage availabilities, and in most regions before 2050 (BloombergNEF 2020b). The financial feasibility of hydrogen-based DRI-EAF steel production will as such depend not only on local renewable energy resources and costs but also on the availability of hydrogen storage and transportation. Policies should therefore focus on scaling the production of green hydrogen and bringing down its costs in the near term.

The expansion of a green hydrogen sector to meet growing demands will require a vast expansion of renewable energy generation and electric grids to avoid hydrogen being generated from dirty electricity. A Paris-aligned scenario developed by IRENA suggests that the share of renewables in global steel production could increase almost 10-fold between 2017 and 2050, corresponding to 20 exajoules (EJ, 1 quintillion, or 10^{18}, joules) (IRENA 2020c). Countries must collaboratively work on developing guarantees of origin to be integrated in industrial policy and standards. Policymakers may also consider the creation of green hydrogen hubs, in which green hydrogen production is located within the proximity of demand clusters, to kickstart the green hydrogen sector. To accelerate the shift from BF-BOFs to DRI-EAF, financial policy support, such as contracts for difference, could help manage risks for steel producers by ensuring that any additional costs compared to the incumbent fuel or technology are covered by the state.

FIGURE 28. Distribution of announced and ongoing low- and zero-carbon steel projects based on technology type



Note: CCUS = carbon capture, utilization, and storage; BF-BOF = blast furnace to basic oxygen furnace; DRI-EAF = direct reduced iron to electric arc furnace.
Source: Authors' analysis of data from Leadit (2021).

Increasing demand for low-carbon steel

Adding to supply-side policies promoting the deployment of novel technologies, policies that stimulate demand for low-carbon steel are an important driver in decarbonizing the steel industry. Such policies could include public procurement targets and policies that neutralize or offset additional costs, such as energy efficiency standards and carbon contracts for difference. With more than half of all steel produced going to the building materials sector, largely ending up in public construction projects, "buy clean" policies that use government spending to stimulate the market for low-carbon products could play an important role in the decarbonization of the steel sector (Dell 2020). Nonstate actors, including major steel consumers, such as the automotive industry, can also leverage voluntary demand specification for green steel to encourage or directly stimulate new green steel production (NewClimate Institute et al. 2019). The car manufacturer Daimler, for instance, has committed to becoming carbon-neutral by 2039, including its supply chains, and is an investor in the H_2 Green Steel start-up in Sweden (Daimler 2021b, 2021a). More broadly, a growing number of automotive

companies are setting Paris-compatible emissions reduction targets (We Mean Business Coalition 2020). Setting emissions reduction targets, including GHGs released across the entire value chain, could increase the demand for low-carbon steel, while also sending a clear signal to steel producers. In this context, national net-zero targets can create synergies by encouraging major consumers to demand low-carbon products.

Addressing the risk of carbon leakage

Steel is a globally traded commodity, which comes with challenges but also opportunities for the decarbonization of the sector. The uneven distribution of carbon-restricting policies and regulations may pose challenges for steelmakers engaging in decarbonization efforts. In regions with stricter regulations on emissions, the risk of carbon leakage is potent and could lead steel producers to move their activities to regions with less strict regulations. This calls for increased international coordination on industrial sector policies and standards. Seeking to avoid global carbon leakage, the European Union, for example, adopted a proposal for the first carbon border tax in July this year (European Commission 2021b). In the following week, a carbon tariff on imported goods, including steel, was introduced in the United States by two Democratic lawmakers (Volcovici 2021). Such an instrument taxes imported goods that do not comply with the European Union's emission standards and, in doing so, could help reduce carbon leakage. The implementation of this type of mechanism could, in turn, incentivize decarbonization outside of its jurisdictions. As another option, product standards tied to energy and/or emissions intensity per tonne of steel could lead to an international "race to the top" in low-carbon technologies.

Incentivizing increased scrap metal use

Although the demand for primary steel is expected to rise, it can be significantly reduced through the increased recycling of scrap steel, which is an efficient and economically feasible way of reducing emissions while also limiting the need for investments in new technology (Bataille 2020; Xylia et al. 2018). In the last decade, however, the share of scrap-EAF in global steel production has remained stable, fluctuating between 21 percent and 26 percent (Figure 27). The expected rise in steel demand in developing regions such as India and Africa will require increased production of primary steel. In developed regions, however, with an already high stock of steel per capita, recycled scrap steel could satisfy large proportions of steel demand, which is not the case in regions with a low steel stock per capita (ETC 2019c). In addition to the limited availability of scrap steel, restrictions with regard to both copper contamination and scrap losses challenge the maximization of steel recycling (ETC 2019c; Xylia et al. 2018). Policies and regulations focused on sorting and recycling to further improve steel recycling can help overcome such barriers.

INDUSTRY INDICATOR 5:
Green hydrogen production

Target: Green hydrogen production capacity reaches 0.23–3.5 Mt (25 GW cumulative electrolyzer capacity) by 2026 and 500–800 Mt (2,630–20,000 GW cumulative electrolyzer capacity) by 2050.

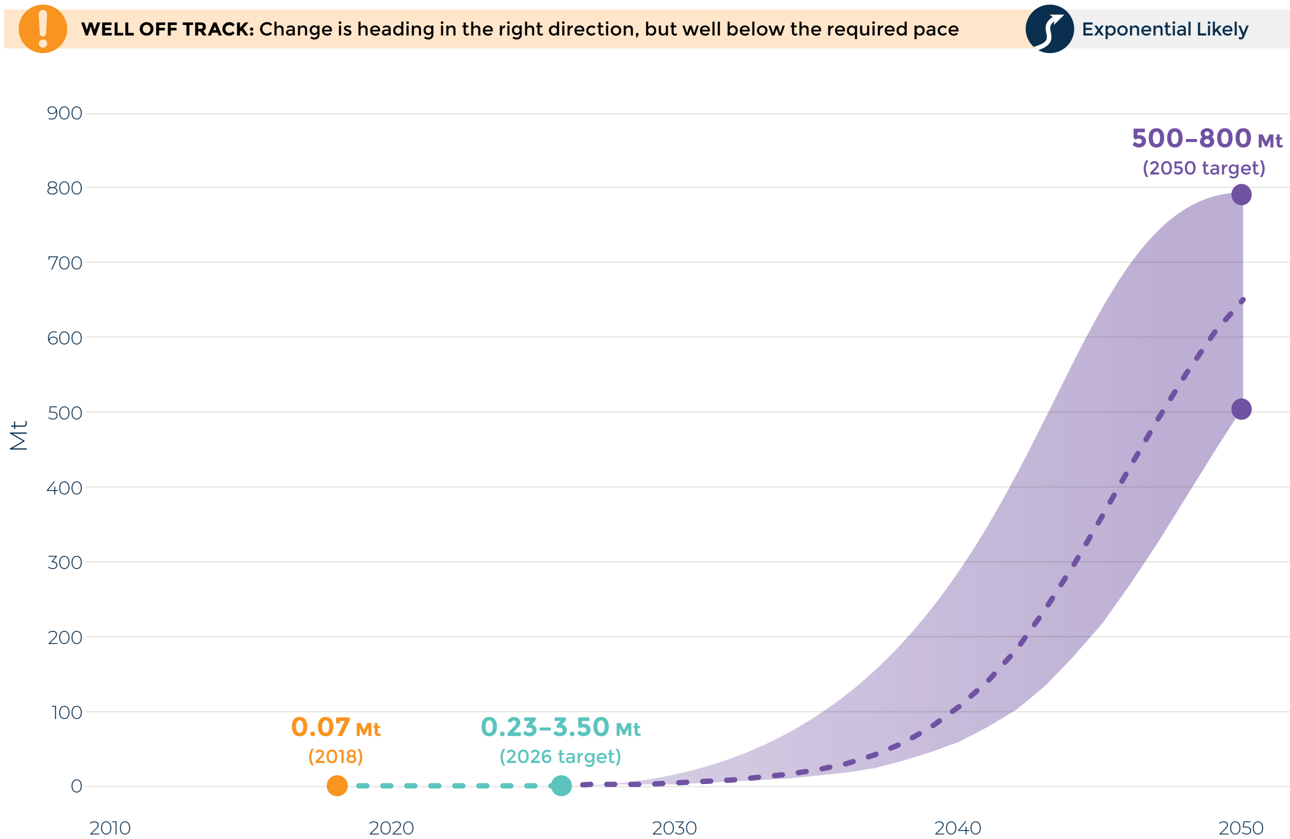
In addition to electrification, green hydrogen—a zero-carbon fuel produced through water electrolysis powered by renewable energy—can help decarbonize hard-to-abate sectors (e.g., steel, cement, long-distance shipping, and aviation) by replacing fossil fuels.

Today, annual global demand for pure hydrogen is around 74 Mt and nearly all existing hydrogen production processes rely on methane or coal with no CO_2 abatement (IEA 2020j). Still in its early phases of development, green hydrogen accounts for less than 0.1 percent of current production (IEA 2019b).

Scenarios aligned with limiting global temperature rise to 1.5°C suggest that hydrogen will supply 15–20 percent of the world's final energy demand by 2050. Recent analysis from the Energy Transitions Commission estimates that this equates to a total annual hydrogen demand of 500–800 Mt—a massive increase from today's levels (Figure 29) (ETC 2021b).[38] Total hydrogen demand estimates by Bloomberg New Energy Finance, the IEA, and the International Renewable Energy Agency also fall in this range (BloombergNEF 2020b; IEA 2020p; IRENA 2020b).

Though the exact electrolyzer capacity needed to produce 500–800 Mt varies depending on electrolyzer efficiency and utilization, approximately 2,630–20,000 GW of electrolyzer capacity will be required by 2050. Estimates from the High-Level Climate Champions suggest that to meet this target, 25 GW electrolyzer capacity with potential to produce 0.23–3.5 Mt green hydrogen per year will be required by 2026.[39] Today, less than 1 GW is operationalized (IRENA 2019c).

FIGURE 29. Historical progress and an illustrative S-curve of what's needed to reach 2026 and 2050 targets for green hydrogen production



Note: Mt = million tonnes. The future trajectory of green hydrogen will likely follow an S-curve, following the pattern of other instances of technology adoption. This figure illustrates what growth in green hydrogen would have to be to reach the targets on an S-curve trajectory—though this is just one potential path among many. Data are currently insufficient to evaluate progress in green hydrogen in a quantitative way, so our evaluation of "well off track" is a qualitative judgment. Green hydrogen is still in the emergence phase of the S-curve and requires the right government support and economic conditions to enter a phase of rapid growth. Whether green hydrogen reaches the diffusion stage and how fast depends on what happens in the near term.

Sources: Authors' analysis and IEA (2019c) for historical data; targets from Race to Zero (2021a).

Enablers of climate action

Cost remains the greatest barrier to green hydrogen adoption (IRENA 2020b; ETC 2021b; BloombergNEF 2020b). Currently, green hydrogen costs $2.5–$4.6 per kilogram—$0.3–$2.9 per kilogram more than hydrogen derived from coal or natural gas (BloombergNEF 2020b). Market factors limiting the applicability and demand for green hydrogen across sectors and renewable energy capacity required to produce green hydrogen at scale must also be addressed. Four interrelated drivers emerge as critical to addressing these challenges: decreasing electrolyzer cost, increasing renewable energy capacity, increasing hydrogen demand across sectors, and multistakeholder coordination.

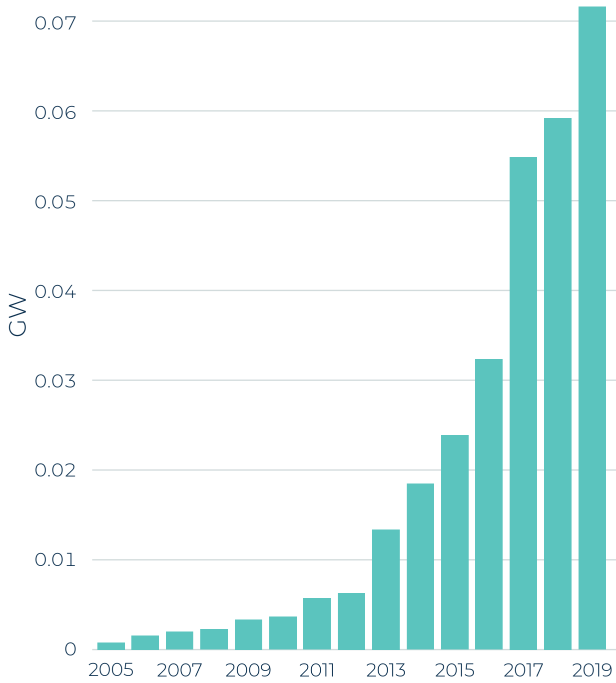
Decreasing electrolyzer cost

One of the largest drivers of green hydrogen cost is the electrolysis process used to produce it. Decreasing green hydrogen cost will require decreasing the cost of electrolyzer units by increasing unit capacity and utilization rates.

There are currently two commercial electrolysis technologies: proton-exchange membrane and alkaline. Both decreased in cost significantly between 2014 and 2019, falling 50 percent and 40 percent, respectively (BloombergNEF 2020b). Dominant in large-scale production, alkaline electrolyzers now cost $850/kW globally, with $300/kW electrolyzers already available in China (ETC 2021b). Regardless of project size, electrolyzers require significant investments in energy and maintenance. Large-scale production projects can help create economies of scale, supply chain standardization, and efficiencies, and can decrease average hydrogen production cost. Both the size and number of large-scale projects are increasing globally, with over 90 GW additional electrolysis capacity planned by 2030 (Figure 30) (Nascimento 2021).

Sustained cost reductions stemming from large-scale production will facilitate further electrolysis deployment at scale. Industry estimates and High-Level Climate Champions learning curve analysis suggest that 5–10 GW annual production capacity may be needed to realize cost reduction of electrolysis for each company (representing about 30 percent of green hydrogen's levelized cost) (High-Level Climate Champions analysis of Schmidt et al. 2017; IRENA 2020b; ETC 2021b; BloombergNEF 2020b).

FIGURE 30. Cumulative installed electrolyzer capacity



Note: GW = gigawatt (1 billion watts).
Source: IRENA (2020b).

Scaling renewable energy supply

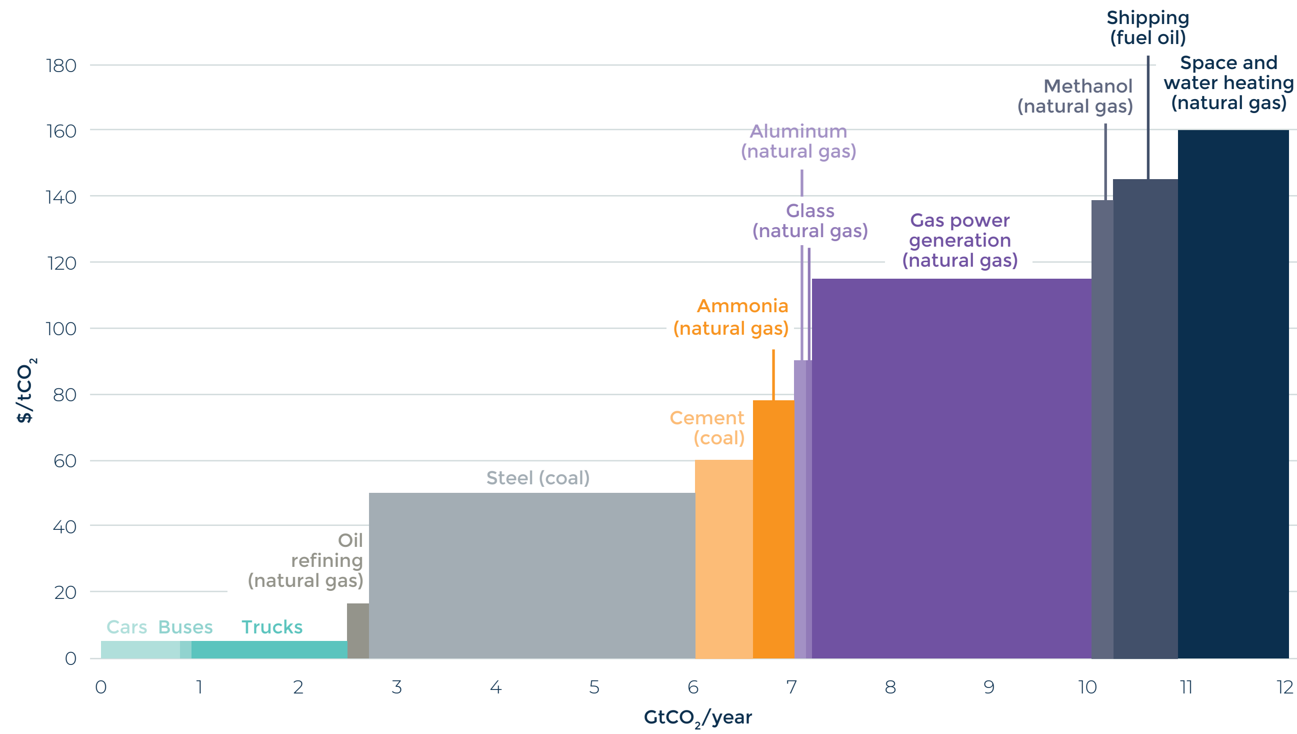
Electrolysis requires significant renewable energy capacity. While reducing the cost of renewable energy is essential to reducing green hydrogen cost, increasing green hydrogen production in line with a 1.5°C pathway will require significantly more renewable energy than is currently available (ETC 2021b; IRENA 2020b). IRENA analysis suggests that producing 19 EJ of green hydrogen, equivalent to around 133 Mt, would require an additional 4–16 terawatts (TW) of wind and solar energy for electrolysis alone (IRENA 2019c). Producing 500–800 Mt of green hydrogen though electrolysis would require between three and six times more capacity; that is, 15–96 TW of renewable electricity. Currently, wind and solar electricity generation capacity for all purposes is just 1 TW. Locating green hydrogen projects near large-scale, renewable energy-dense sites will be critical to increasing green hydrogen production and adoption.

Increasing hydrogen demand across prioritized hard-to-abate sectors

Consensus has not yet emerged on exactly how hydrogen will be used across industrial processes and for which sectors it should be prioritized. Early demand is likely to arise in sectors where hydrogen is already in use (e.g., chemical production or oil refining), where green hydrogen is closest to cost parity with fossil fuel-based solutions (e.g., fuel cell heavy-duty vehicles), and where there is policy pressure to reduce CO_2 emissions (e.g., shipping and aviation) (ETC 2021b). Hydrogen roadmaps, now established in 12 countries, can help countries determine exactly how to prioritize green hydrogen use across sectors based on end-use efficiency and availability of natural resources (IRENA 2019c, 2020c).

Once priority sectors are identified, a number of tools can be used to increase hydrogen demand. Carbon pricing is among the most effective policy levers that can incentivize adoption by enabling green hydrogen to reach price parity with other fuels across different sectors (Figure 31). Nineteen countries and the European

FIGURE 31. Marginal abatement curve for hydrogen and indicative carbon price required in each sector for hydrogen to compete with the cheapest fuel alternative



Note: tCO_2 = tonnes of carbon dioxide. $GtCO_2$ = gigatonnes of carbon dioxide per year. Sectoral emissions are based on 2018 figures. Parentheses indicate cheapest alternative fuel source. This analysis indicates the carbon price necessary for green hydrogen to compete in each sector based on 2020 prices. For economy-wide carbon pricing consistent with a 1.5°C scenario, see Finance Target 3.

Source: BloombergNEF (2020b).

Union are promoting hydrogen through supportive decarbonization policies such as carbon contracts for difference in addition to cap-and-trade schemes and fossil fuel subsidy phaseout (BloombergNEF 2020b).

Transitioning to green hydrogen in sectors such as steel, buildings, and shipping will require investment in retrofits, new equipment, or new fuel storage (ETC 2021b; IRENA 2020a; European Commission 2020a). The cost of adopting green hydrogen will likely be a significant barrier. Policymakers can incentivize green hydrogen adoption by raising the cost of carbon and setting ambitious emissions reductions targets. China, for instance, designates hydrogen as a priority technology in its net neutrality strategy and launched its national carbon market in July 2021 (Yin and Yep 2021). Though still early, China's carbon-pricing system, combined with measures to promote fuel cell vehicles and investment in hydrogen development, is expected to help drive hydrogen demand domestically and internationally (Casey 2021).

Multistakeholder coordination

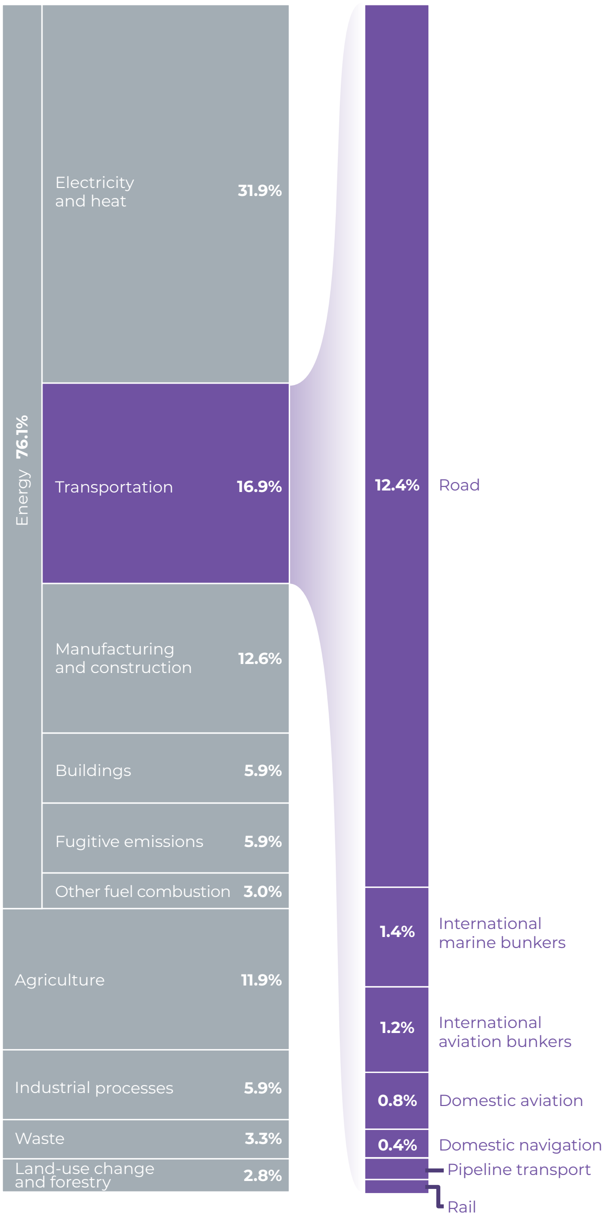
Coordination across public and private stakeholders will be critical to building out the overall hydrogen market and integrating green hydrogen use into the economy at scale. Governments are well positioned to lead this effort through tax incentives to support development of hydrogen production and infrastructure (McDonald et al. 2021). Large-scale demonstration projects, known as hydrogen clusters, can also help overcome market design barriers by bringing together actors across a local economy to demonstrate the full hydrogen value chain. These projects involve the integrated development of hydrogen production, storage, transport, and end-use in one centralized location, which can help address uncertainty around investment in green hydrogen and spark further hydrogen developments (ETC 2021b). Hydrogen clusters are being developed in the European Union, Australia, Saudi Arabia, and South Korea (COAG Energy Council 2019; European Commission 2020a; Stangarone 2021; Robbins 2020).

Multistakeholder partnerships are also helping to create an enabling environment for green hydrogen. HyDeal Ambition, a collaboration between policymakers, industry, and civil society, is developing a green hydrogen project pipeline and value chain collaboration to help deliver the European Union hydrogen strategy (Gupta 2021). On the private sector side, the Green Hydrogen Catapult, a partnership between leading energy companies, aims to drive the price of green hydrogen below $2 per kilogram and deploy 25 GW of renewables-based hydrogen production by 2026 (Deign 2020).

6 TRANSPORT

Transport accounts for approximately 16.9 percent of global GHG emissions (8.3 GtCO_2e emissions in 2018) (Figure 32) (ClimateWatch 2021) and is the fastest growing source of emissions after industry (Ge and Friedrich 2020). Road transport is responsible for the lion's share of these emissions, with rail, aviation, and shipping all comprising a much smaller proportion, each around 1 percent or less of global emissions but growing at a faster rate (ClimateWatch 2021; Crippa et al. 2019).

FIGURE 32. Role of the transport sector in global greenhouse gas emissions



Source: ClimateWatch (2021).

WHILE TECHNOLOGICAL SOLUTIONS such as electric vehicles (EVs) are capturing the zeitgeist with announcements by major vehicle manufacturers and countries related to moving away from the internal combustion engine (see IEA 2021c), achieving full decarbonization of the transport sector while reducing the externalities it currently produces cannot be achieved solely by a change in technology. An often-used framework that helps organize the multiple solutions that will help achieve decarbonization of the sector is Avoid-Shift-Improve (ASI) (Dalkmann and Brannigan 2014). Under this approach, the whole sector (and especially governments through policies and investments) should work toward avoiding the need to travel by using land use tools to bring opportunities closer to citizens, shifting travel toward more efficient, less carbon-intensive modes of travel such as public transport, walking, and cycling, and finally improving the carbon-intensity of the remaining travel modes by means of technology, such as electric vehicles and cleaner fuels.

In this chapter we examine the transition in the transport sector through nine indicators. Indicators 1–7 are related to the road subsector and include the share of trips made by private light-duty vehicles (LDVs) (depicting modal shifts, in line with the shift part of the ASI framework) (indicator 1); the carbon intensity of land-based passenger transport (indicator 2); the share of electric LDVs in total sales and stock (indicators 3 and 4, respectively); sales of zero-emissions buses (indicator 5); sales of zero-emissions medium- and heavy-duty vehicles (MHDVs) (indicator 6); and the share of low-emissions fuels (indicator 7). Indicator 8 is related to the aviation subsector; specifically, the share of sustainable aviation fuel. Indicator 9 covers the shipping subsector, tracking the share of zero-emissions shipping fuels. For seven of the nine indicators, historical rates of change are headed in the right direction but are below levels required for 2030; for one (modal split – percentage of trips done by LDVs), the historical rate of change is headed in the wrong direction entirely; and, for the remaining one, data are insufficient to assess the historical rate of change and gap in action (Table 10). The choice of indicators skews toward those relating to technological solutions, but this is not intended to be interpreted as a prioritization of such solutions. The availability of quality global-scale historical data and modeling approaches is greatest for a number of these indicators, which enables the derivation of associated 1.5°C-compatible targets.

Avoid strategies will play a crucial role in reducing emissions from the transport sector. However, due to challenges in identifying a concise set of indicators for which historical data were available, progress toward implementing Avoid strategies is not tracked in this report. Nonetheless, strategies including changes to zoning laws that support higher densification to reduce the number and distance of trips, as well as demand-management interventions to disincentivize travel, are powerful levers available to policymakers aiming to foster a more sustainable, equitable transportation system. They should be thoroughly considered, together with changes in technology. For further reading on how to implement these types of strategies and their mitigation potential, please refer to Litman and Steele (2017).

In addition to promoting mitigation, the shifts needed in the transport sector to help limit warming to 1.5°C can also bring socioeconomic benefits. For example, road vehicles are currently responsible for more than two-thirds of urban air pollution (Khreis et al. 2019), so reduced dependence on internal combustion engines would lead to improved local air quality and significant health co-benefits. Air pollution is linked to premature death in adults due to heart and lung disease, strokes,

TABLE 10. Summary of progress toward 2030 transport targets

Indicator	**Most recent historical data point** (year)	2030 target	2050 target	Trajectory of change	Status	Acceleration factor
Share of trips made by private LDVs (%)	43.60% (2020)	36–46	No target established (insufficient data)	Exponential change possible		n/a; U-turn needed
Carbon intensity of land-based transport (gCO_2/pkm)	104 (2014)	35-60	Near zero	Exponential change possible	?	Insufficient data
Share of EVs in LDV sales (%)	4.26 (2020)	75-95	100 by 2035	Exponential change likely		n/a; in diffusion stage of S-curve
Share of EVs in the LDV fleet (%)	0.55 (2020)	20–40	85–100	Exponential change likely	!	n/a; in diffusion stage of S-curve
Share of BEVs and FCEVs in bus sales (%)	39 (2020)	75 by 2025	100 in leading markets by 2030	Exponential change likely		n/a; in diffusion stage of S-curve
Share of BEVs and FCEVs in MHDV sales (%)	0.30 (2020)	8 by 2025	100 in leading markets by 2040	Exponential change likely	!	n/a; in emergence stage of S-curve
Share of low-emissions fuels in the transport sector (%)	4.26 (2018)	15	75 to 95	Exponential change possible	!	12x
Share of SAF in global aviation fuel supply (%)	0.10 (2019)	10	100	Exponential change likely	!	n/a; in emergence stage of S-curve
Share of ZEF in international shipping fuel supply (%)	No data	5	100	Exponential change likely	!	n/a; in emergence stage of S-curve

Note: n/a = not applicable; gCO_2/pkm= grams of carbon dioxide per passenger kilometer; EV = electric vehicle; LDV = light-duty vehicle; BEV = battery electric vehicle; FCEV = fuel-cell electric vehicle; MHDV = medium- and heavy-duty vehicle; SAF = sustainable aviation fuel; ZEF = zero-emission fuel.

Sources: For data, ITF (2021); IEA (2017a; 2020n); BloombergNEF (2021a); and WEF (2020). For targets, authors' analysis of projects based on BloombergNEF (2021a); CAT (2020a; 2020b); Race to Zero (2021a); and Osterkamp et al. (2021).

heart attacks, and other chronic respiratory diseases, among others; it is also responsible for premature deaths in children from acute lower respiratory infections such as pneumonia (CCAC 2021). Additionally, experts note the socioeconomic benefits of shifting to safer roads through walking, cycling, shorter trips, and public transport that can reduce traffic fatalities and improve health through physical activity. Public transport also helps to provide equitable access to jobs, education, and services.

It is important to note here that as countries improve their transport fleets, negative impacts may be transferred, sometimes across national borders. For example, as advanced economies have introduced more stringent fuel efficiency standards, older vehicles have been shipped to developing countries that typically lack effective standards and regulations (UNEP 2020b). This export of old, polluting, and unsafe vehicles is an unintended but damaging consequence of upgrading vehicle fleets in wealthier countries. Thus, when transforming the transport sector, attention to impacts across the entire globe is critical.

Some of the transitions envisaged in the transport sector also depend on rapid scaling up of battery manufacturing (the current announced production capacity for 2030 would cover only 50 percent of required demand in that year) (IEA 2021). Mining the valuable minerals needed for these batteries has historically been accompanied by conflicts and significant social and environmental costs (see more in Chapter 11, "Equity and just transition")—important issues that are not yet resolved (IISD 2018). Finally, while full electrification of road transport is possible, it will increase pressure on electricity grids, potentially making the sector vulnerable to power disruptions (IEA 2021c). Fuel diversification could help to support resilience and energy security (IEA 2021c), and a reduced reliance on motorized transportation through Avoid and Shift policies and solutions will be crucial to reducing the potential negative effects of relying solely on electricity. Multiple targets in this section include increased levels of less carbon-intensive fuels, including biofuel. In all cases, the use of biofuels should include a comprehensive accounting of their emissions impacts, including land-use change (e.g., displacing food production or natural ecosystems) and other negative climate impacts to avoid artificially low accounting, and an unintended increase in emissions.

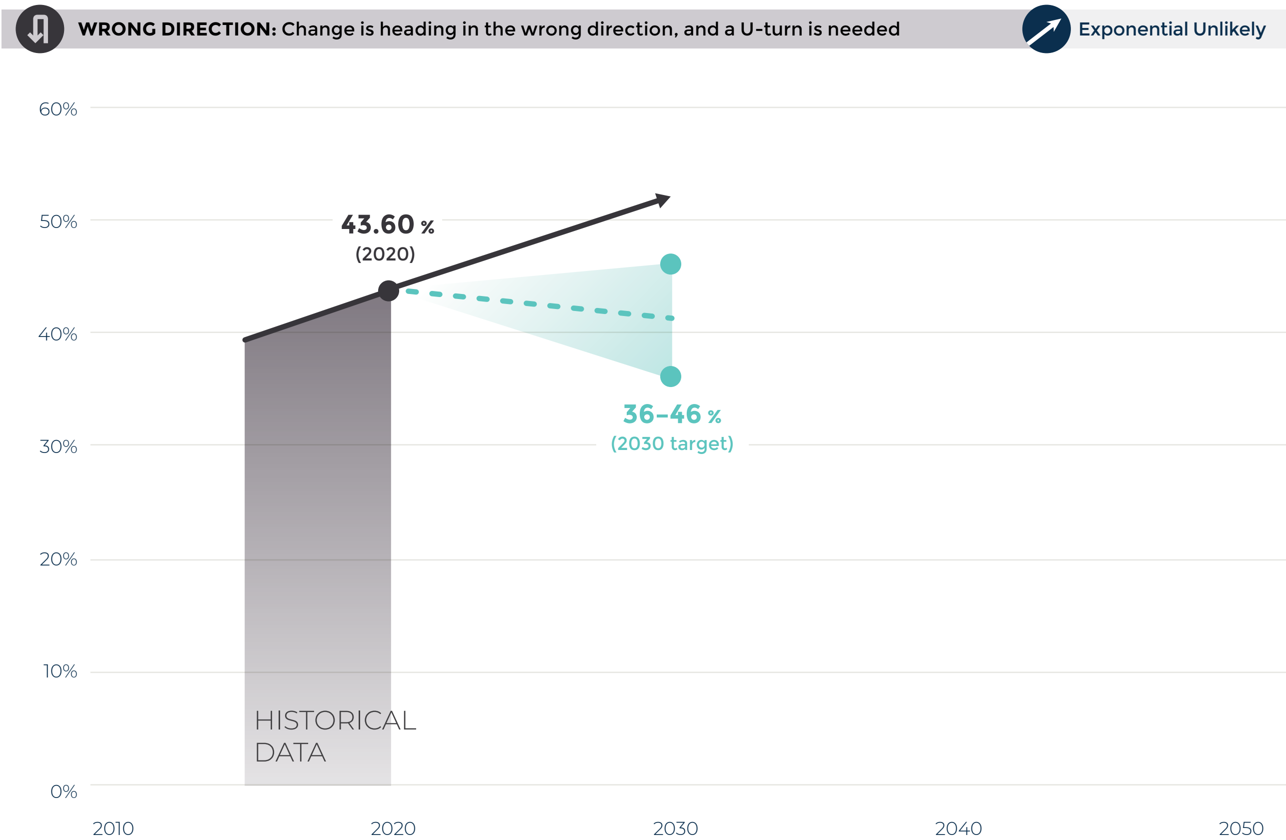
TRANSPORT INDICATOR 1:

Share of trips made by private light-duty vehicles (modal shift)

Target: People around the world reduce the percentage of trips made in private LDVs by between 4 percent and 14 percent, relative to business-as-usual levels, by 2030.

Today, 75 percent of CO_2 emissions from the transport sector come from road transport, and 87 percent of these are from light-duty vehicles and trucks (SLOCAT 2021). While the focus of mitigation measures in the transport sector toward 2030 and 2050 has been mostly on technological changes, reducing the demand for travel, particularly using light-duty vehicles, must play a significant role in reaching the Paris Agreement's goals by 2050 (IEA 2021c; ICCT 2020a). Given that travel behavior is heavily influenced by how the transport system is designed, it is the responsibility of policymakers to create an environment where consumers can choose more sustainable modes of transport than private motor vehicles. Policymakers must also ensure equal access to transport opportunities.

FIGURE 33. Historical progress toward our 2030 target for the share of trips made by private light-duty vehicles

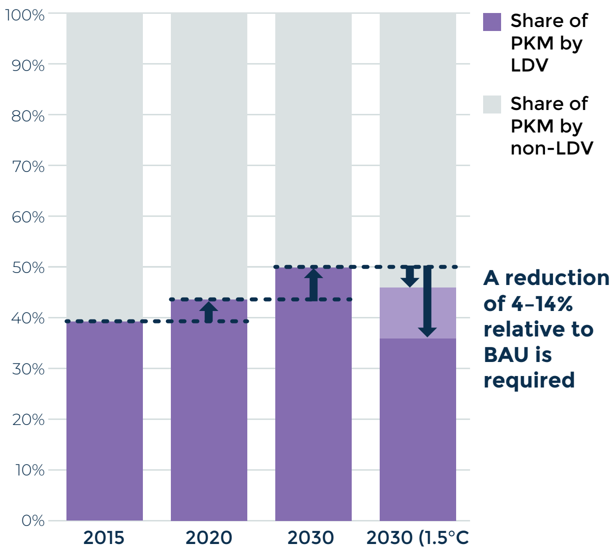


Sources: ITF (2021) for the historical data; the 2030 target derived from authors' analysis and calculations for the projections based on Bloomberg New Energy Finance Electric Vehicle Outlook 2021 (BloombergNEF 2021a).

Historically, due to the preponderance of investments and policies that prioritize motor vehicles, the percentage of people who use private motor vehicles as their primary mode of transportation has increased worldwide (see Figure 33). Among other reasons, the proven link between economic development and motor vehicle usage explains this upward trend. Under current projections, the total number of light-duty vehicles in the world will increase from 1.3 billion in 2015 to 1.4 billion in 2030 (BloombergNEF 2021a), mostly in developing countries. This means that, under a business-as-usual scenario, the total number of people using motor vehicles for their travel will increase.

Our analysis shows that, since current projections of EV penetration are falling short of targets (see transport indicators 3–6), there is a gap that will need to be filled by reduced demand, notably a move away from motor vehicle travel. This gap will be exacerbated by the slow turnover of light-duty vehicles, which in the United States is 12 years but is likely higher in other places around the world (IHS Markit 2021), making the replacement of the fleet by EVs even slower. Specifically, the global percentage of motor vehicle trips (expressed as passenger kilometers, or pkm) should decrease from its predicted 50 percent to between 36 percent and 46 percent (see Figure 34),

FIGURE 34. Share of passenger kilometers by transport mode



Note: BAU = business as usual; LDV = light-duty vehicle; PKM = passenger kilometers. See Box 6 on the methodology used for the design of this target.

Source: Percentage of motor vehicle modal split in 2015 and 2020 from ITF (2021).

which means they should stay close to 2020 rates or, to meet the higher EV targets, decrease by 8 percentage points from 2020 levels. While EVs are a critical piece of reaching the Paris climate goals, they must be used in tandem with investments in public transportation, walking, and cycling infrastructure, as well as policies to encourage use of modes of transportation other than motor vehicles and to reduce the need to use private motor vehicles as the default mode. Looking at regional projections, these targets mean that Asia, Africa, and Latin America can accommodate modest growth in private motor vehicle trips if countries in Europe and North America reduce their own percentage of trips taken in private motor vehicles (ITF 2021). See Box 6 for an explanation of the methodology developed for this modal shift indicator's targets.

BOX 6. Methodology used for the design of modal shift target

In the scenario used in Transport Indicator 4 (electric vehicles' share of global light-duty vehicle fleet) target electric vehicle (EV) penetration is 20–40 percent of global vehicle stock by 2030. Our analysis compared the bottom and top of the target range against the business-as-usual (BAU) scenario projected in the Bloomberg New Energy Finance (BNEF) Electric Vehicle Outlook 2021 Report, in which EVs will make up 12 percent of the global vehicle stock in 2030. There is therefore a gap of 8–28 percent in the number of EVs between a BAU and a Paris-aligned scenario. We propose closing this gap by shifting trips that would be done in EVs to nonmotorized vehicle modes, including walking, cycling, and public transport. We assume in this analysis that these non-motor vehicle modes will be either zero emissions (e.g., walking and cycling) or fully electrified (transit) by 2030.

While shifting away from motor vehicle travel can mitigate GHG emissions (Bakker et al. 2014), there are additional co-benefits to this transition around equity and health. As noted in the introduction, reducing the use of cars can not only improve air quality and reduce mortality from respiratory illness, but it can also reduce road fatalities, currently the number one cause of death for children and young adults 5–29 years old globally, equivalent to 1.3 million deaths (WHO 2021). In addition to preventing deaths, active modes of transportation, including walking and cycling, have also been linked with decreased levels of mortality due to an increase in physical activity (Götschi et al. 2015).

Moving society away from car ownership and use also brings economic benefits. For one, the energy efficiency of automobiles is low compared to non-motor vehicle modes, meaning a shift toward the latter would reduce overall energy use in the sector, therefore allowing for a decoupling of economic growth and energy use (Böhler-Baedeker and Hüging 2012). Private vehicles are also inefficient in their use of space. There are between three and four parking spaces per car in the United States (Chester et al. 2010), which amounts to vast areas of unproductive land that could be used for amenities such as parks or, as demonstrated by the pandemic, extensions of shops and restaurants. Cars are, furthermore, parked 92 percent of the time (Shoup 2011), making them a very expensive yet unproductive and inefficient asset that loses value with time. As expensive and depreciating assets, cars are inherently inequitable, pushing people into cycles of deepening

poverty, especially when they become a necessity to access jobs, groceries, and health care. In the United States, the population at the lowest quintile of income spends 32 percent of their income on transportation costs, simply because they need a car in order to access their daily lives (U.S. Bureau of Labor Statistics 2019). Finally, traffic congestion from inefficiently utilized private vehicles generates economic losses for society as a whole (National Household Travel Survey 2017).

While EVs might help mitigate CO_2 emissions and reduce air pollution, they will not help improve any of these social and economic problems, something shifting to other more efficient and less expensive modes of transportation can achieve.

Enablers of climate action

Multiple factors make the transition away from motor vehicle usage difficult. The biggest barrier to achieving the necessary changes is the lock-in effect of past urban land use decisions that encourage sprawl, coupled with induced demand for motorized transport created by past investments in roads, parking, and highways. The more than a century of investment in this type of infrastructure makes it hard to achieve sudden and meaningful changes. Despite this barrier, two enabling factors can help reverse this trend: shifting existing and projected public and private investments in infrastructure toward non–motor vehicle modes and implementing policies that discourage motor vehicle use.

Shifting transport investments

Governments have historically prioritized investments in roads over other infrastructure, thus favoring motor vehicle users (Lefevre et al. 2016). Between 1995 and 2019, road infrastructure investment across 15 countries made up an average of 61 percent of total transport investment (ITF 2021). By investing in motor vehicle infrastructure, motor vehicle usage demand will continue to be induced (Lee et al. 1999), which will lead away from the goal of this indicator. To counterbalance this trend, governments need to shift their investment priorities toward other types of investments, notably walking and cycling infrastructure as well as public transport infrastructure. In addition to infrastructure, governments will need to consider how they will incentivize the adoption of EVs. New cars are mainly purchased by the wealthy, meaning that direct purchasing incentives for EVs are a regressive policy that benefits primarily high-income households (CRS 2019). Again, shifting incentives away from cars toward other modes of transportation and enabling infrastructure will provide more equitable economic returns and social outcomes.

Adopting enabling policies

Land use policy measures: Higher levels of densification have been linked to lower per-capita emissions (Ribeiro et al. 2019) and make travel by transit, walking, and cycling more available due to closer proximity to desired destinations. Policymakers can therefore implement zoning regulations encouraging dense and mixed-land uses on a connected network of multimodal streets.

Governments will also need to actively discourage motor vehicle usage. While unpopular, these types of policies, known as transportation demand management (TDM) policies, are justified by the externalities that motor vehicle usage generates.[40] TDM policies include measures such as removing parking minimums in new developments, increasing parking costs, congestion charging schemes, higher fuel taxes, or per-kilometer fees for electric vehicles, among others.[41]

TRANSPORT INDICATOR 2:
Carbon intensity of land-based transport

Targets: The carbon intensity of land-based passenger transport falls to 35–60 gCO_2/pkm by 2030 and reaches near zero by 2050.

In 2014, the last year of available data, the global average carbon intensity of land-based passenger transport, which covers trips made by car, bus, train, and motorcycle, was 104 grams of CO_2 per passenger kilometer (gCO_2/pkm) (IEA 2017b). This does not include the life-cycle emissions generated by the various forms of land-based transport (the 2030 and 2050 targets do not include them either). While life-cycle emissions are an important consideration when promoting specific alternatives to fossil fuel vehicles, including an analysis of them is beyond the scope of this report.

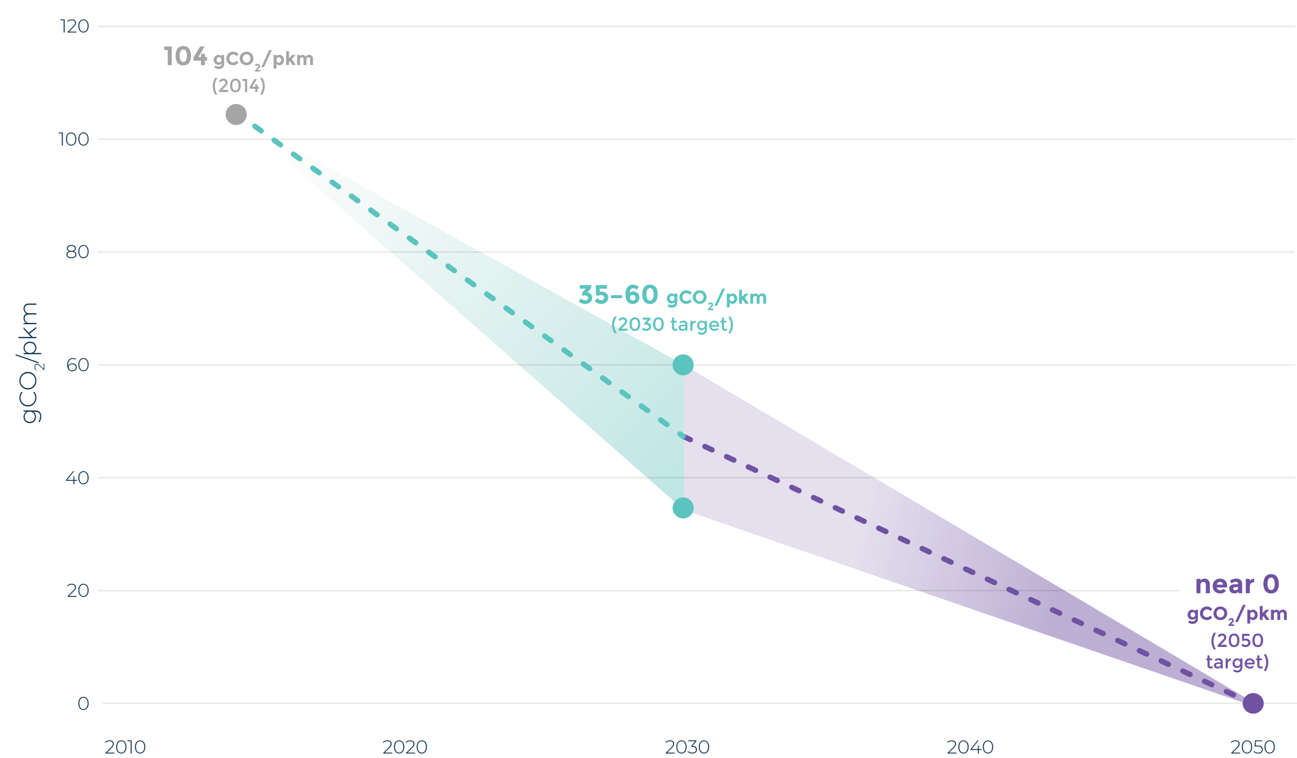
The carbon intensity of land-based passenger transport varies dramatically across countries; for example, the average trip in India emits roughly five times less CO_2 per kilometer than the average trip in the United States (IEA 2017a). This can largely be explained by the dominance of travel by car in the United States, whereas bus and train travel play a much larger role in India. The European Union recently implemented a limit of 95 gCO_2/km for new cars and 147 gCO_2/km for light commercial vehicles, the most stringent in the world. The equivalent for new cars in the United States is 121 g/km, while in China it is 117 g/km, and in Japan it is 105 g/km (VDA 2020).

To ensure alignment with the Paris Agreement's 1.5°C temperature goal, the global average carbon intensity would need to be cut to between 35 and 60 gCO_2/pkm by 2030 and reach near zero by 2050 (see Figure 35). Achieving this target will require different approaches fit for purpose in individual countries and their existing transport mix. However, broadly speaking, a reduction in carbon intensity of existing transport options combined with encouraging the switch to low- or zero-carbon forms of transport will be needed everywhere.

Technologies needed to achieve a steep reduction in carbon intensity of the vehicle fleet are available now at rapidly falling cost. Price parity between battery electric vehicles and fossil fuel equivalents in all vehicle segments is expected by 2027 in Europe (BloombergNEF and Transport & Environment 2021). These rapid cost reductions are expected to lead to S-curve-shaped growth for EVs, which could help to achieve the necessary steep decline in emissions intensity. Measures to expedite the removal of polluting vehicles from the secondhand market and prevent their sale to developing countries will help assist the formation of a global S-curve. Electrifying existing rail networks can help to mitigate emissions from this segment, which will experience higher demand due to modal shift, while more remote or less utilized routes could employ hydrogen powered trains to replace currently used diesel models (Logan et al. 2021). This would also help ensure that a modal shift achieved in the freight sector from road to rail results in the greatest possible emissions reductions.

FIGURE 35. Historical progress toward 2030 and 2050 targets for the carbon intensity of land-based 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. Data are insufficient to calculate acceleration factor needed to reach 2030 target.
Sources: For historical data, IEA (2017a); for targets, CAT (2020a; 2020b).

Enablers of climate action

Reducing the overall carbon intensity of land-based passenger transport will take a concerted effort from multiple angles, given that it requires a multifaceted transformation across technology use and individual behavior (ACEA 2015). Governments could play a central role in developing effective and targeted policies to overcome these barriers and help fast-track the necessary transition to low-carbon transport.

Changing mobility behaviors

The transition to zero-emissions cars will occur over many years. Reducing dependence on motor vehicles over the short and medium term is key to rapidly bringing overall carbon intensity down. Changes in the behavior of individuals will help greatly, especially in wealthy countries where the reliance on and prevalence of cars is highest but also in developing countries where rapid motorization is occurring. A major shift away from private vehicle travel over this decade and beyond to other less energy-intensive modes like cycling, walking, e-scooters, and public transport will be crucial to rapidly decarbonizing the transportation sector.

To effect behavior change on the scale needed, efforts will be required on many fronts. These could include public awareness and education campaigns, investments in infrastructure like bicycle storage and paths for bicycles and walking, and expanded public transport and ride-sharing services, financial incentives to individuals and employers to encourage modal shift and creating pedestrian- and cyclist-friendly car-free zones (Koska and Rudolph 2016; Savan et al. 2017). An ex-post analysis of such measures in various European cities demonstrated, however, that particular consideration must be given to each city's unique characteristics to determine which mix of policies is most appropriate, and how they might need to be tailored accordingly (Dijk et al. 2018).

Pairing supportive policies with increased public finance to scale low-carbon transport technologies

Industrial policy, the domain of federal governments, can help reorient existing industries or nurture nascent ones that focus on production of technologies necessary for the transition to a low-carbon transport sector. One form this can take is the disbursement of grants or subsidies for start-ups and those companies engaged in the early stages of technology development, or that are selling products at the early-adopter phase as electric and fuel cell vehicles are in many countries. Long-term policy commitments to develop specific technologies and their necessary supply chains can also help them scale up. This is the case, for example, for advanced biofuels that involve dramatically lower land and water consumption and do not compete with food production (IRENA 2019a).[42] Mandating the purchase of zero-emissions vehicles for government fleets is a way to generate stable early demand for these technologies and is an important step in fostering the growth of overall sales and domestic manufacturing industries.

The provision of adequate resources for public transportation services and infrastructure, and ensuring that routes are serviced using low-emissions vehicles, is critical. Public transport is primarily the domain of state and local governments, but these bodies also have a crucial role to play in planning for walking and cycling-friendly built environments, and implementing such measures as intracity restrictions for polluting vehicles and incentives like bike-sharing schemes that promote active mobility.

Federal and state funding could help ensure adequate infrastructure in built environments to encourage modal shift. Federal governments could also introduce metrics that track the direction of infrastructure investments toward projects that will help lower the average carbon intensity of transport and away from emissions-causing projects like highway expansion.

Supporting R&D for new technologies

Some technologies, including electric cars, buses, and trains, are already mature and simply need to be incentivized to be rolled out at scale (IEA 2020g). However, reducing the cost of these technologies further and increasing their range will speed the transition. This will require breakthroughs in key nested technologies like lithium-ion batteries and their manufacturing processes, and the development of superior battery technology (Cui et al. 2020; Rachel and Brown 2021; Macduffie and Light 2021).

For some applications, however, existing technologies are not suitable, or remain cost-prohibitive. This is the case, for example, for many rural train services that would require large investments to electrify the entire line they run on. Hydrogen fuel cell models could fill this niche, provided the hydrogen is produced with renewable energy, but they remain significantly more expensive than existing diesel models. Further innovation in fuel cell technology and achieving economies of scale in manufacturing will be required to boost adoption (Logan et al. 2021).

This is also the case for hydrogen fuel cell buses, which could provide a way to maximize emissions reductions in countries where the power sector remains carbon intensive. Hydrogen fuel cell models currently also have an advantage over batteries for long distance routes because of their superior range (Element Energy 2017; Logan et al. 2020; S&P Global Platts 2021). The current rapid improvement in battery technologies, however, may yet lead them to become competitive with fuel cells in this regard.

Given the importance of achieving a considerable reduction in reliance on motor vehicles (especially privately owned), care must be taken not to skew efforts too much toward pursuing technological solutions rather than shifting behavior and transport preferences to walking, cycling, and mass transit options.

TRANSPORT INDICATOR 3: Share of electric vehicles in light-duty vehicle sales

Targets: Electric vehicles account for 75–95 percent of total annual light-duty vehicle sales by 2030 and 100 percent by 2035.

Policies to phase out internal combustion engine (ICE) cars and encourage the uptake of electric vehicles are becoming more prevalent, but the scope and ambition of many of these efforts fall short of what is needed. Between 75 and 95 percent of global light-duty vehicle sales would need to be electric vehicles by 2030 to achieve a 1.5°C-compatible pathway for the transport sector, reaching 100 percent well before 2050. A widespread and rapid shift to zero- and low-carbon modes of transport like walking, cycling, and public transport may reduce the need to achieve such a steep increase in global EV sales.

Electric vehicle sales have been growing rapidly, reaching 4.3 percent of global light-duty vehicle sales in 2020. Global sales of electric vehicles grew at a compound annual growth rate (CAGR) of 50 percent from 2015 to 2020. There was some slowdown in 2019, when the CAGR was only 13 percent (BloombergNEF 2021a). In 2020, during the COVID-19 pandemic global sales increased 67 percent globally, led by a sharp increase in Europe, but in some countries EV LDV sales fell, such as in Japan and Canada (EAFO 2021; BloombergNEF 2021a; IEA 2021c).

The future trajectory of electric vehicle sales depends on whether they continue to experience high rates of growth, driven by manufacturers scaling up production, falling costs, and government targets to phase out fossil fuel vehicle sales. Preventing the export of used ICE cars to developing countries can also help to ensure the fastest possible adoption rates. Falling upfront costs are key, as EV lifetime maintenance and fuel costs are already considerably lower than for fossil fuel counterparts (Logtenberg et al. 2018).

Given the growth trends of EVs, it doesn't make sense to chart projections with linear extrapolation. Instead, the future trajectory of EV sales as a share of the light-duty vehicle market will likely follow an S-curve, following the pattern of other instances of technology adoption, including the automobile itself. There is little literature evaluating EV S-curves. It is impossible to project S-curves in the early stages of their growth with any

level of certainty, and efforts to make such projections in the early stages have failed in the past (Kucharavy and De Guio 2011; Crozier 2020).

Despite extreme uncertainties in projecting S-curves at the early stages, Grubb et al. (2021) do project an S-curve by extrapolating the historical global growth rates of EV sales' market share. They assume that the shape of the S-curve will be symmetrical in that the acceleration in the first half is mirrored by the deceleration after the midpoint. They assume that the highest value that EV sales will reach is 100 percent of total sales and use that to project the curve. They find that their modeled growth of EV sales in terms of market share would be on track for the Paris-consistent trajectories they identify. However, our targets require higher levels of EV sales than the benchmarks used by Grubb et al. (2021), so when we adjusted this method to our targets EV sales were not on track (Figure 36).

There are promising signs, but it does appear that growth in EV sales must accelerate, though much uncertainty remains over how much acceleration is needed. This is a rapidly developing field, and there will likely be methodological improvements to S-curve evaluations in the future.

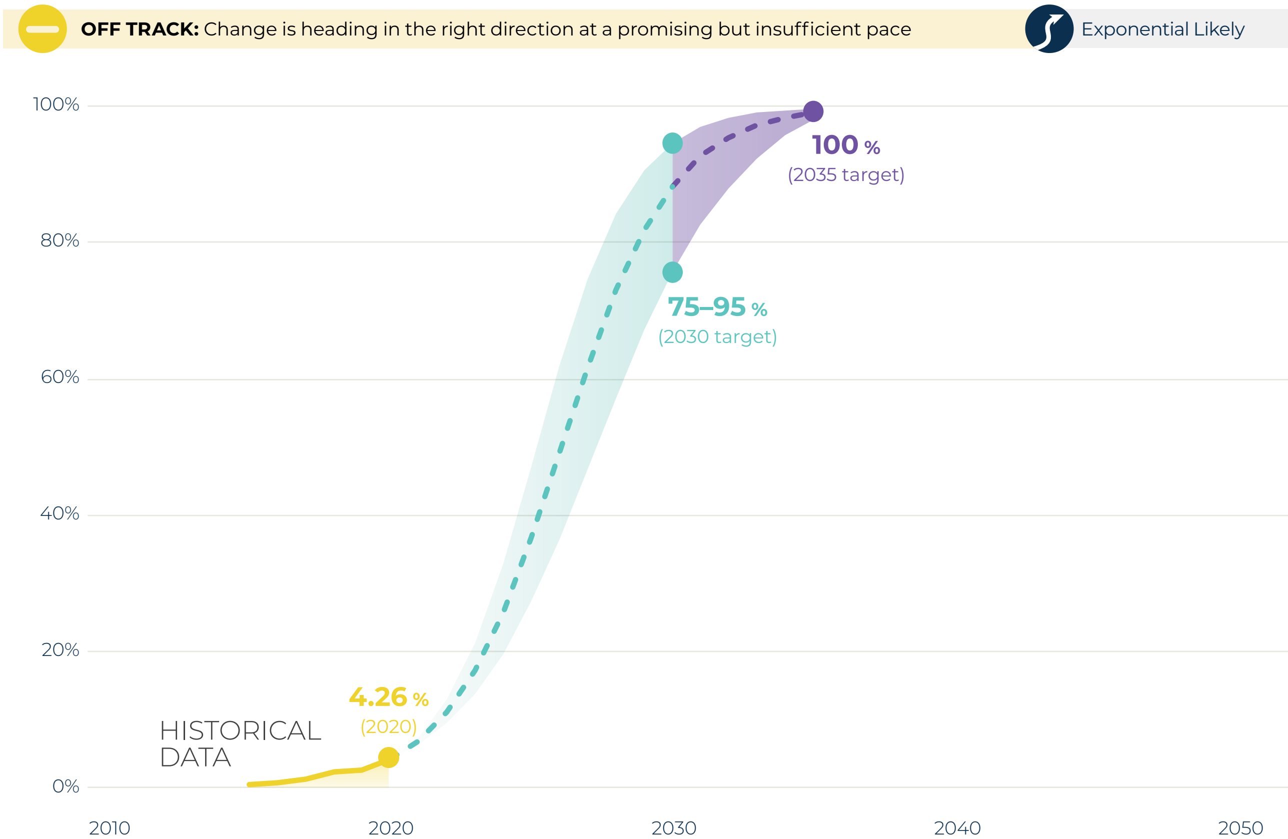
One way to reduce the required steepness of this curve is to encourage a modal shift to public transport (see Transport Indicator 1) or electric micromobility. This would simultaneously ease the burden of battery production and the amount of clean energy generation needed to transition this sector, while providing co-benefits like improved mobility and access, and reduced congestion and traffic accidents.

Enablers of climate action

EV sales have increased significantly globally, particularly in leading markets like China and the European Union, but additional action is needed to meet Paris-aligned targets. Barriers include

- upfront cost;
- lack of charging infrastructure; and
- consumer hesitancy (BloombergNEF 2020a).

FIGURE 36. Historical progress and an illustrative S-curve of what's needed to reach 2030 and 2035 targets for the share of electric vehicles in light-duty vehicle sales



Sources: For historical data, authors' analysis and BloombergNEF (2021a); for targets, CAT (2020a; 2020b).

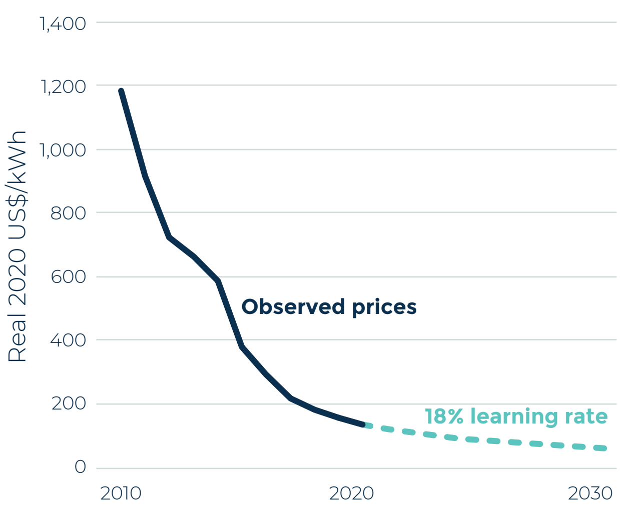
While drivers of increasing sales vary depending on EV market conditions, three stand out: decreasing battery price, developing charging infrastructure, and implementing supply- and demand-side policies to incentivize EV adoption.

Investing in R&D to decrease battery price

For EV manufacturing to compete with ICE manufacturing costs, battery pack price must reach a tipping point of $100/kWh (BloombergNEF 2020a; Boudway 2020). Currently, the average cost of lithium-ion batteries is $137/kWh (Henze 2020). Trends are promising: battery pack prices fell from $1,183/kWh in 2010 to $156/kWh in 2019 (BloombergNEF 2020a). This 87 percent reduction can be attributed to technological improvements and economies of scale as production and deployment of lithium-ion batteries increased. Based on an observed learning rate of 18 percent, BloombergNEF (2021a) estimates that prices will continue to fall, reaching $92/kWh by 2024 and $58/kWh by 2030 (Figure 37). Slower price declines in the next decade are due to technological constraints concerning lithium-ion. R&D investment will be needed to test and scale alternative cathode and anode technologies (Grubb et al. 2020; Masais et al. 2021).

Initiatives involving supply-side actors, policymakers, and civil society are in place to develop new battery technologies and scale lithium-ion battery production. A Stanford University study found that lithium-metal batteries have the potential to hold twice the electricity per kilogram of lithium-ion batteries (Shwartz 2020). On the supply side, Tesla is developing silicon-anode and high-nickel cathode technologies, which could decrease battery price by 5 percent and 15 percent, respectively (Hawkins 2020; Spector 2020). Policymakers are also acting. Europe's Green Deal, for example, allocates €550 billion to climate protection and green technology, including lithium-ion battery R&D and manufacturing (Abnett and Green 2020).

FIGURE 37. Lithium-ion battery outlook



Note: kWh = kilowatt-hour.
Source: BloombergNEF (2021a).

Accelerating installment of charging infrastructure

Concerns about running out of power and lack of charging infrastructure are a significant barrier to EV adoption (Glandorf 2020; Woodward et al. 2020; Rajper and Albrecht 2020). By the end of 2020, over 1.36 million public charging points had been installed globally, and since 2012 annual installation has grown at a compound annual growth rate of 39 percent (BloombergNEF 2021a). Policymakers can accelerate the development of accessible charging infrastructure through a combination of dedicated funding, regulations, and incentives. Specific strategies include subsidizing construction, waiving licensing fees for new charging stations, establishing charging point requirements for new gas stations, and integrating charging into a smart grid system (Meszaros et al. 2020; McLane and Liu 2020). Types of chargers needed (i.e., home and work, street-level, and fast charging) will vary by country depending on a range of factors including levels of semidetached and detached housing, vehicle fleet composition, and behavioral factors like commuting practices (BloombergNEF 2020a).

Despite increases in charging infrastructure, growth remains concentrated in the leading EV markets: China, Europe, Japan, and the United States (BloombergNEF 2020a). Even in advanced markets, charging infrastructure lacks consistent standards and remains fragmented. Ensuring that public charging is available outside of urban clusters, such as along highways or in public parking areas, enabling interoperability across markets, and setting standards for charging infrastructure will support EV sales (Colle et al. 2021).

Combining supply- and demand-side policies to promote the shift to EVs

Governments can increase EV sales through subsidies, tax credits, and direct purchasing incentives (IEA 2020g). Norway, for example, offers a variety of benefits to EV drivers, including exempting EVs from road and purchase or import taxes. Incentives are reevaluated frequently and are scheduled to be reviewed and adjusted according to market conditions at the end of 2021 (Norsk Elbilforening 2021). The Government of India has also used incentives to spark EV demand, recently approving a $1.4 billion EV subsidy program to increase demand (Carpenter 2019). As the EV market develops, policymakers can also drive EV sales and use by facilitating a preowned leasing and sales market for EVs and batteries (Sclar and Werthmann 2019).

On the supply side, policymakers are setting increasingly stringent efficiency standards and EV sales targets. Over 20 countries have committed to completely phasing out the sale of ICE passenger vehicles by or before 2040. In response, several companies, including General Motors, Volkswagen, Volvo, and BMW have committed to launching new EV models, investing in battery R&D, and limiting or eliminating ICE production entirely (Race to Zero 2021b).

Supply- and demand-side policies can be implemented effectively at different stages of market development or used together to maximize EV adoption. China, for example, has used a combination of supply- and demand-side strategies, leveraging demand-side schemes to stimulate EV market growth and subsidizing EV purchases starting in 2013 (Chang 2014). The country is now phasing out subsidies, transitioning to supply-side mandates with the goal of increasing EVs to 40 percent of total sales by 2030 (Stauffer 2021).

Currently, most EV subsidies are regressive. In the United States, for example, EV purchasers need to make over $66,000 per year to receive the full tax benefit available (Osaka 2021). Countries that provide direct subsidies for EV purchases also benefit higher-income consumers while EVs remain more expensive than ICE vehicles (Camara et al. 2021). Though EV accessibility will improve as prices continue to fall, equitably targeting benefits to increase EV availability to all income levels will be critical going forward (Linn 2021).

TRANSPORT INDICATOR 4: Share of electric vehicles in the light-duty vehicle fleet

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

The rapid growth in EVs' share of annual LDV sales began only recently, so the share of EVs in the global LDV fleet remains very low, at less than 1 percent in 2020 (BloombergNEF 2020a, 2021a). With a flurry of government policy in this area across numerous countries in recent years, including bans on fossil fuel car sales and subsidies to stimulate demand, we expect to see EVs constituting a significant proportion of the total LDV stock in this decade. While reaching 100 percent sales of new vehicles is a critical milestone en route to decarbonization of the transport sector, what is most important is the eventual removal of all fossil fuel vehicles from our roads.

To ensure achievement of the 1.5°C temperature goal of the Paris Agreement, 20–40 percent of the global LDV fleet would need to be electric by 2030, reaching 85–100 percent by 2050. Crucially, this means that new LDV sales must reach 100 percent well before 2050, and the sale of used EVs must be strongly supported in order to ensure a rapid diffusion of the technology to all drivers. In addition, concerted efforts to scrap old fossil fuel cars well before the end of their useful life will be critical to ensure that the global fleet reaches zero emissions as rapidly as possible.

In its 2020 EV Outlook, BloombergNEF projects a share of global stock of just 9 percent by 2030 (BloombergNEF 2020a). As with EV sales, the growth of the EV fleet share will likely follow an S-curve. With so few EVs on the road today, it is not possible to derive a robust S-curve that depicts future growth. What is possible is to show what it should look like if we are to meet the targets (Figure 38). This graph is derived from a simple formula and is not the only shape an S-curve could take to meet the targets, but it gives a general sense of where the market share needs to be compared to where it is.

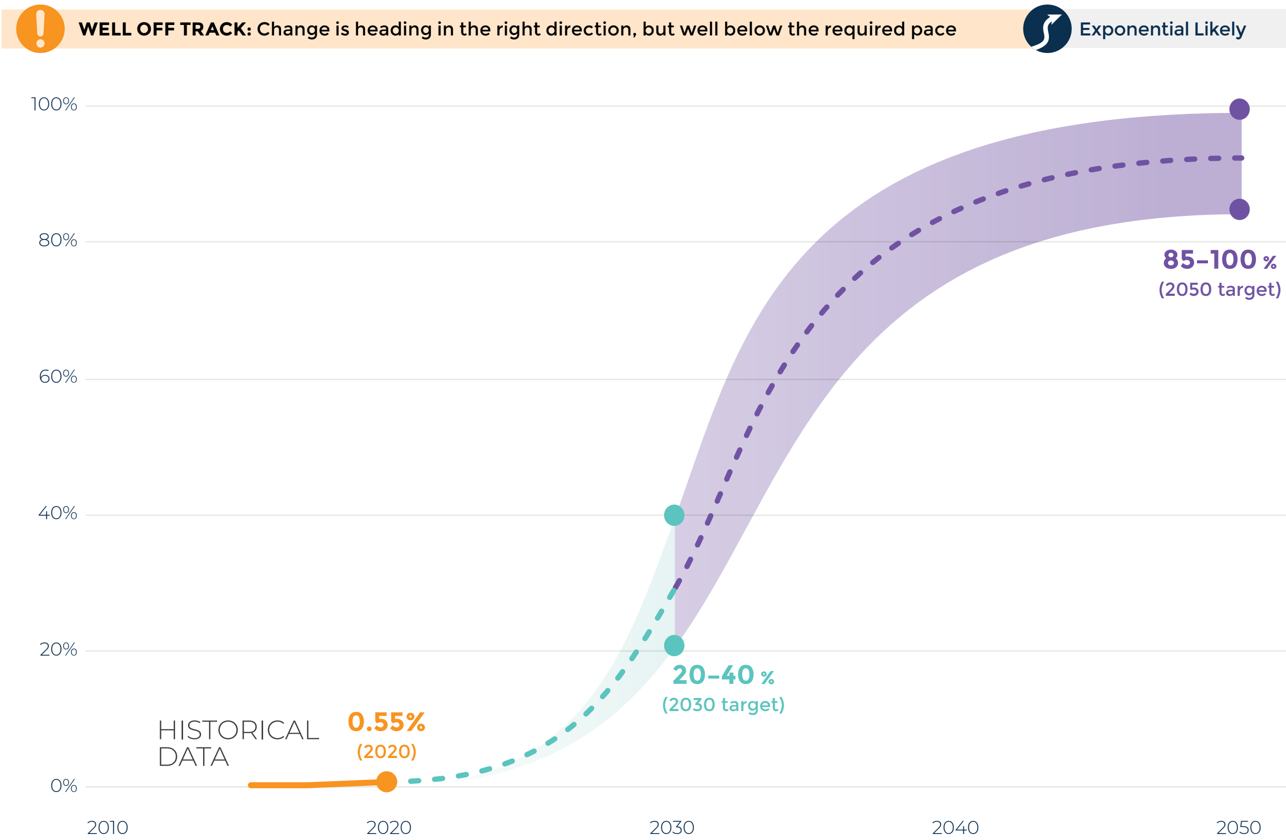
Enablers of climate action

Key challenges to increasing the EV fleet are:

- accelerating vehicle turnover and retirement of ICE vehicles. Under a business-as-usual scenario, passenger vehicle fleets can take up to 20 years to turn over (McConnell and Leard 2020);
- managing ICE vehicle spillover into developing economies (UNEP 2020c); and
- ensuring that infrastructure, such as electricity and vehicle charging points, meets the requirements of an increased EV stock (BloombergNEF 2020a; Gaventa 2021).

Strategies to overcome these challenges will vary by region depending on EV sales and overall EV market development. Key actions include setting ICE phaseout dates, electrifying corporate and government fleets, managing electricity demand to support an increasing number of EVs, and coordinating the preowned ICE vehicle market. It is also important to note that EV sales and fleet growth are interrelated—barriers to EV sales will inevitably inhibit EV fleet growth and measures to increase EV sales or the EV fleet will also help increase the other. While enablers in this section address what is needed to accelerate ICE phaseout and support a growing EV fleet, fully transitioning passenger vehicles to EVs will require strong leadership to address both the sale and fleet components.

FIGURE 38. Historical progress and an illustrative S-curve of what's needed to reach 2030 and 2050 targets for the share of electric vehicles in the light-duty vehicle fleet

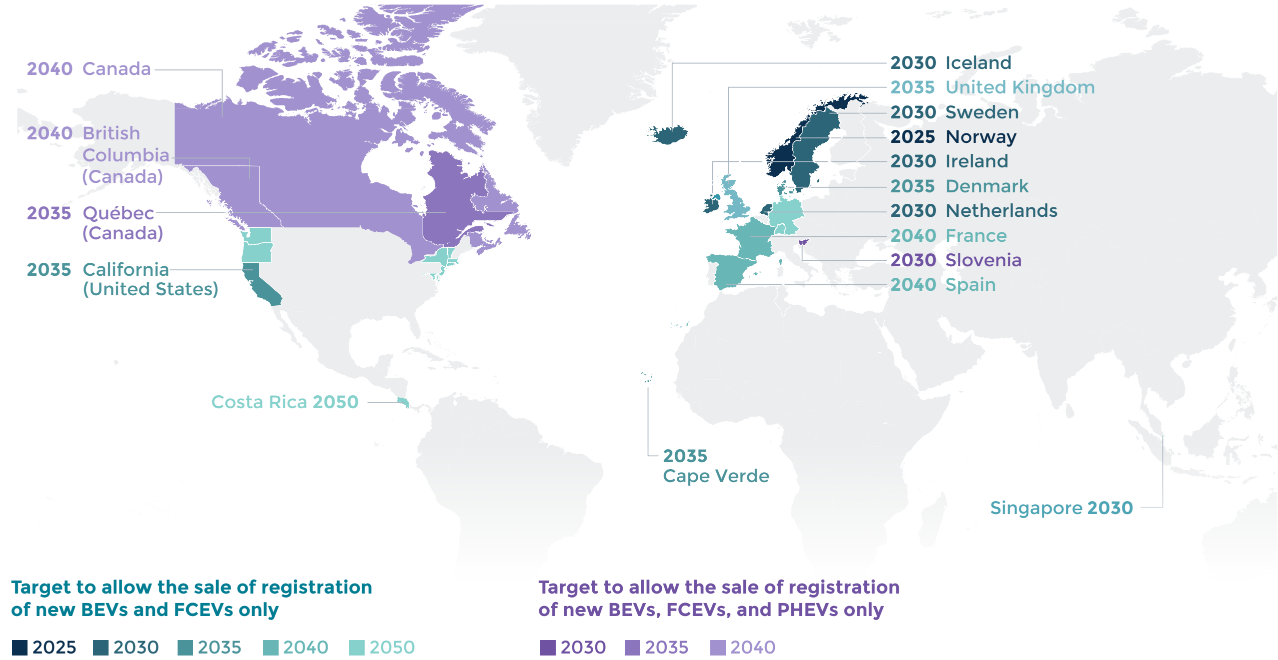


Sources: For historical data, authors' analysis and BloombergNEF(2021a); for targets, CAT (2020a; 2020b).

Setting ambitious targets to phase out ICE vehicles

Seventeen governments have expressed policy goals for phasing out ICE vehicle sales and are integrating targets in a variety of ways (Climate Center 2021). Very few of these commitments, however, have yet been enshrined into law. The Canadian province of British Columbia stands out as one of the first places to pass a law formalizing an ICE phaseout date and introducing penalties for selling or leasing ICE vehicles past 2040. The United Kingdom introduced similar policies to ban ICE sales by 2030 and hybrid sales by 2035 (BloombergNEF 2020a). Vehicle buyback programs can also enable a faster fleet turnover. For instance, California's Voluntary Accelerated Vehicle Retirement program provides a monetary incentive for vehicle owners to trade in or surrender ICE vehicles (California Air Resources Board 2021). With few exceptions, ICE phaseout targets are concentrated in countries with developed EV markets—specifically Europe and parts of North America (Figure 39). For emerging economies to realistically phase out the use of ICE vehicles, EV sales, supporting infrastructure, and alternative transport options will need to be expanded (Wappelhorst and Cui 2020).

FIGURE 39. Governments with set targets for phasing out sales of all new internal combustion engine passenger cars



Note: BEV = battery electric vehicle; FCEV = fuel cell electric vehicle; PHEV = plug-in hybrid electric vehicle.
Source: Wappelhorst (2021).

Demonstrating corporate and government leadership on fleet transitions

Businesses account for about half of all light-duty vehicles purchased (IEA 2020g). Transitioning corporate fleets to EVs can greatly increase the global EV stock—in the European Union, for instance, transitioning corporate fleets to EVs could lead to a 24-fold increase in the European Union EV fleet by 2030 (Colle et al. 2021). Momentum is building. Companies including DHL, Ikea, Amazon, FedEx, and UPS, as well as ride-sharing companies including Uber, Lyft, and Shuttl, have set targets to electrify vehicle fleets (Race to Zero 2021b). Civil society coalitions, including the Climate Group's EV100 and the Ceres-coordinated Corporate Electric Vehicle Alliance, are helping to drive progress by providing platforms to share best practices, advocate for supportive policies, and leverage aggregate corporate demand (Climate Group 2021; Ceres 2021). Transitioning government vehicle fleets can also help increase EV stock and advance the overall EV market. President Biden's recent commitment to transition the U.S. federal fleet to EVs would add over 600,000 EVs to the U.S. vehicle fleet (GSA 2021).

Corporate and federal commitments have incentivized vehicle manufactures to invest in and commit to increased EV production. Ford and General Motors, for instance, have committed to 100 percent EV sales by 2035 and invested $11 billion and $27 billion in EV development, respectively (Hawkins 2021).

Managing electricity demand

Power systems will need to integrate EV charging, while supporting existing energy needs. As EV adoption increases, energy demand is likely to spike at peak charging times (BloombergNEF 2020a). A number of strategies have emerged to manage these spikes, including smart charging systems, which optimize EV charging cycles to match the conditions of the power system, and time-of-use energy tariffs, which disincentivize charging during peak hours (BloombergNEF 2020a; IRENA 2019c). Bidirectional smart charging systems, such as vehicle-to-home and vehicle-to-building systems, may also help increase grid flexibility and integrate renewable energy sources by enabling EVs to act as decentralized storage resources to fill energy gaps (IRENA 2019c). Research on impacts of bidirectional charging systems on battery life and energy efficiency currently shows mixed results (Tchagang and Yoo 2020; Apostolaki-Iosifidou et al. 2017; Uddin et al. 2017). Additional research is needed to determine how smart charging can be optimized at scale to maximize grid flexibility benefits while minimizing efficiency loss and battery degradation. Public and private sector actors can enable EV grid integration by building out public and workplace charging points to reduce demand on home charging.

In emerging economies, insufficient electricity supply is a significant barrier to EV adoption (Gaventa 2021). This may be a particular challenge in areas with inconsistent power supply and countries with oil-based economies, where electricity is more expensive than conventional fuel (Meszaros et al. 2020). To support a growing EV fleet in these regions, overall energy systems will need to be built out. In combination with strategies that decrease overall private vehicle demand, ongoing renewable energy development and implementation of mini-and off-grid networks over the next decade will help enable more resilient electricity grids and drive EV integration and fleet expansion.

Working together to tighten regulations on used vehicle markets

As EV adoption takes off in leading markets, strong institutions and coordinated stakeholder action across the global used ICE vehicle market will be critical to meeting EV fleet targets. Currently, the three largest exporters of used vehicles are the European Union, Japan, and the United States. Seventy percent of these vehicles go to developing countries with little regulatory guidance for ICE sales (Figure 40) (UNEP 2020c). This spillover is counterproductive to efforts to phase out ICE vehicles and increase the EV fleet globally and reflects the need to better manage demand for private vehicles overall. Policymakers in importing countries have had some success implementing age limits for imported vehicles. Kenya, for instance, has an age maximum of eight years for imported vehicles (Gaventa 2021). Other policies include fiscal incentives for buyers importing low- or zero-emissions vehicles (e.g., waived import tax or reduced registration fees for low-emissions, hybrid, or electric vehicles); a progressive import tax for vehicles based on age and CO_2 emissions; and development of alternate transportation modes such as public transportation, walking, or biking.

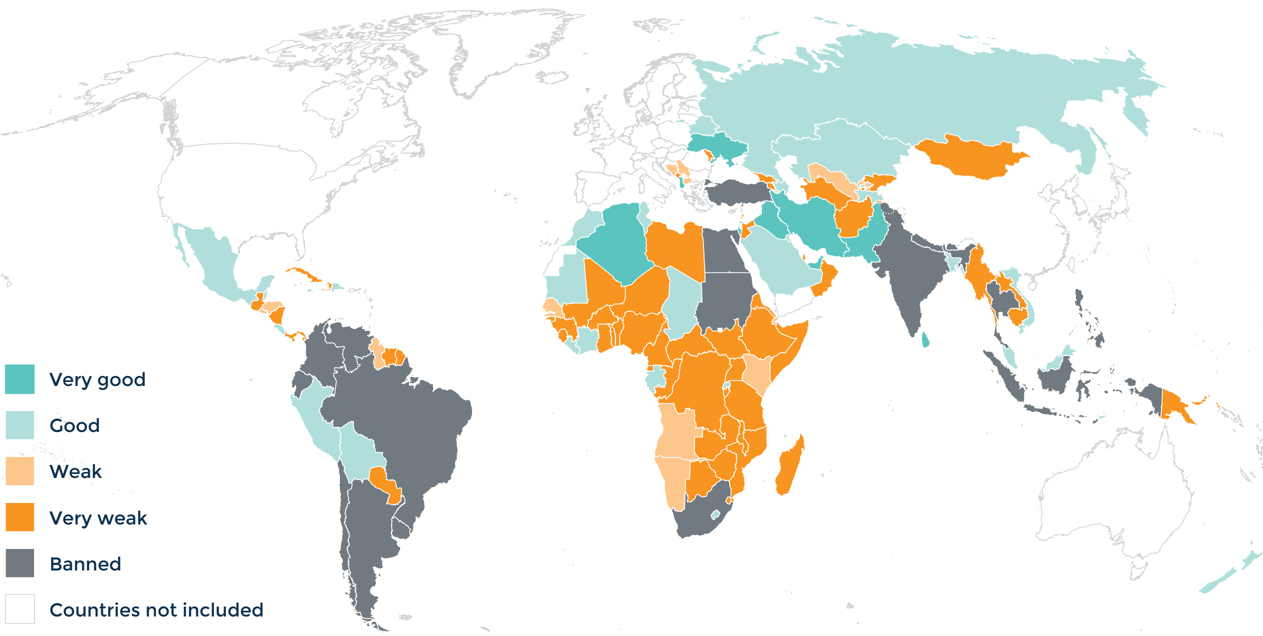
At present, there is no regional or global agreement on the trade of used ICE vehicles. Coordination between importing and exporting countries to set progressive ICE phaseout targets and support the development of enabling EV infrastructure will be key to equitably phasing out ICE vehicles globally and accelerating EV fleet growth (UNEP 2020c).

TRANSPORT INDICATOR 5: Share of battery electric vehicles and fuel cell electric vehicles in bus sales

Targets: Battery electric vehicles and fuel cell electric vehicles make up 75 percent of global annual bus sales by 2025 and 100 percent by 2030 in leading markets.[43]

Buses contributed roughly 8 percent of road transport and 6 percent of total transport CO_2 emissions in 2019, which equates to around 1.4 percent of global CO_2 emissions in the same year (IEA 2020f). In addition, many current bus models have diesel engines that emit both N_2O and high levels of particulate matter. Their replacement with clean electric or hydrogen fuel cell models will therefore reduce emissions harmful to

FIGURE 40. Used light-duty vehicle regulatory map



Note: The classification of the above countries is determined as follows: Very good—a used light-duty vehicle (LDV) Euro 5 or more emissions standard adopted and/or age limit of three years or less; Good—a used LDV Euro 4 emissions standard adopted and/or age limit of four or five years; Weak—a used LDV Euro 3 emissions standard adopted and/or age limit of between six and eight years; Very weak—no used LDV Euro emissions standard adopted and/or age limit of nine years plus or no age limit; Banned—represents a complete restriction on used vehicle imports.
Source: UNEP (2020c).

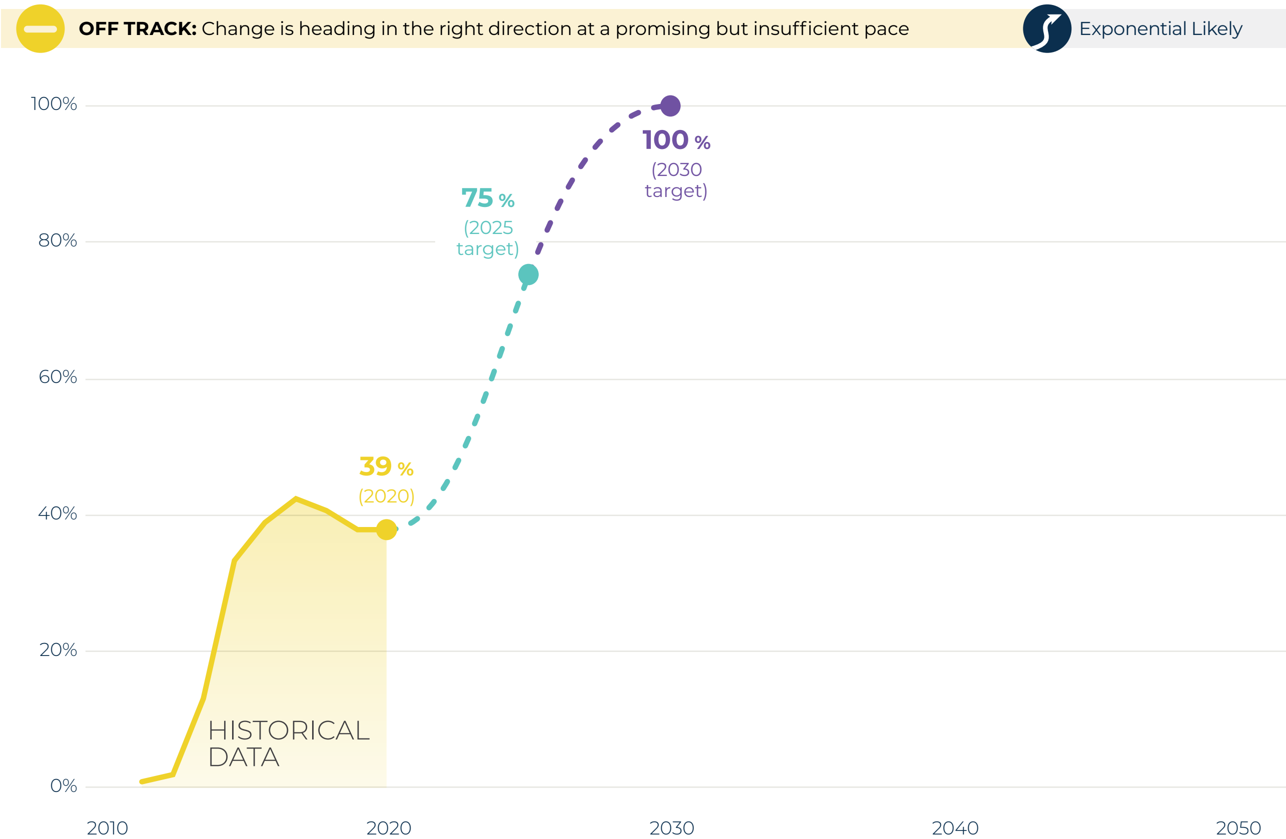
human health, particularly in urban areas (Khomenko et al. 2021). Replacing diesel school buses also serves to protect children, who are especially vulnerable to the negative health effects caused by air pollution.

In 2020, the share of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) in global bus sales was 39 percent. This strong level of demand comes primarily from China, where sales of these types of buses were almost 50 percent higher than sales of fossil fuel equivalents (BloombergNEF 2020a). Sales of EV buses in China experienced rapid, nonlinear growth shortly after the introduction in 2009 of subsidies for EV bus purchases by subnational governments. Annual EV bus sales soared from 1,000 in 2011 to roughly 100,000 in 2016 (Government of China 2009; BloombergNEF 2021a). The dip in the global share of electric and hydrogen fuel cell buses (Figure 41) is due to what is expected to be a temporary fall in Chinese sales, which are projected to reach a record 125,000 by 2025 (BloombergNEF 2021a). Projections also show rapid but not exponential growth outside of China, suggesting that further policies are needed in these countries to achieve the 1.5°C targets (BloombergNEF 2021a).

In order to be aligned with the Paris Agreement's 1.5°C temperature goal, the share of BEVs and FCEVs in global bus sales would need to reach 75 percent by 2025, and in leading markets would need to hit 100 percent by 2030. With no other country in the world coming close to China's advanced position in the transition away from fossil fuel buses, urgent intervention will be required in other countries, particularly in leading markets.

When growth does begin in other countries besides China, it may follow an S-curve, like other instances of technology adoption. China's rapid transformation of bus sales demonstrates that change can occur quickly with the right policy support. Despite the temporary ebb in annual sales, China's bus fleet is expected to be more than 40 percent EV by 2024. Maintaining the strong growth needed to reach the 1.5°C targets will require other countries to find policy options that enable them to mirror China's experience (BloombergNEF 2021a)

FIGURE 41. Historical progress toward 2025 and 2030 targets for the share of battery electric and fuel-cell electric vehicles in bus sales



Note: Graph shows share of battery electric vehicle bus sales only; fuel cell electric vehicle bus sales were near zero for all countries except China, where they numbered roughly 2,500 units in 2019.

Sources: For historical data, BloombergNEF (2021a); for targets, Race to Zero (2021a).

and ideally to avoid similar ebbs in adoption. In terms of reducing transport emissions, buses could be considered low-hanging fruit, as many bus fleets are owned by municipalities or state governments, granting a high level of government control over adoption rates. In addition, many buses are used in urban mass transit roles, meaning they can return to their depot when necessary to be charged, or can be substituted with a ready-charged vehicle. The considerable increase in electricity demand at depots, however, can pose technical challenges that need to be accounted for. This logistical advantage of city buses makes them uniquely suited to accommodate the lower range and relatively long recharging times of electric buses compared to fossil fuel models. This advantage also applies to fuel cell vehicles, as an extended network of hydrogen refueling stations is not necessary given their ability to refuel at depots.

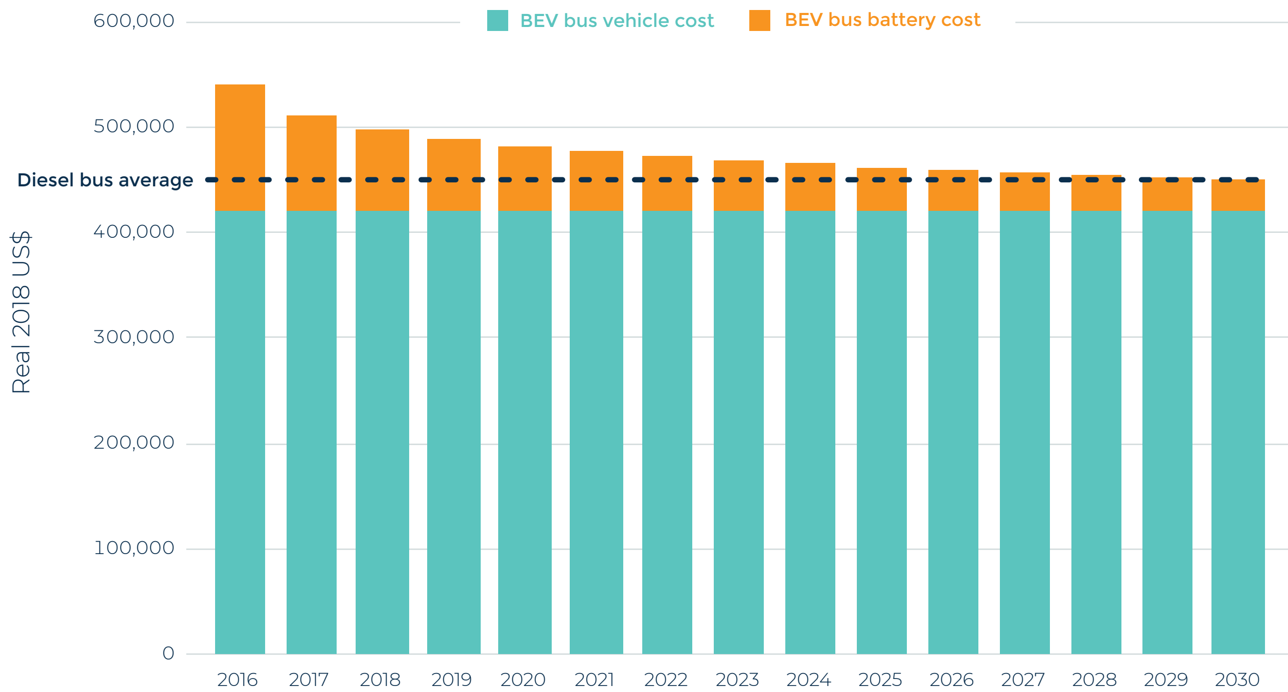
Enablers of climate action

The upfront costs of BEV and FCEV buses and the availability of charging and refueling infrastructure are key barriers challenging the transition to BEV and FCEV buses (Sclar et al. 2019; Li et al. 2019). Economic and other enabling policies are expected to make such zero-emissions vehicles (ZEVs) more attractive to transit and bus fleet operators in markets other than China (BloombergNEF 2020a). Declining capital costs, incentives to support manufacturers and fleet operators and scaled-up deployment of charging and refueling infrastructure, particularly at locations like depots and public transit hubs (where buses make frequent stops), can therefore enable widespread adoption (BloombergNEF 2019b; ETC 2019e).

Reducing upfront costs through technological improvements

BEV buses are already competitive with diesel buses in terms of total cost of ownership (TCO) due to lower operating and maintenance costs. However, the higher upfront costs of BEV and FCEV buses compared to diesel buses remain a key barrier to widespread adoption as vehicle upfront cost is often the main criterion in procurement cost models that municipalities and transit operators rely on for decision-making (BloombergNEF 2018; Li et al. 2019). The upfront cost of a BEV bus can be up to 50 percent higher than that of a diesel-powered bus (Shell 2020b), but improvements in battery performance and declining battery prices are expected to bring upfront cost parity soon. BEV buses with 110 kWh and 200 kWh batteries are expected to reach upfront cost parity between 2025 and 2028 (see

FIGURE 42. Upfront cost comparisons of battery electric vehicle buses (with a 200 kWh battery) and diesel buses in Europe



Note: kWh = kilowatt-hour. As this figure demonstrates, Bloomberg New Energy Finance projects declining battery costs to be the key factor in reducing upfront costs.
Source: BloombergNEF (2018).

Figure 42), while buses with 250 kWh batteries are expected to reach upfront cost competitiveness by 2030 (BloombergNEF 2018). FCEVs offer range flexibility and quicker refueling times compared to BEVs and are expected to be more suitable for longer distance routes requiring frequent service (ETC 2019e; IEA 2020f). However, manufacturing and adoption of FCEVs is less mature than BEVs, and current price estimates indicate that upfront cost of FCEV buses may be 2–3 times higher than diesel-powered buses (Deloitte and Ballard 2020).

Establishing strong purchase incentives

In addition to cost reductions achieved via technological improvements and economies of scale, several policy instruments can be used to help reduce upfront costs. For example, strong purchase incentives will increase adoption (ICCT 2021). Along with China, markets in Europe, the United States and emerging markets such as India offer national or subnational grants and subsidies to lower upfront costs of BEVs and FCEVs (BloombergNEF 2020a). Other emerging financing mechanisms, such as battery leasing schemes,[44] like the one being piloted in the Proterra Park City project in Utah (United States), may lower upfront costs by allowing vehicle owners to cover the battery component of the upfront cost through savings in operation and maintenance costs accumulated over time (BloombergNEF 2018). Leasing mechanisms and joint procurement agreements between two or more bus operators can also play a role in driving adoption, particularly in emerging economies, by enabling cost- and risk-sharing (Welch et al. 2020). Cities like Bogotá (Colombia) and Santiago (Chile) have increased BEV bus adoption by improving risk- and cost-sharing through public-private partnerships, or concession bus-procurement models that allow fleet providers to finance, procure, and maintain ZEV fleets and provide ZEV buses to bus operators or municipalities under stable long-term contracts (Graham and Courreges 2020). Green procurement initiatives like California's ZEV bus mandate, which requires all municipal buses purchased from 2029 to be BEV or FCEV buses (IEA 2021g), can also boost demand and accelerate the diffusion of BEV and FCEV buses.

Scaling up charging and refueling infrastructure

Characteristics such as short-distance transit routes, especially for urban buses, and regular returns to depots allow bus fleet operators different options to address charging or refueling, which will vary according to topography and climate (BloombergNEF 2018; ETC 2019e). While overnight charging at depots is currently the cheapest charging option for BEV bus operators, it requires buses to have larger battery packs, which increases upfront costs (Naimoli and Tsafos 2020). Combining depot

charging with fast charging infrastructure deployed at bus stops or bus terminals can allow buses to operate with smaller batteries and reduce upfront costs (BloombergNEF 2019b).

Lack of charging or refueling equipment standardization can inflict additional equipment costs and force bus operators to choose from a limited number of bus models (Gurman 2021; Li et al. 2019). Bus manufacturers like Irizar, Solaris, VDL, and Volvo have signaled their intention to establish common charging standards after agreeing to ensure interoperability of their BEV buses with charging infrastructure provided by ABB, Heliox, and Siemens in 2016 (BloombergNEF 2018). Wireless electric road systems (ERS) on bus routes are also being developed and tested. A pilot project in Lund, Sweden, has demonstrated that an ERS spanning only 1.3 kilometers through the city center can power the city's entire bus network while also allowing other vehicles to utilize the same charging infrastructure (Intelligent Transport 2020). Similarly, battery swapping can allow bus operators to overcome the longer charging times of BEV buses. Pilot projects in South Korea and India have shown that depleted batteries in buses can be replaced with fully charged batteries within 1–2.5 minutes (NREL 2021).

Deploying hydrogen refueling stations at bus depots and public transit hubs to support adoption of FCEV buses will also require coordinated planning and investments among government, industry, and transit officials. Different targets are being announced to scale up the deployment of hydrogen refueling infrastructure. In the United States, the California Fuel Cell Partnership has outlined a target of deploying 1,000 refueling stations in the state by 2030, while the Hydrogen Roadmap Europe report has announced a target of deploying 3,700 refueling stations by 2030 across the European Union (BloombergNEF 2020e). Growth in FCEV adoption will also require significantly expanded production of clean hydrogen to lower the price of hydrogen at refueling stations (IEA 2021c; Matalucci 2021).

Setting bus electrification targets and adopting supportive policies

Bus electrification targets can help develop markets for BEV and FCEV buses. The number of national and subnational bus electrification targets is rising. Thirty-six different cities, including Bogotá, London, Los Angeles, Jakarta, and Paris, signed the C40 Fossil Fuel Free Streets Declaration signaling their commitment to procuring only zero-emissions buses from 2025 (C40 Cities 2021). The European Union's mandate that 30 percent of all bus sales must be ZEVs by 2030 is expected to increase the share of BEV buses in the region's fleet by a factor of five, while emerging markets like Chile and Colombia have also implemented sales mandates (BloombergNEF 2020a; UNEP 2019). Along with financial incentives to lower the upfront cost of vehicles, stronger ZEV sales targets can create stable and substantial market demand and allow manufacturers to attain economies of scale (ICCT 2021).

In addition to targets, a variety of complementary policies and incentives, including subsidies, mandates, air quality targets and emissions standards, and manufacturing incentives, can enable widespread adoption of BEV and FCEV buses (ETC 2019e; IEA 2021c).

Financing research and development

Along with policies to increase the availability of clean power supply, R&D investments for smart charging solutions and establishing stable interconnected grid systems are needed to ensure that electricity supply and grid constraints do not hinder widespread adoption, particularly in emerging markets that face power-supply and grid-capacity constraints (Rocky Mountain Institute 2020). Transit agencies and operators generally do not have deep technical expertise in electricity infrastructure planning. Maintaining grid performance and stability to support widespread BEV adoption will require the participation of multiple stakeholders, including utilities and grid operators who can assess long-term power supply requirements and deploy new powerlines or upgrade existing grid infrastructure (Li et al. 2019). In addition to adopting standards for charging and refueling equipment, R&D investments to lower the cost of charging or refueling stations are other priorities for widespread adoption (BloombergNEF 2019b; ICCT 2021).

TRANSPORT INDICATOR 6:

Share of battery electric vehicle and fuel cell electric vehicles in medium- and heavy-duty vehicle sales

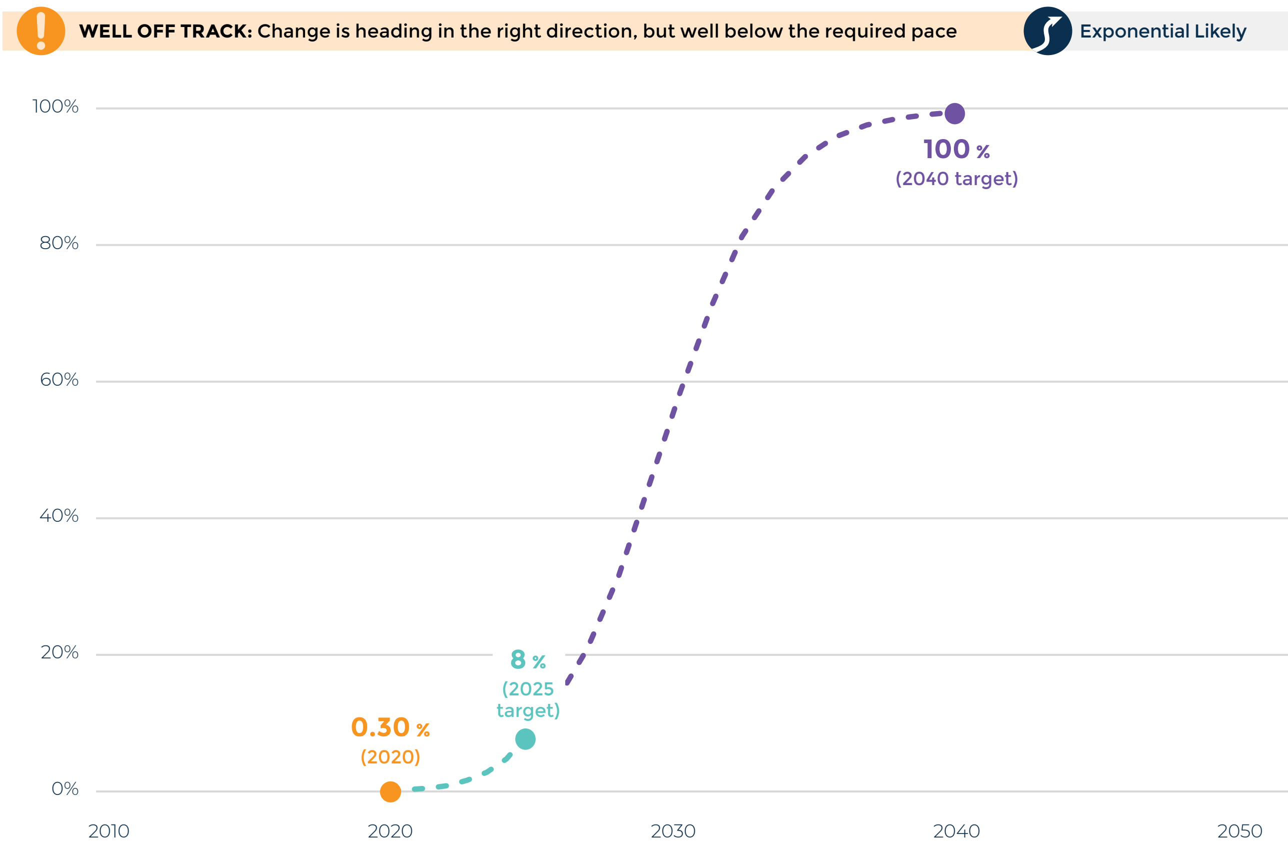
Targets: Battery electric vehicles and fuel cell electric vehicles make up 8 percent of global annual medium- and heavy-duty vehicle sales by 2025 and 100 percent in leading markets[45] by 2040.

In 2020, the share of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) in global medium- and heavy-duty vehicle (MHDV)[46] sales was 0.3 percent (BloombergNEF 2021a). This was entirely made up of battery electric vehicles, as fuel cell MHDVs are so far not commercially available. As with buses (see Transport Indicator 5), the bulk of global demand in 2019 came from China, which accounted for 60 percent of total sales. Europe accounted for 23 percent of sales.

In order to be aligned with the Paris Agreement's 1.5°C temperature goal, the share of BEVs and FCEVs in global MHDV sales would need to reach 8 percent by 2025, and in leading markets it would need to hit 100 percent by 2040. With BEVs constituting such a small percentage of total current sales, there is an urgent need to bring these technologies to commercial maturity and stimulate their adoption across the world if this transport subsector is to achieve 1.5°C compatibility. See Figure 43 for an illustrative S-curve trajectory for BEVs and FCEVs in the global MHDV fleet.

MHDVs made up 29.5 percent of road transport emissions and 21.7 percent of total transport CO_2 emissions in 2019,

FIGURE 43. Historical progress and an illustrative S-curve of what's needed to reach 2025 and 2040 targets for the share of battery electric and fuel-cell electric vehicles in medium- and heavy-duty vehicle sales



Note: BEV = battery electric vehicle; FCEV = fuel cell electric vehicle. The future trajectory of electric medium- and heavy-duty vehicle (MHDV) sales as a share of the market will likely follow an S-curve, following the pattern of other instances of technology adoption. This figure illustrates what growth in MHDV sales would have to be to reach the targets on an S-curve trajectory—though this is just one potential path among many. For the sake of simplicity, this illustrative S-curve uses global sales for both the 2030 and 2040 targets, when the actual goal is 8 percent globally by 2030 and 100 percent for leading markets by 2040. Data are currently insufficient to evaluate the pace of progress in MHDV sales in a quantitative way, so the evaluation of "well off track" was a qualitative judgment. MHDV sales are still in the emergence phase of the S-curve and require the right government support and economic conditions to enter a phase of rapid growth. Whether MHDV sales reach the diffusion stage and how fast depends on what happens in the near term.

Sources: For historical data, authors' analysis and BloombergNEF (2021a); for targets, Race to Zero (2021a).

almost equaling the combined global aviation and shipping emissions for that year (IEA 2020f). In addition, MHDVs, which run almost exclusively on diesel, are a significant source of other emissions that are harmful to human health, such as particulate matter, nitrogen oxides, and sulfur oxides. A switch to BEVs and FCEVs would reduce premature deaths due to air pollution, while also eliminating a key source of urban noise pollution, which has been linked to numerous negative impacts on human health (European Environment Agency 2020). Heavy-duty vehicles are also disproportionately involved in road fatalities. New electric models can be designed with safety considerations such as low floor cabs and greater visibility, enabled by electric motor design that does not require a large front end (Broom 2021).

As the infrastructure needed for operating zero-emissions long-haul routes is not yet in place, most electric MHDVs currently in operation are used in urban roles with short routes, which accommodates their limited range and need for recharging (EDF 2021). Initial efforts to increase the adoption of electric models could therefore be aimed at companies and government agencies that are engaged in these kinds of applications.

The first long-range heavy-duty electric trucks have begun to enter the market, with Volvo releasing its first models in Europe in 2021 (Volvo 2021). The slated arrival of the Tesla Semi in 2022 means there will soon be models available in Europe and North America. This could enable a rapid increase in sales if sufficient charging infrastructure and government incentives are in place.

In the United States, several delivery companies and the US Postal Service have already announced either partial or full electrification of their vehicle fleet, demonstrating the commercial viability of these models (Reuters 2020). In addition, recent and expected ongoing growth in e-commerce suggests the overall size of such fleets is likely to grow over the coming years (eMarketer 2020). City-level policymakers can implement bans or restrictions on polluting vehicles in city centers, where many deliveries occur. This is already a driver of EV deployment and could lead to a rapid uptake of EVs in corporate delivery fleets.

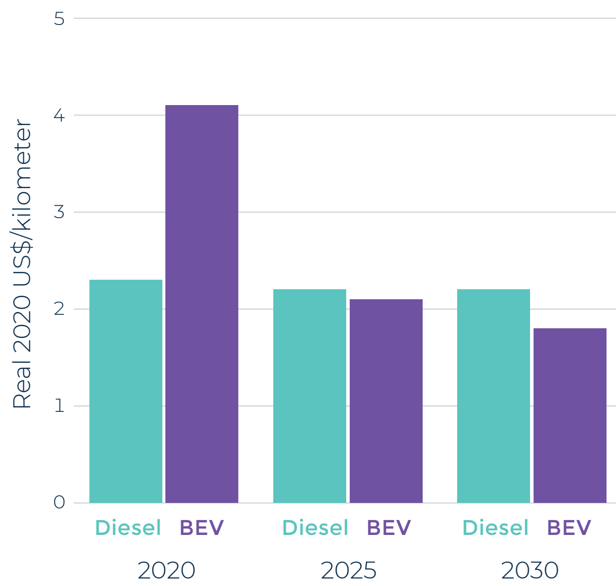
Enablers of climate action

The higher total cost of ownership (TCO)[47] of BEV and FCEV trucks[48] relative to diesel trucks and the limited availability of charging and refueling infrastructure are key barriers to widespread adoption (Victor et al. 2019). The diffusion of BEV and FCEV trucks is expected to begin as they reach TCO parity with diesel trucks (BloombergNEF 2020g; Phadke et al. 2021). Along with TCO reductions, providing strong market signals to manufacturers and fleet operators through policies such as sales requirements or performance standards and ramping up deployment of charging or hydrogen refueling stations can accelerate the adoption of such zero-emissions vehicles (Welch et al. 2020).

Driving down costs through technological improvements to reach total-cost-of-ownership parity with diesel trucks

Due to reductions in capital costs arising from rapidly declining lithium-ion battery prices and improvements in battery range, BEV trucks are expected to reach TCO parity with diesel trucks between 2025 and 2030, as shown in Figure 44 (Welch et al. 2020; BloombergNEF 2020g). R&D investments and targeted incentives to support battery manufacturing can make this happen sooner (MacDonnell and Facanha 2021). The average energy density of batteries

FIGURE 44. Five-year total-cost-of-ownership outlook for a heavy-duty vehicle in urban-duty cycles in China



Note: km = kilometer; BEV = battery electric vehicle.
Source: BloombergNEF (2021a).

has tripled since 2010 and batteries are now capable of offering longer ranges at lower costs and with negligible reductions in payload capacity (Field 2020). Currently available BEV truck models can cover up to 483 kilometers on a single charge—making BEVs more feasible for different applications including urban deliveries, drayage,[49] and other regional haul operations (Phadke et al. 2021). BEV truck models with a range of 595 kilometers and at least 998 kilometers are expected to be available during 2022 and after 2023, respectively (IEA 2020s).

FCEVs are expected to be more suitable than BEVs for replacing diesel-powered trucks in long-haul heavy-duty[50] applications, as FCEVs offer range flexibility and quicker refueling times (IEA 2020s; BloombergNEF 2020g).[51] Fuel cell system costs and the price and availability of clean hydrogen remain key challenges. Since there are no mass market applications for fuel cell systems other than powering FCEVs, reducing fuel cell system costs will depend on increasing the production of FCEVs, with current estimates indicating a learning rate of 22 percent (BloombergNEF 2020e).[52] FCEV trucks can reach TCO parity with diesel trucks for long-haul heavy-duty applications by 2030 if fuel cell system costs decline from $243/kW to below $100/kW and the price of hydrogen at refueling stations drops to $4 per kilogram or below from the current average of $10 per kilogram (BloombergNEF 2020e).[53] Achieving such targets may require investments totaling $105 billion within the next decade to expand FCEV manufacturing and deploy hydrogen refueling infrastructure (BloombergNEF 2020a). FCEVs can be considered for those niche applications that are least favorable to BEVs, including construction mining, construction, or agricultural vehicles, where FCEVs can offer advantages such as lower impacts on payload capacity and quicker refueling times compared to BEV trucks (Heid et al. 2021).

Expanding charging and refueling infrastructure

The BEV charging infrastructure market is maturing rapidly, with currently available charging technologies supplying a power output of up to 350 kW and potentially more than 1 MW by 2023 (Welch et al. 2020). Between 2015 and 2019, the cumulative global investment in charging infrastructure for commercial BEVs totaled $13.6 billion, and more than 481,000 commercial chargers[54] were available

across Europe, China, and the United States in 2019 (BloombergNEF 2020g). Coordinated efforts by regional stakeholders can enable the development of zero-emissions freight zones and ensure that charging stations are deployed in high-use areas like busy freight corridors, distribution centers, or trucking depots. Deploying chargers in such areas can offer higher utilization rates and improved returns on investment (ETC 2019e). Additionally, incentives for smart charging solutions, including co-siting with renewable energy or energy storage facilities, are needed to maintain grid performance and efficiency (MacDonnell and Facanha 2021).

Far less progress has been made in the deployment of hydrogen refueling infrastructure—with only 350 public refueling stations available in the United States, China, Europe, Japan, and Korea as of March 2020 (BloombergNEF 2020e). Significant government and industry investment is necessary to scale up deployment, with the cost of installing a hydrogen refueling station ranging from $2 million to $3 million in the United States, $1 million to $2 million in Europe, and $2.4 million to $3 million in Japan (Schreffler 2019; Welch et al. 2020).

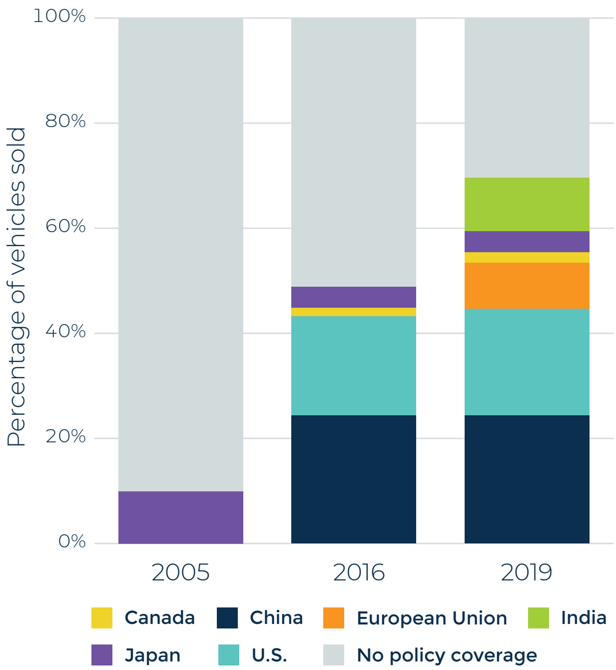
Setting standards that send a strong signal to manufacturers

Sales requirements for BEV and FCEV trucks can increase both competition among manufacturers and model availability (ICCT 2017; ETC 2019e). California's Advanced Clean Trucks (ACT) rule, for example, requires that the sales share of class 2b to class 8 zero-emissions vehicle (ZEV) trucks[55] increase to 75 percent by 2035 from 9 percent in 2024 and specifies sales targets that manufacturers have to meet (California Air Resources Board 2020). Fuel economy or CO_2 standards are becoming more prominent. In 2019, fuel economy or CO_2 standards covered 70 percent of global truck sales, compared to 5 percent in 2005 (IEA 2020q). Canada, China, the European Union, India, and the United States have implemented fuel economy or CO_2 emissions standards for trucks, while South Korea is aiming to implement MHDV efficiency standards by 2022 (IEA 2020s). See Figure 45.

Other key actions, including municipal fleet purchase requirements and fleet ZEV adoption commitments, can rapidly increase market demand. Current purchase commitments from private and municipal fleets and logistics companies in markets like China, Switzerland, and the United States could create demand for at least 130,000 new BEVs and FCEVs (Welch et al. 2020). Governments are also offering financial incentives like point-of-sale rebates and vouchers to cover cost differences between ZEV and diesel-powered trucks.

Such actions are providing strong market signals to manufacturers. The European Automobile Manufacturers Association—with major manufacturers like Scania, Daimler, Volvo, Ford, DAF, Iveco, and MAN—has committed to reaching 100 percent fossil-free sales share by 2040 (EAMA 2020). As the commercialization of BEV and FCEV trucks continues to gather pace, smoothly transitioning widespread ZEV adoption will require coordinated planning and spending by actors including governments, utilities, and industry to support sufficient deployment of reliable charging and refueling infrastructure (ICCT 2020b).

FIGURE 45. Heavy-duty vehicle sales in countries with adopted fuel economy or emissions standards



Source: IEA and Teter (2020).

TRANSPORT INDICATOR 7:

Share of low-emissions fuels in the transport sector

Targets: The share of low-emissions fuels in the transport sector reaches 15 percent by 2030 and 70–95 percent by 2050.

A low-emissions fuel is a fuel that, when consumed, does not result in a net increase in carbon emissions. Low-emissions fuels include electricity from zero-carbon sources, green hydrogen, synthetic fuels made using green hydrogen, and certain biofuels.[56] The global share of low-emissions fuels in the transport sector remained stable between 1 percent and 2 percent throughout the 1990s, before beginning to rise early in the new century (IEA 2020o). Increased demand was especially pronounced in Brazil, the United States, and the European Union, where it increased 4-fold, 11-fold, and 22-fold, respectively, between 2000 and 2018, due in large part to the introduction of biofuel-blending mandates (Colares 2008; U.S. Department of Energy 2021; Transport Policy 2018).[57] Between 2014 and 2017, however, increases in both biofuel and electricity demand did not outpace the increase in demand for fossil fuels. In 2018, the global share of low-emissions fuels for transport was 4.3 percent; however, much of this share consists of unsustainable conventional biofuels, highlighting the urgency of transitioning to advanced biofuels, and scaling up electrification.

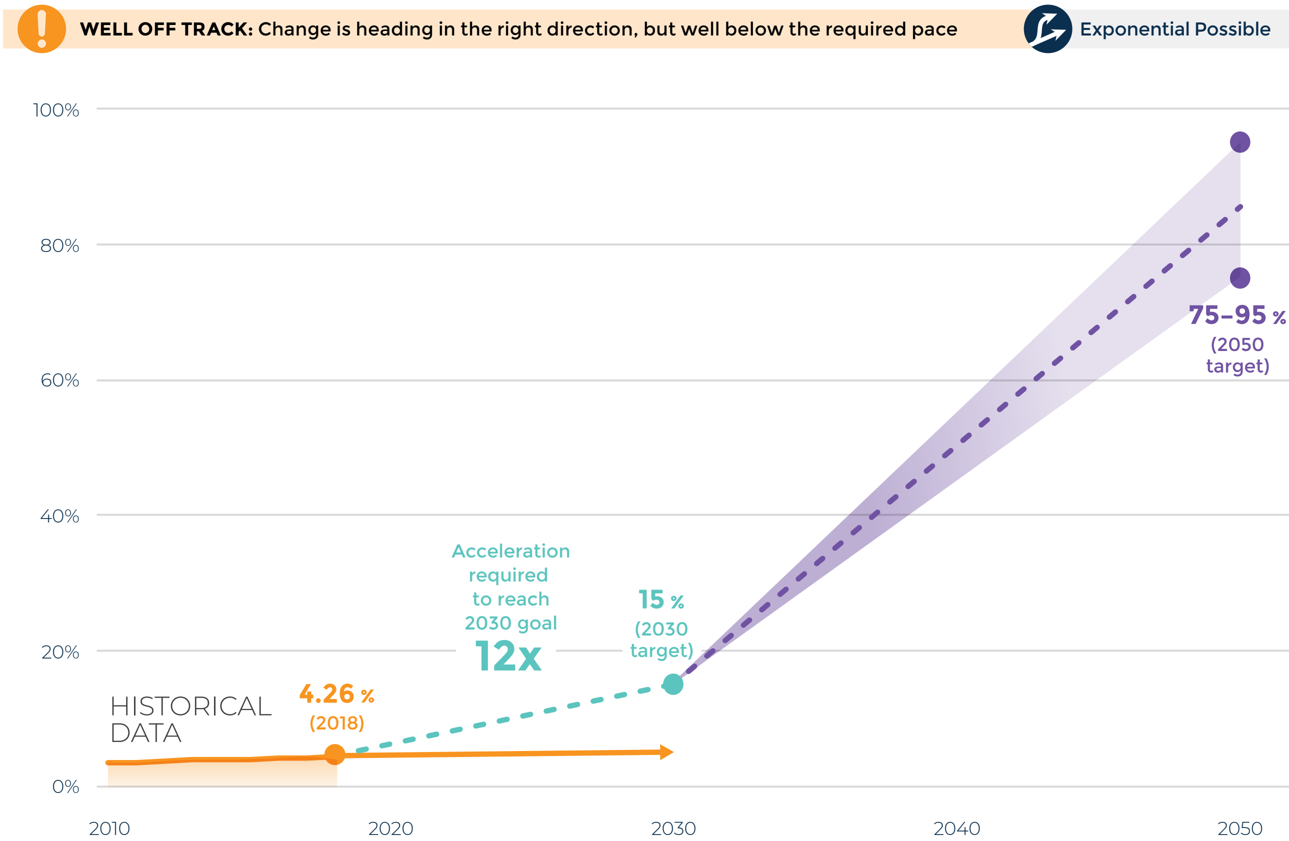
If the global transport sector is to align with the Paris Agreement's 1.5°C temperature goal, low-emissions fuels will need to start rapidly displacing fossil fuels to reach a 15 percent share by 2030, climbing to between 70 percent and 95 percent by 2050 (see Figure 46). Much of the heavy lifting to reach these targets will need to come from the electrification of a rapidly increasing share of land-based transport, but there is also great potential for advanced biofuels to reduce emissions from the existing stock of fossil fuel vehicles. Over the medium and long term, hydrogen and synthetic fuels made with hydrogen are likely to be required to decarbonize harder-to-abate transport emissions from the shipping, aviation, and long-distance land freight sectors. Some of these key technologies are expected to possibly see S-curve shaped growth that, if realized, would contribute greatly to achieving the 1.5°C targets.

Eliminating diesel and gasoline demand from land-based transport alone would drastically reduce the overall global demand for oil, as road transport accounted for more than 40 percent of total oil demand in 2019 (BloombergNEF 2020d). Reduced oil demand would eliminate the need for continued exploration in increasingly remote and sensitive ecosystems like the Arctic and offshore locations, reducing the likelihood of highly destructive spills (Hjorth 2019). Shifting from conventional to advanced biofuels also could ease demand for valuable arable land and help keep global food prices stable (IRENA 2019a).

Enablers of climate action

The transport sector continues to rely heavily on fossil fuels. Rail, which has undergone widespread electrification, is the only widely used form of motorized transport to have made significant progress in the adoption of an alternative fuel source. Substituting low-emissions fuels for those used across the various modes of transport is complicated by the diverse characteristics of each vehicle type. Consequently, numerous kinds of low-emissions fuels and enabling technologies will need to be developed in conjunction, each with its own unique technological and institutional challenges. Governments

FIGURE 46. Historical progress toward 2030 and 2050 targets for the share of low-emissions fuels in the transport sector



Sources: Data from IEA (2020n); targets from CAT (2020b, 2020a).

could play a leading role in catalyzing the development and diffusion of these fuels, funding research, and devising effective policies to support the wide rollout of newer transport technologies, while seeking new and innovative ways to foster international cooperation for transport solutions that span national borders (Cames et al. 2021; IEA TCP 2020).

Establishing supportive policies and increasing public finance for low-emissions fuels

Low-emissions alternatives to both jet fuel and marine bunkers are less advanced in their development than electric motor vehicles. The production of synthetic fuels, which are still prohibitively expensive but could be used in both aviation and shipping, requires hydrogen as an input, so supporting the development of a green hydrogen industry is a necessary intervention in the short term to enable long-term decarbonization (see Industry Indicator 5). Support could include setting a green hydrogen production target, mandating the mixing of green hydrogen into the natural gas network, and subsidizing the purchase of electrolyzers to increase demand and help manufacturers reach economies of scale and thus bring down prices (IRENA 2020b). Similarly, investing in an aggressive expansion of renewable energy generation would lead to greater production of low-cost zero-emissions energy, a key requirement for scaling up green hydrogen production (Royal Society 2019). Countries with favorable renewable energy resources may be the best candidates for large-scale synthetic fuel production (Luderer et al. 2018).

Prioritizing R&D for low-emissions fuels

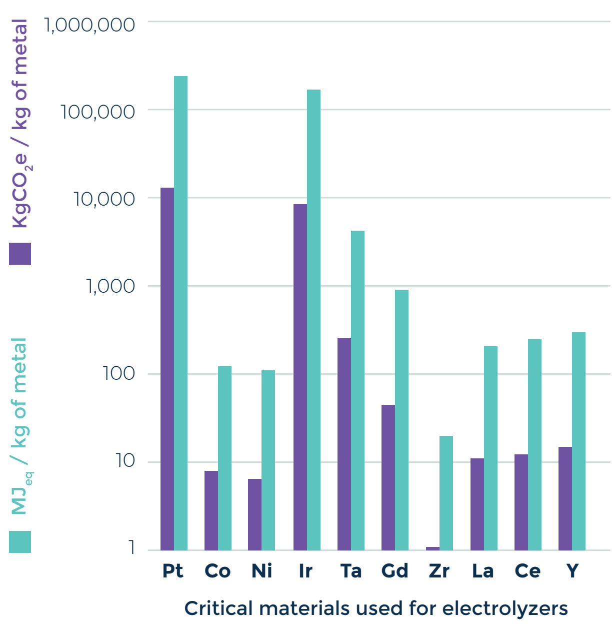
Several key innovations are still required to bring low-emissions fossil fuel alternatives to market and scale them up to the levels necessary to achieve wide-ranging emissions reductions. Improvements in electrolyzer[58] technology is one such example. The current cost of electrolyzer technology is prohibitive but three strategies have been found to reduce costs over time: increasing module size, increasing manufacturing scale, and improving stack design and cell composition (IRENA 2019a). Improved cell composition could lead to higher efficiency, durability, and density, and cheaper alternatives could be substituted for rare, expensive, and emissions-intensive materials like platinum.

Figure 47 shows the relative energy and emissions intensity of various elements used in electrolyzer construction, with commonly used platinum requiring the most energy and producing the most emissions, followed closely by iridium.

The use of biofuels is often promoted as part of the solution to reduce transport emissions; however, conventional biofuels require large amounts of arable land and water for their production, the impacts of which may not be fully captured in emissions accounting. This renders their widespread use as a substitute for fossil fuels unsustainable (Delucchi 2010). In the United States, the production of one gallon of ethanol, the most used biofuel, requires between 13 and 240 gallons of water (Wu et al. 2018).

Advanced biofuels produced from nonfood or nonfeed alternatives, such as algae or waste organic matter, do not compete with food production and, if developed, could play a significant role in the transition to low-carbon transport. This is especially the case for hard-to-abate sectors such as aviation (see Transport Indicator 8) and for vehicles still on the road years after fossil fuel vehicle sales have ceased. But enabling widespread

FIGURE 47. Global warming potential and cumulative energy demand for critical materials used in electrolyzers



Note: $kgCO_2e$ = kilograms of carbon dioxide equivalent; MJeq = megajoule equivalents; Pt = platinum; Co = cobalt; Ni = nickel; Ir = iridium; Ta = tantalum; Gd = gadolinium; Zr = zirconium; La = lanthanum; Ce = cerium; Y = yttrium.
Source: Nuss and Eckelman (2014).

adoption of advanced biofuels will require significant, ongoing investment in research and development to reduce their cost and bring them to scale (IRENA 2019a).

Improving global coordination to create a green hydrogen market

National governments will inevitably play a significant role in introducing the necessary measures at a domestic level to develop and generalize the use of new low-emissions transport fuels, but they are in a unique position to also facilitate the creation of international forums for cooperation. Regarding the development of green hydrogen and synthetic fuels, individual countries can choose to forge ahead as pioneers in this field, but achieving the necessary global scale of diffusion and the needed capacity and infrastructure will require global coordination of efforts (Cames et al. 2021). For example, transportation of hydrogen across land borders will likely require coordination on blending limits and upgrades to natural gas infrastructure.

Countries with a natural advantage in renewable energy resources and favorable access to key trading routes are prime candidates to establish the necessary scale of green hydrogen production that will not be possible in many countries. In particular, South Korea and Japan, both countries with large industrial and transport energy demand but limited suitable land for new renewable energy projects,[59] will rely heavily on other countries to fulfill their future green hydrogen demand. Establishing effective international institutions with broad participation will be critical to advancing the development of the global green hydrogen market needed to fulfill such demand (see Industry Indicator 5).

One recently established example is Germany's Power-to-X (PtX) Hub, which promotes partnerships, initiatives, and processes to broaden and share the knowledge on promising PtX technologies,[60] while fostering market development by identifying global funding and matching it with projects (PtX Hub 2021). To date, collaborations, events, and trainings have occurred in Brazil, Chile, and Costa Rica. Numerous other constellations of cooperation are possible, including those that focus specifically on one transport subsector like aviation or shipping, or that primarily aim to facilitate the development of global e-fuel supply chains (Cames et al. 2021).

While several countries have begun to develop hydrogen strategies, few concrete incentives exist for catalyzing a rapid scaling up of green hydrogen production capacity. Australia even recently blocked a 26 GW wind and solar green hydrogen facility despite having a national hydrogen strategy (Vorrath 2021). Supporting the rapid development of such projects should be a priority for countries that envisage large-scale future hydrogen production.

TRANSPORT INDICATOR 8: Share of sustainable aviation fuel in global aviation fuel supply

Targets: Sustainable aviation fuel comprises 10 percent of global aviation fuel supply by 2030 and 100 percent by 2050.

Aviation is currently responsible for 3 percent of global CO_2 emissions (1 Gt). This share is projected to rise to 4.5 percent[61] by 2050 (2 Gt) absent a change in trajectory as demand for air travel recovers from the COVID-19 pandemic and continues to grow (WEF 2020). Moreover, experts project that other GHG emissions from burning jet fuel increase the climate impacts of aviation by more than three times compared to the impacts from CO_2 alone (Lee et al. 2021).

In order to decarbonize aviation, a combination of behavioral and technological interventions will be required. These interventions include demand management techniques, energy efficiency measures, and, in the long term, hydrogen and electric battery aircraft technologies that do not rely on fossil-based jet fuel. However, demand management and energy efficiency measures cannot significantly decarbonize the industry on their own, and hydrogen and electric battery planes are not expected to be commercially available for several decades—and may only be able to decarbonize short- and medium-haul flights. An additional solution is therefore required (ETC 2019c).

Sustainable aviation fuel (SAF)—already widely researched, partially developed, and capable of driving significant near- and long-term mitigation—offers a particularly viable medium-term contribution to a decarbonization pathway for aviation. SAF is a fuel source that is nearly chemically identical to fossil-based jet fuel but, when produced following up-to-date emissions accounting standards, is made without using any fossil sources. There are currently multiple technologically viable pathways for producing SAF, the most prominent of which include hydrogenated esters and fatty acids (HEFA), gasification + Fischer-Tropsch synthesis (gasification-FT), alcohol-to-jet, and power-to-liquid production pathways.[62] Notably, each of these SAF technologies can be used directly in existing aviation infrastructure and equipment up to a certain blend constraint (which may vary by pathway), meaning that major equipment overhauls are not necessary for facilitating SAF uptake.

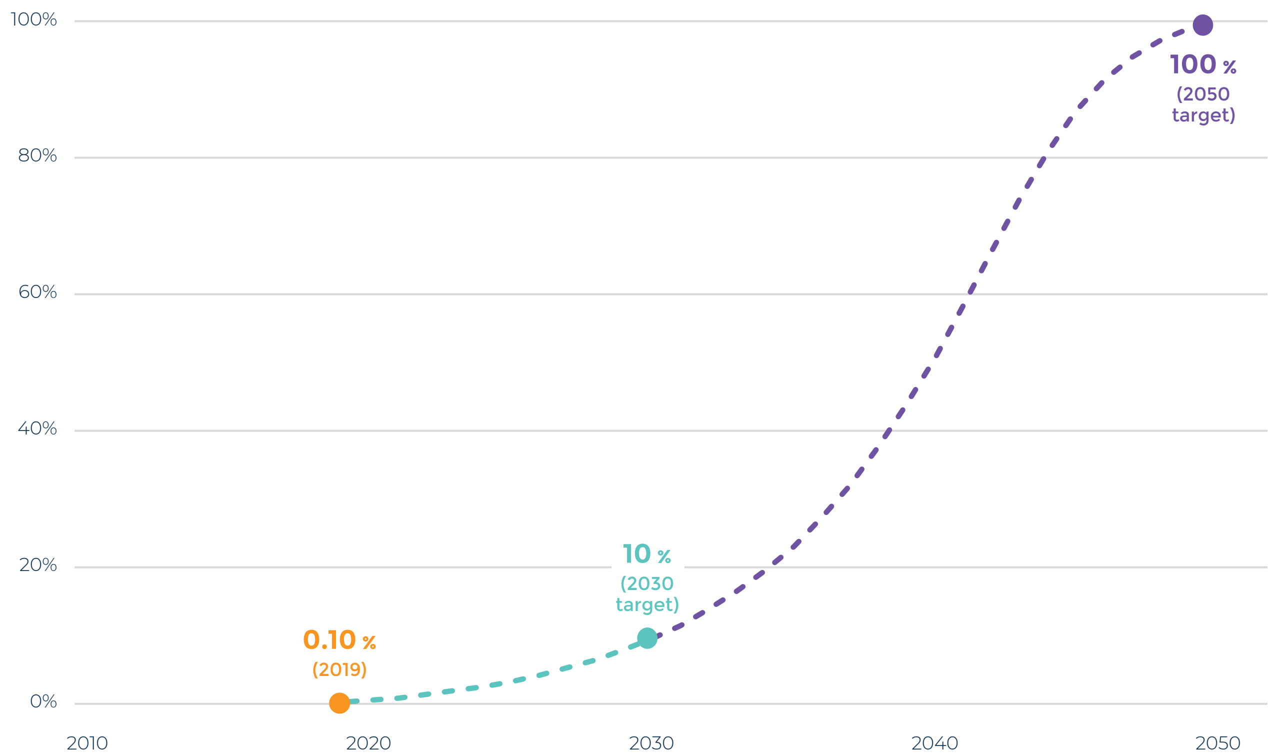
As most SAF pathways (HEFA, gasification-FT, and alcohol-to-jet) rely on some quantity of biomass inputs, it is important to consider the SAF solution in light of ongoing concerns about biomass-based fuels and energy (bioresources) (Searchinger et al. 2019). Indeed, because production of purpose-grown bioresources requires large amounts of land for crop growth, and because the availability of land is limited by many other demands (e.g., growing food to feed an increasing population, preserving biodiversity, and promoting climate mitigation through reforestation), experts generally advise that policymakers refrain from setting bioresource targets (ETC 2021a; Searchinger et al. 2019). However, recent estimates suggest that a small amount—some 40 to 60 EJ—of strictly limited sustainable biomass inputs from waste and residues that do not have other uses and thus do not jeopardize valuable land resources will be available for decarbonizing only the hardest-to-abate sectors by midcentury (ETC 2021a). As the aviation challenge has no other near-term viable solutions and will require less than 40 EJ of biomass for total decarbonization, many leading reports argue that SAF should be prioritized as an exception to the general guidance against bioresources for energy (ETC 2021a; WEF 2020; Le Feuvre 2019).

Today, SAF comprises under 0.1 percent of global aviation fuel supply, as the HEFA pathway is the only one of the four that has reached commercial deployment (the other three pathways are currently in development and pilot stages).[63] However, it has been estimated that global SAF uptake should reach 10 percent by 2030 and 100 percent by 2050 (Race to Zero 2021b). Reaching these targets will require a significant acceleration in the development and deployment of all technologically viable SAF pathways (see Figure 48).

FIGURE 48. Historical progress and an illustrative S-curve of what's needed to reach 2030 and 2050 targets for the share of sustainable aviation fuel in global aviation fuel supply

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

Exponential Likely



Note: The future trajectory of sustainable aviation fuels (SAFs) as a share of the market will likely follow an S-curve, following the pattern of other instances of technology adoption. This figure illustrates what growth in SAF market share sales would have to be to reach the targets on an S-curve trajectory—though this is just one potential path among many. Data are currently insufficient to evaluate the pace of progress in SAF sales in a quantitative way, so our evaluation of "well off track" is a qualitative judgment. SAFs are still in the emergence phase of the S-curve and require the right government support and economic conditions to enter a phase of rapid growth. Whether SAFs reach the diffusion stage and how fast depends on what happens in the near term.

Sources: For historical data, WEF (2020); for targets, Race to Zero (2021a).

Enablers of climate action

Given the high costs and limited production capacity of SAF today, the global SAF market is still small. Accordingly, a diverse portfolio of both supply- and demand-side measures will be necessary to lower costs, accelerate development, and promote widespread uptake of the technology. These measures can be divided into two primary categories: ensuring access to production inputs including biomass, renewable energy, green hydrogen, and large-scale sustainable captured CO_2; and implementing policies and financing interventions to incentivize both increased supply of and demand for SAF.

Increasing access to production inputs

First, to produce each of the four SAF pathways, a combination of different inputs, including sustainable biomass, clean and affordable renewable energy, green hydrogen, and sustainable CO_2,[64] are needed.[65] Each of these inputs require a certain set of enablers of its own to fully saturate the market (see Power Target 2 and Industry Target 5 for reviews of renewable energy and hydrogen, respectively), although good progress has been made to date in harnessing and producing each. The most important factor in ensuring that the proper enabling environment is in place to promote global SAF uptake is earmarking adequate quantities of these inputs specifically for SAF. Indeed, since there are many other competing uses for available sustainable biomass, renewable energy, green hydrogen, and sustainable CO_2 resources, policymakers should ensure that their planning allocates enough of each to fully support realization of their 2030 and 2050 goals for SAF uptake.

Incentivizing increases in SAF supply and demand

In addition to ensuring that the inputs needed to produce SAF are accessible, policy and financing interventions that directly incentivize or even mandate increases in both supply of and demand for SAF are also important for enabling further uptake, particularly given the high costs of SAF compared to fossil-based alternatives. Such interventions may include, but are not limited to, the following (WEF 2020; ETC 2019d; Le Feuvre 2019):

- Regulatory portfolio mandates, which specify a gradually increasing percentage of aviation fuel that must be produced from sustainable sources, following rigorous emissions accounting standards.
- Financial derisking measures for production facilities, such as grants and loan guarantees for investors and production facility developers, which incentivize the building of increased capacity for SAF development.
- Incentives for SAF usage: cost-of-difference mechanisms, direct subsidies for the use of low-carbon fuels, and other support for SAF users, which incentivizes uptake.
- Fossil fuel taxes, which, when designed effectively, impose a carbon tax on the emissions generated by less expensive fossil-based aviation fuels to level the playing field for SAF to compete financially.[66]

Actors from both government and the private sector have a role to play in promoting the implementation of these and other interventions. While policymakers can advance portfolio mandates, taxes, and financial derisking measures in their jurisdictions, industry actors (e.g., airlines) may also enact internal-facing programs that explicitly target their individual, but often large, multinational company operations. Such action from both government and industry leaders can ensure that as many actors as possible are targeted. Civil society can also work with industry leaders to lobby government for countrywide policy and financing options in order to expand interventions beyond leading companies and governments.

Although SAF—primarily the HEFA pathway—has only recently entered the commercial market, several policy interventions that have already been enacted by government and industry actors serve as promising examples from which other public and private leaders can learn. For instance, the International Civil Aviation Organization has implemented the Carbon Offsetting and Reduction Scheme for International Aviation, which intends to facilitate carbon-neutral growth of aviation beyond 2019 levels through a mix of out-of-sector carbon offsets, efficiency improvements, and SAF deployment. Although this program provides relatively weak incentives, and may depend heavily on carbon offsets, weakening its effectiveness, it does include a detailed set of methodologies for calculating GHG reductions from

SAF use. In another example, the European Commission has also launched the Biofuels Flightpath Initiative, which is tasked with studying financial tools that can be implemented to aid SAF production facility development (ICAO 2021). On the industry side, a coalition of large airlines including American Airlines, Delta Air Lines, JetBlue Airways, Southwest Airlines, and United Airlines have recently committed to making 2 billion gallons of SAF available annually to U.S. aircraft operators in 2030, presumably through the implementation of regulatory mandates (Airlines for America 2021).[67]

Ultimately, these steps are encouraging foundations upon which to build, but much greater global action is needed to reach the 2030 and 2050 targets for SAF uptake. To this end, other countries, regions, and industry actors should glean lessons in best practice from these early starters as they embark on establishing appropriate enabling environments of their own.

TRANSPORT INDICATOR 9:
Share of zero-emissions fuels in international shipping fuel supply

Targets: The share of zero-emissions fuels reaches 5 percent for international shipping fuel supply by 2030 and 100 percent by 2050.

Maritime shipping, the backbone of global commerce, accounts for almost 3 percent of global GHG emissions (IMO 2020). Roughly 85 percent of these emissions come from international shipping, namely the transport of goods by container ships, bulk carrier ships, and tankers (ETC 2019b). While shipping has become more energy-efficient since 2012, emissions from the sector could increase by up to 30 percent above 2008 emissions by 2050 due to a continued increase in demand for internationally shipped goods (IMO 2020).

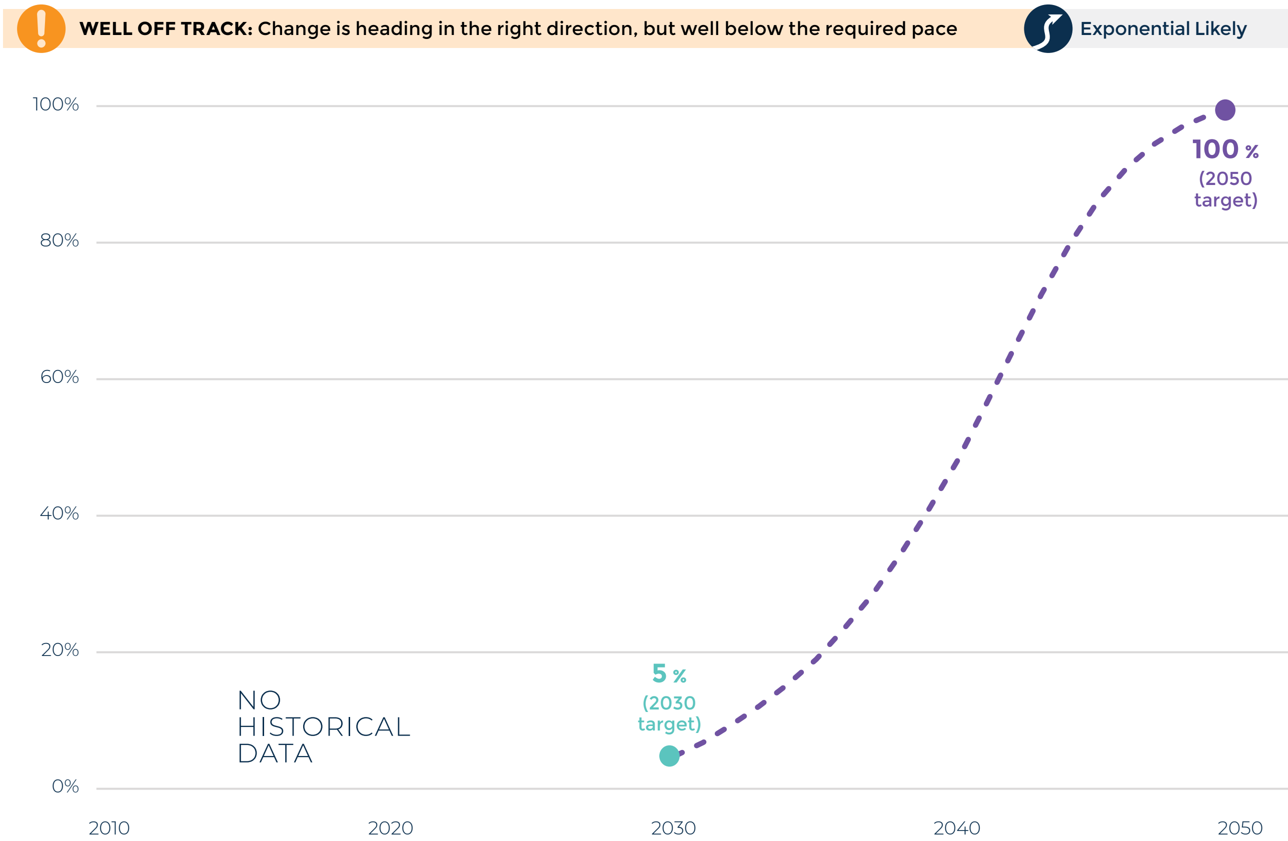
A suite of solutions will be needed to align international shipping with a 1.5°C pathway, including demand management measures, energy efficiency measures, and zero-emissions fuels (ETC 2019b). However, due to the expected growth in demand, full decarbonization is only possible if long-haul shipping vessels transition away from carbon-intensive heavy fuel oil (HFO) to zero-emissions fuels. Zero-emissions fuels include sustainable biofuels (e.g., biomethanol), synthetic carbon-based fuels (e.g., methanol combined with direct air capture), and blue and green hydrogen and ammonia. 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 2019b; BloombergNEF 2020c; Victor et al. 2019; Shell 2020a). Green ammonia, however, is favored over hydrogen because it requires less onboard storage, is easier to handle as it requires less cooling, and has lower flammability (Englert and Losos 2021).

The role of liquified natural gas (LNG), once thought to be a potentially scalable and cleaner fuel than HFO (specifically in terms of sulfur emissions), is now being debated as to what extent it could actually contribute to decarbonizing shipping. Recently analysis suggests that LNG might not actually decrease life-cycle GHG emissions compared to HFO regardless of the engine used, due largely to upstream methane leakage (Englert et al. 2021; Pavlenko et al. 2020). Furthermore, switching to LNG risks disincentivizing zero-emissions fuels because it would require high capital investment that could not be used to support drop-in zero-emissions fuels (Englert et al. 2021; Victor et al. 2019).

Scenarios aligned with a 1.5°C pathway suggest that at least 5 percent of fuel used in international shipping will need to be zero-emissions fuel by 2030 and 100 percent of fuel by 2050 (Osterkamp et al. 2021) (Figure 49). There will most likely be a mixed portfolio of zero-emissions fuels as different fuels are being shown to be optimal for different ship types, sizes, and operating profiles (Englert and Losos 2021). Recent analysis suggests that ammonia will take a leading role over the next decade and grow more rapidly after about 2040. Ammonia could supply 75–99 percent of the market for shipping fuel by 2050 (Raucci et al. 2020).

Analysis by University Maritime Advisory Services (UMAS) and the High-Level Climate Champions has identified priority segments of the international shipping industry that could be targeted for action to advance the 2030 zero-emissions fuel goal. Decarbonization of these priority segments would greatly benefit from coordinated stakeholder action. Container shipping is a prime candidate, as only a few ports and deep-sea routes account for a large share of shipping volume. Ammonia and liquefied petroleum gas tankers are also well-suited to early action because their storage and systems are well-suited for ammonia. Finally, niche

FIGURE 49. Historical progress toward 2030 and 2050 targets for the share of zero-emissions fuel in international shipping fuel supply



Sources: Targets from Osterkamp et al. (2021) and Race to Zero (2021a).

international routes (noncontainer shipping) between countries that have supportive national policies for green hydrogen and ammonia could be targeted, such as Chile-United States, Japan-Australia, Dubai-Singapore, Australia-Singapore, and Denmark-Norway (Cronin 2021).

Enablers of climate action

Zero-emissions fuels for international shipping are still in the early emergence phase of technological deployment. While the technologies exist to produce these fuels, there are multiple challenges to accelerating deployment in international shipping to ensure that these fuels are available in the right quantities and at the right locations.

One key challenge is cost. HFO is one of the dirtiest and cheapest fuels available, so zero-emissions fuels will likely never be competitive without policy and industry support. At a green hydrogen price of $2 per kilogram, a carbon price of at least $108/t$CO_2$, higher than nearly all enacted carbon prices today, would be needed to make ammonia more competitive with HFO (BloombergNEF 2020c). Furthermore, the cumulative total capital investment required to decarbonize international shipping is estimated to be $1 billion to $1.9 billion (Raucci et al. 2020). Fuel supply infrastructure costs, that is, the costs to produce green hydrogen and ammonia, comprise 85–90 percent of total capital costs. The remaining 10–15 percent costs include onboard-ship costs (e.g., capital costs for equipment including machinery, storage, and energy efficiency investments) (Raucci et al. 2020).

A second challenge is that no internationally trading shipping vessels are currently equipped to use green hydrogen or ammonia, so ship and engine manufacturers' concerns about safety, storage, and costs have not been appropriately tested and addressed.

A third challenge concerns the significant amount of hydrogen that will be required and whether this demand will be prioritized over hydrogen demands from other sectors. A negligible amount of green ammonia for shipping is currently being produced (Gallucci 2021; Victor et al. 2019).

Recent studies suggest that investments in ZEF pilot projects, early policy action at national and regional levels, and greater coordination between the public and private sector can help address these challenges in the near term.

Investing in pilot projects

One of the key drivers to decarbonize international shipping will be major investment in more coordinated large-scale demonstration and testing of zero-emissions fuel technology, especially hydrogen and ammonia (Victor et al. 2019). This will help address concerns about hydrogen's flammability and ammonia's toxicity and corrosiveness, and questions relating to onboard storage, all of which will require new design and management measures (Englert and Losos 2021). Generating this level of investment will require strong support from the International Maritime Organization, national governments, industry actors, and investors (ETC 2019b; Victor et al. 2019). Several demonstration projects will be testing hydrogen- and ammonia-powered ships as soon as 2024 (Gallucci 2021), and coalitions to catalyze action are growing. For example, the Getting to Zero Coalition aims to bring a wide variety of over 120 public and private stakeholders together to scale up demonstrations and pilots (Global Maritime Forum 2021).

Regional and national policy action

The International Maritime Organization is the UN agency responsible for regulating shipping emissions. In 2018, it released its initial strategy to reduce GHG emissions, establishing a target of a minimum 50 percent reduction in GHG emissions by 2050 relative to a 2008 baseline. The strategy has been criticized for not being aligned with a 1.5°C pathway and vagueness concerning how the target might be achieved (Serra and Fancello 2020). It is likely necessary that "first mover" national and regional government initiatives will need to generate evidence that can support stronger global policies, such as an international green fuel mandate, and create ambition loops with industry actors (ETC 2019b; Victor et al. 2019; Englert and Losos 2021). Policies recommended by experts include economic incentives to promote zero-carbon fuels like national procurement mandates and shipping emissions targets, as well as policies that disincentivize the lock-in of HFO and LNG fuels, like a carbon tax (ETC 2019b; Englert et al. 2021). Policy action is also needed to ramp up hydrogen production. Many leading economies are already betting big on hydrogen. Australia has committed about US$500 million to back new hydrogen projects under its National Hydrogen Strategy (Australia Department of Industry, Science, Energy and Resources 2019) and China's 13th Five-Year Plan outlines a target of supporting demand for 60 million tonnes of hydrogen by 2050 (Matalucci 2021). The United States recently called for a 100 percent reduction in shipping emissions by 2050. These efforts need to ramp up substantially, however, to ensure adequate supplies.

Strengthening coordination between public and private sectors

Another key driver for international shipping is likely to be coordination by national governments and ports along priority deep-sea routes and niche international routes to aggregate economy-wide demand for hydrogen-derived fuels and agree on emissions and/or fuel standards (Victor et al. 2019; Lewis 2020). National governments, ports, and major industry players like ship and engine manufacturers, ship operators, and fuel providers can motivate action by setting industry targets. Existing coalition efforts, like those by Getting to Zero, need to be scaled up with stronger government engagement (Victor et al. 2019).

TECHNOLOGICAL CARBON REMOVAL

To achieve the Paris Agreement goal of limiting warming to 1.5°C, the latest climate science indicates that we need to reach net-zero CO_2 emissions by midcentury. Reducing new emissions into the atmosphere is essential and should be the priority, but it is not enough if we want to avoid the worst impacts of climate change. We will also need to pull carbon out of the air to counterbalance emissions that will be very difficult to mitigate in the coming decade or two (e.g., long-haul aviation) and to deal with excess CO_2 already in the atmosphere through carbon dioxide removal (CDR or carbon removal) (National Academies of Sciences, Engineering, and Medicine 2019).

CARBON REMOVAL CAN INCLUDE NATURAL approaches, like tree planting, as well as technological solutions like direct air capture (DAC)—both will be critical parts of a larger carbon removal portfolio (see Chapter 8, "Land use and coastal zone management," for discussion of natural carbon removal approaches).[68] A portfolio of approaches also reduces cost and the risk that any one solution will fail to provide the expected level of removal (Mulligan et al. 2020). Solutions like tree planting are generally ready for wider deployment, but they are ultimately limited by land availability, can compete with agricultural production, and have inherent issues related to the permanence of carbon storage (National Academies of Sciences, Engineering, and Medicine 2019). Technological carbon removal includes approaches like DAC, carbon mineralization, and bioenergy with carbon capture and storage (BECCS), which are less ready for deployment than natural solutions but have attracted increased interest and public and private investment recently as it has become clearer that carbon removal will be needed alongside mitigation (Institute for Carbon Removal Law 2021).

A key indicator for tracking progress on carbon removal is identifying how many tonnes of carbon have been captured from the air and stored permanently (Table 11).

Permanent storage requires the secure sequestration of CO_2 from the atmosphere, either through injection into deep geological formations, or through the creation of stable carbonate minerals. To count as carbon removal, CO_2 must be captured from the atmosphere; for example, via direct air capture or photosynthesis (point source capture, for example at a cement or fossil fuel power plant, is preventing emissions from entering the atmosphere and would be mitigation rather than carbon removal). Once CO_2 is captured, it can also be sold for use in various products rather than being injected underground to help offset the cost of capture. When used in products, the duration of storage varies depending on the product: uses like beverage carbonation and fuel production provide storage for days to weeks (so would not count as permanent removal), whereas use in building materials provides virtually permanent storage. Only a small portion of the CO_2 captured from the atmosphere today is stored permanently.

DAC provides few co-benefits aside from jobs, and uses nontrivial amounts of energy to operate, which must be non-carbon emitting to provide the greatest carbon removal benefit. Renewable energy is an obvious choice to power DAC: in some cases, production that would otherwise be curtailed could be used or new

TABLE 11. Summary of progress toward 2030 technological carbon renewal target

Indicator	Most recent historical data point (year)	2030 target	2050 target	Trajectory of change	Status	Acceleration factor
Rate of technological carbon removal ($MtCO_2$ removed/yr)	0.52 (2020)	75	4500	Exponential possible		n/a; U-turn needed

Note: n/a = not applicable; $MtCO_2$/yr = million tonnes of carbon dioxide per year.

Sources: For historical data, authors' analysis, as well as EPA (2020); Doyle (2021); and Climeworks (2021). Targets based on IPCC (2018) and Fuss et al. (2018).

capacity can be constructed. BECCS provides energy as a part of its process, offset by the energy required to power the capture equipment and to access and transport the feedstock. Other processes such as gasification can provide energy services (e.g., hydrogen production) while also allowing for storage of process-based CO_2. Depending on the specific approach used, mineralization can provide the co-benefit of storing CO_2 in products like concrete or remediation of mine tailings, but it also requires energy to access and transport feedstock materials.

Scale-up of carbon removal will require consideration beyond just tonnes of carbon removed. Environmental, social, and equity impacts also need to be considered for each approach to ensure that, among other concerns, carbon removal deployment doesn't exacerbate existing pollution burdens, benefits and negative impacts are equitably distributed, and stakeholders are informed and can provide input into project plans.

TECHNOLOGICAL CARBON REMOVAL INDICATOR 1: Rate of technological carbon removal

Targets: The rate of technological carbon removal (e.g., DAC, mineralization, and BECCS) scales up to sequester 75 $MtCO_2$ annually by 2030 and 4.5 $GtCO_2$ annually by 2050.

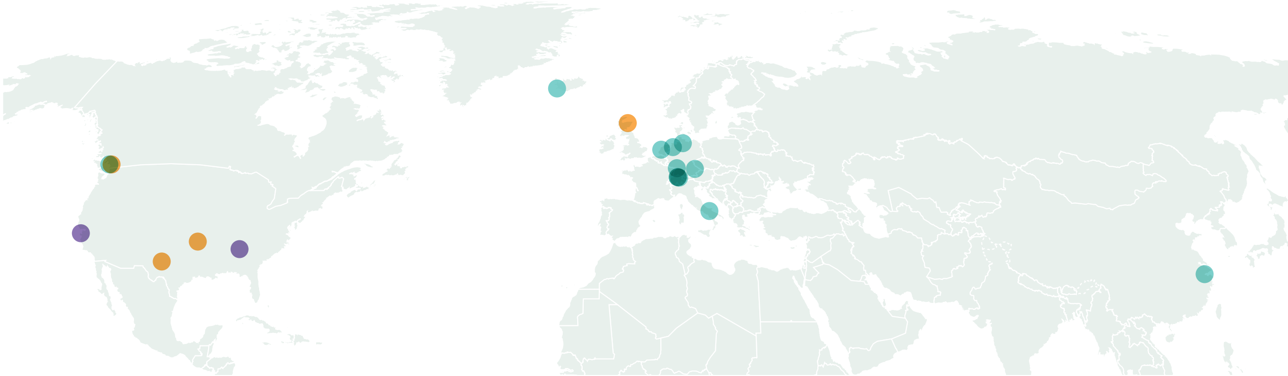
Technological carbon removal, as assessed here, includes DAC, carbon mineralization—for example, through enhanced weathering—and BECCS. The amount of carbon removal that will be needed by 2050 depends on how much decarbonization has happened by that time as well as the amount of carbon removed through natural solutions. Recent comprehensive assessments point to a potential need for roughly 8–10 $GtCO_2$/year in carbon removal from both natural and technological solutions by 2050 (National Academies of Sciences, Engineering, and Medicine 2019; IPCC 2018), with roughly 5–6 $GtCO_2$ of that being provided by natural approaches (Roe et al. 2019; Fuss et al. 2018). Considering the Paris-compatible scenarios assessed by the IPCC that meet sustainability criteria set out in Fuss et al. (2018), around 4.5 $GtCO_2$/yr from technological CDR may be needed by 2050 (roughly equivalent to the combined GHG emissions of the European Union and Japan in 2018), with an interim target of 75 $MtCO_2$/yr by 2030 (roughly equivalent to the GHG emissions of Austria in 2018) in order to limit warming to 1.5°C (IPCC 2018; ClimateWatch 2021).[69] The scale-up of carbon removal would need to accelerate significantly to reach the 2030 and 2050 targets.

DAC, which uses large fans to push air over reactive chemicals that bind CO_2, is promising because it can be configured to have a smaller land area footprint to capture CO_2 than many other carbon removal approaches. While trees would need an estimated 860 km^2 to capture 1 million tonnes of CO_2 per year, today's DAC systems would require 0.4–24.7 km^2, with almost all of the land in the larger configurations used for renewable energy (Lebling et al. 2021). DAC also has flexibility in where it can be sited—for example on marginal land or near geologic storage basins to reduce transport costs for captured CO_2. At the same time, DAC plants have nontrivial energy requirements and must be coupled to renewable or other zero-carbon energy sources to achieve their maximum potential as a carbon removal technology. Today, only a few companies are developing DAC, with a total of around 6,000 tCO_2 captured per year (though not all of that is stored permanently) (BPC 2021). A handful of projects are in the pipeline, including two that would capture up to 1 million tCO_2/yr (one in Texas that would do enhanced oil recovery (EOR) and one in Scotland that would do non-EOR geological storage) (Carbon Engineering 2020, 2021) (Figure 50).

BECCS involves burning biomass and capturing and storing the resulting emissions. Plants pull CO_2 from the air through photosynthesis and then that embodied carbon is captured by CCS equipment upon combustion and stored underground. Climate mitigation models assessed in the IPCC's SR15 rely heavily on BECCS, but there are concerns about its large-scale deployment due to significant land area needs for energy crops that could impact food security or result in land-use change that increases emissions and is potentially misaligned with broader sustainability goals (Fuss et al. 2018). More recent assessments include roles for waste biomass gasification to hydrogen and CO_2 (Larson et al. 2021; Baker et al. 2020). A handful of biomass-based carbon removal projects are in development in the United States, with a few more in the planning stages in other countries (CATF 2020; AU 2020; Weetch 2021).

Mineralization, also referred to as enhanced weathering, involves accelerating natural reactions between

FIGURE 50. Locations of demonstration and commercial direct air capture plants



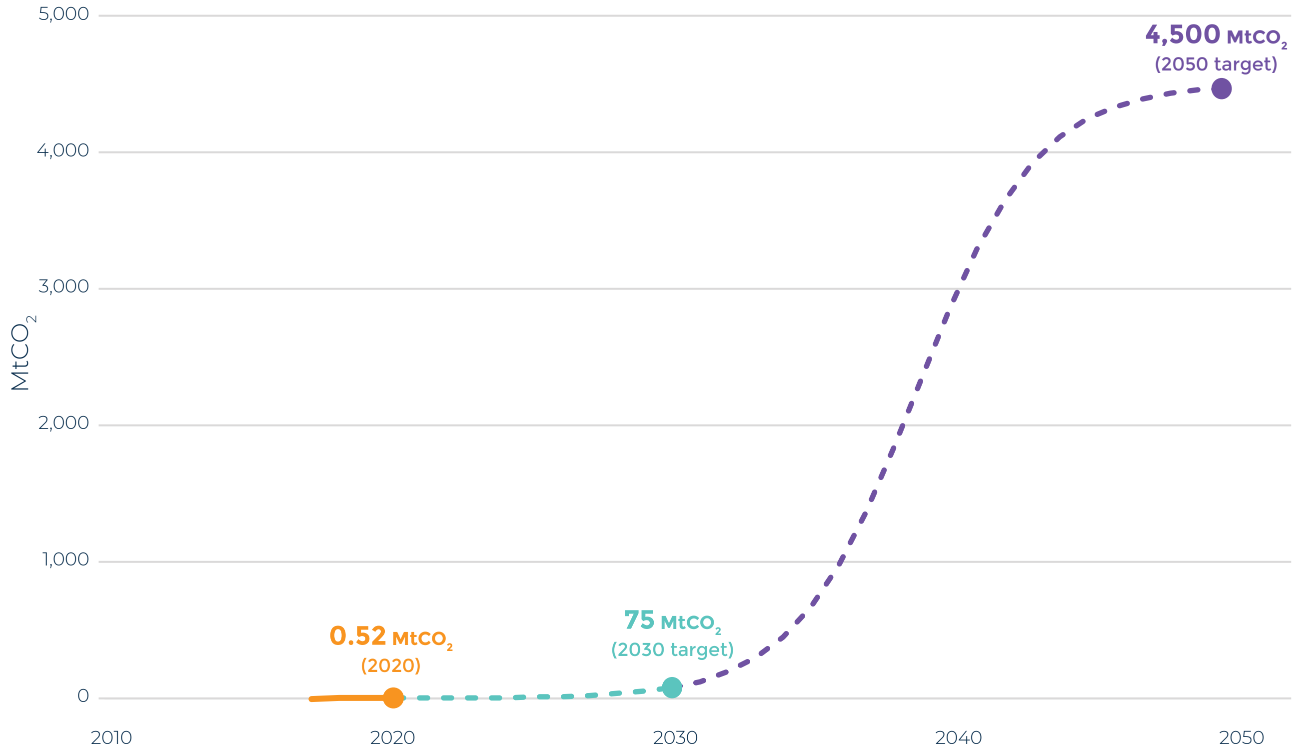
Note: Figure includes demonstration and commercial scale plants from 1 to 1,000,000 tonnes of CO_2 per year capture capacity.
Source: Carbon180 (2021) and BPC (2021).

certain minerals and CO_2. There are several ways to do this, including adding certain types of crushed rock to agricultural land, coastal areas, or the open ocean or accelerating reactions of certain mine tailings or industrial waste with ambient air (National Academies of Sciences, Engineering, and Medicine 2019). Mineralization can also be used to store already captured CO_2 by injecting CO_2-enriched fluids into certain types of rock or to include the CO_2 in products like cement and concrete. Mineralization, where CO_2 chemically reacts to form solid carbonates, is of particular interest given that CO_2 is permanently stored, unlike carbon stored terrestrially, which can be returned to the air when trees are cut down or burned, for example (Jeffery et al. 2020). A few companies are using CO_2 (not necessarily from DAC) to make building materials (e.g., Blue Planet, Solidia Technologies) and to develop projects that store captured CO_2 underground via mineralization (e.g., Climeworks Orca plant) or both capture and store CO_2 via mineralization (e.g., Project Vesta and Green Sand) (AirMiners 2021).

Reaching 2030 and 2050 goals will require rapid scale-up across a portfolio of approaches to reduce costs and the risk that any one approach fails to provide sufficient removal (Mulligan et al. 2020) (Figure 51). Achieving this will depend on several factors, including policy support, federal and private investment, market demand, and others.

FIGURE 51. Historical progress and an illustrative S-curve of what's needed to reach 2030 and 2050 targets for the rate of technological carbon removal

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



Note: $MtCO_2$ = million tonnes of carbon dioxide. The historical data in this graph only show CO_2 that has been captured from the air and put in permanent geologic storage; CO_2 captured from the air but not stored permanently is not included here (and CO_2 captured from point sources and stored permanently is also not included). To be on track for reaching the 2030 target, the historical rate of change needs a step change in action.

The future trajectory of technological carbon removal may follow an S-curve, following the pattern of other instances of technology adoption. This figure illustrates what growth of technological carbon removal would have to be to reach the targets on an S-curve trajectory—though this is just one potential path among many. Data are currently insufficient to evaluate the pace of progress of technological carbon removal in a quantitative way, so our evaluation of "well off track" is a qualitative judgment. Technological carbon removal is still in the emergence phase of the S-curve and requires the right government support and economic conditions to enter a phase of rapid growth. Whether it reaches the diffusion stage and how fast depends on what happens in the near term.

Sources: For historical data, authors' analysis, as well as EPA (2020); Doyle (2021); and Climeworks (2021). Targets based on IPCC (2018) and Fuss et al. (2018).

Enablers of climate action

Key obstacles to accelerating carbon removal technologies today include high cost, insufficient supportive policies, insufficient demand, and the need for enabling infrastructure. Additionally, carbon removal, unlike other sectors that provide an economic good or service that people pay for directly, is above all a public good, which can also pose challenges for scale-up. Several supportive measures can address these barriers.

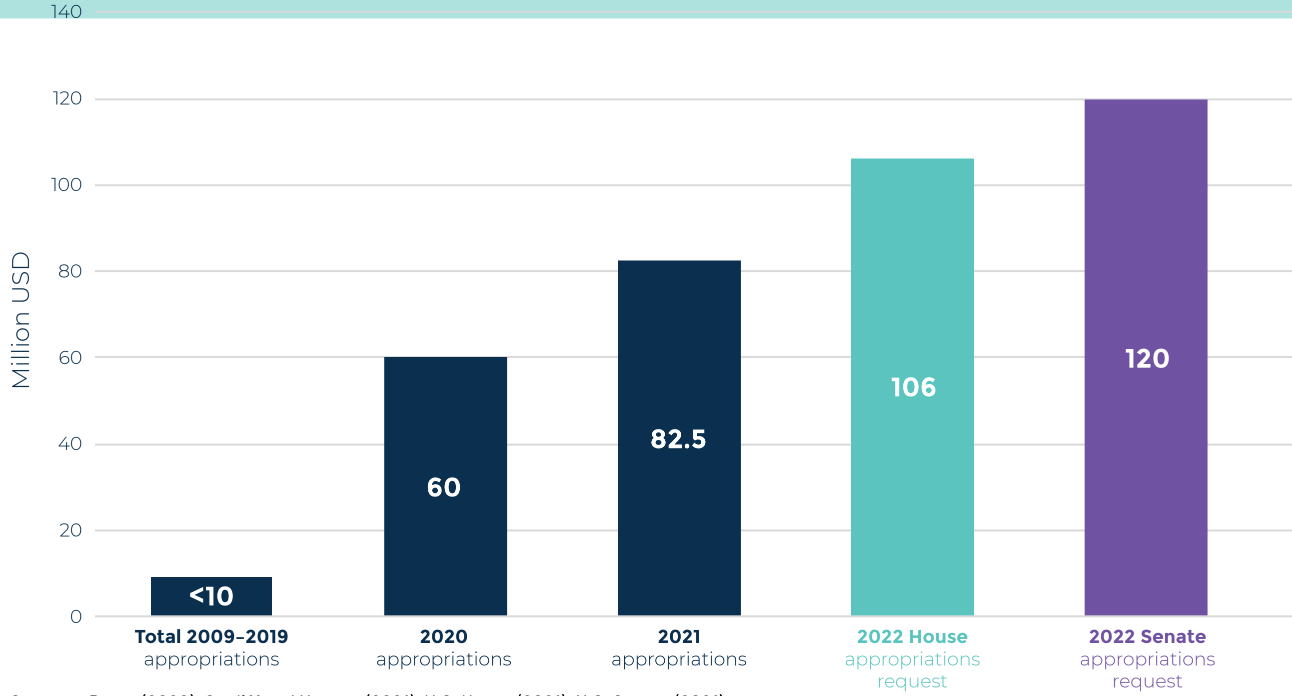
Scaling up federal investments in RD&D

Government investment in RD&D is needed to develop entirely new carbon removal approaches and refine proposed and existing ones to help optimize technologies and pathways and bring down costs. In the United States, for example, federal investment in carbon removal RD&D has increased from around $10 million total from 2009 to 2019 to $82.5 million in 2021 (Figure 52), as it has become clear that carbon removal will need to play a potentially significant role.

Adopting supportive policies that incentivize deployment of CDR

Supportive policies incentivize deployment in a variety of ways: reducing investment or operating costs, creating regulation that enhances certainty for project development, reducing financing costs, or providing incentives to procure certain products, among others. The 45Q tax credit in the United States provides a credit of \$35–\$50/tCO_2 captured and has been a driver for the only large-scale DAC project (as well as a number of CCS projects) to enter planning stages. At

FIGURE 52. U.S. federal funding for carbon removal research, development, and demonstration at the Department of Energy



Sources: Burns (2020); Cunliff and Nguyen (2021); U.S. House (2021); U.S. Senate (2021).

the state level, California's low-carbon fuel standard was revised in 2019 to include DAC and provides a credit close to \$200/tCO_2 today for DAC development anywhere.[70] A number of pieces of legislation propose increasing the 45Q credit value to better cover the costs of early DAC plants, which are expected to range from \$250–\$600/tCO_2 (Keith et al. 2018; Tollefson 2018), while other legislation includes new tax credits and other policies that would support deployment.

Establishing corporate commitments, coupled with investments in technological CDR

Corporate commitments and investments in carbon removal technology have increased in the past few years. As many countries have set net-zero commitments, companies have taken similar action to reduce their own emissions and respond to customer and investor concerns over climate change. Companies like Microsoft and Amazon have pledged to reduce their own emissions and have also invested in carbon removal projects to help them reach net zero and even net negative for Microsoft. Other companies, like the financial services provider Stripe, have not only pledged to purchase tonnes of carbon removal but have also provided upfront investments to support project development (Stripe 2021). Many other companies have indicated a long-term goal of net zero but have not provided details on how those targets will be achieved (Institute for Carbon Removal Law 2021). Corporate commitments are critical to increasing the supply of carbon removal but must complement internal emissions reductions goals based on climate science.

Expanding enabling infrastructure

Enabling infrastructure, such as CO_2 pipelines, geological storage, and abundant renewable and zero-carbon energy to power carbon removal projects, is critical to scaling up carbon removal technology. CO_2 pipelines would be needed where CO_2 is captured in a different location from storage or use and would be relevant for DAC and BECCS (as well as for CO_2 captured through CCS at industry or power facilities). There are around 5,200 miles of CO_2 pipelines already in the United States (U.S. Council on Environmental Quality 2021), but this network would need to be significantly scaled up to accommodate the expected need in a few decades. Estimates for geological storage capacity vary, but the National Academies (2019) point to a global technical potential of 2,000 GtCO_2 through the end of the century. This amount may be lower in practical terms based on locations of capture in relation to storage, and even with this high potential, each site needs to be validated, and annual injection rates may be limited to avoid pressure buildup. For DAC, abundant zero-carbon energy will be needed to power DAC facilities to maximize net carbon removal. Based on the energy requirements of the systems we have today, capturing a billion tonnes of CO_2 could use up to 10 percent of U.S. energy consumption today (National Academies of Sciences, Engineering, and Medicine 2019; Mulligan et al. 2020).

Creating markets for products made with captured CO_2

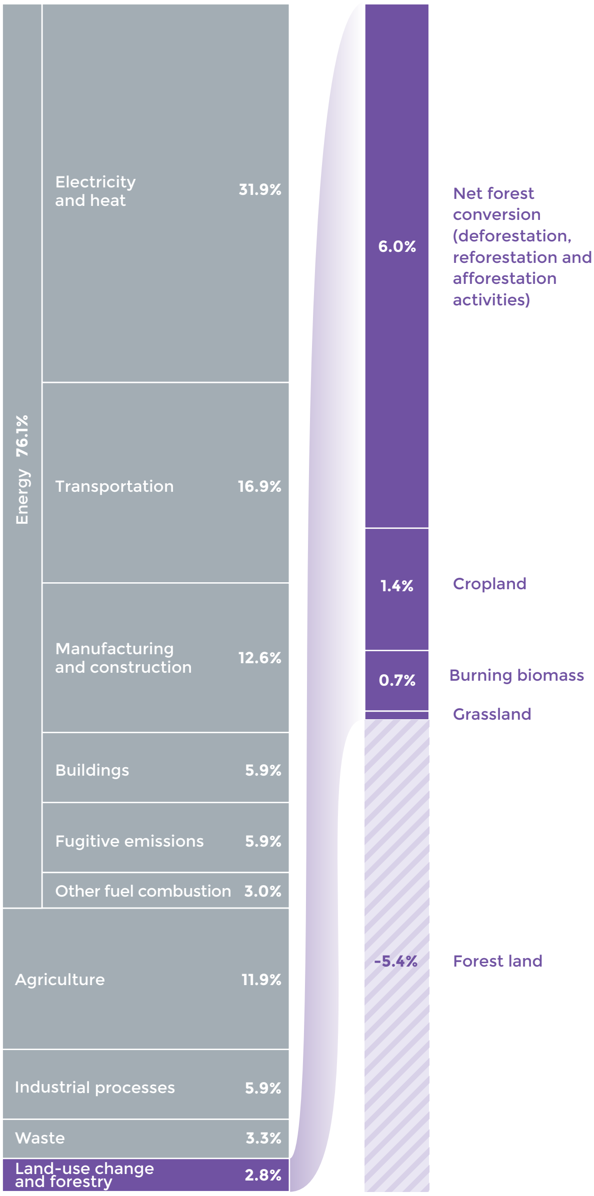
Large-scale markets for products made with captured CO_2 can provide a demand signal to project developers and an economic incentive for captured CO_2. While dedicated storage in underground geologic formations maximizes net carbon removal, building up the market for products made with captured CO_2 can help compensate for high capture costs in the near term. Utilization pathways vary in degree of permanence, ranging from synthetic fuels, which provide very short-lived storage but can be a less carbon-intensive alternative to conventional jet fuel, to use of CO_2 as a curing agent for concrete made with novel cement, which provides permanent storage. Market incentives that focus on utilization of captured CO_2 in more permanent storage media (e.g., in the buildings sector) are particularly important to foster and support (Jeffery et al. 2020).

While many factors in the enabling environment show that change is moving in a direction that will help facilitate a more rapid scale-up of carbon removal technology, we are still far from where we need to be in terms of developing and deploying these technologies to be on a trajectory for multigigatonne-scale removal by midcentury. These technologies hold significant promise, but, ultimately, we want to minimize the extent to which we need to rely on them in the future, which means reducing emissions as much as possible in the coming few decades as well as scaling up deployment of natural carbon removal approaches.

8 LAND USE AND COASTAL ZONE MANAGEMENT

Land use is both a major source of emissions and a major natural carbon sink (Roe et al. 2019; IPCC 2018, 2019; Griscom et al. 2017; Searchinger et al. 2019). Depending on the way land is used in future, it can either contribute to or help solve global climate change.

FIGURE 53. Role of the land-use and coastal zone managment sector in global greenhouse gas emissions



Note: Estimates of greenhouse gas emissions from forestry are subject to high uncertainties. Data featured in this figure are from ClimateWatch (2021), which relies on 2018 forestry emissions data from FAOSTAT. This differs from IPCC (2019), which includes older forestry emissions data from FAOSTAT, as well as data from a number of other global models, to estimate net CO_2 emissions from land use and land-use change.
Source: ClimateWatch (2021).

BETWEEN 2007 AND 2016, FOR EXAMPLE, annual net CO_2 emissions from land use and land-use change were approximately 5.2 ± 2.6 GtCO_2 (IPCC 2019). And in 2018, according to one estimate, emissions from land use change and forestry accounted for 2.8% of global GHG emissions (Figure 53) (ClimateWatch 2021).

Improved protection, management, and restoration of forests, peatlands, coastal wetlands, and grasslands are essential for limiting warming to 1.5°C by the end of the century. This includes stopping deforestation as a top priority, and then increasing restoration. These efforts can also help communities better adapt to the impacts of climate change by building resilience and reducing vulnerabilities to extreme weather events. For example, mangroves protect coastal lands against rising seas and tidal surges, while inland forests moderate temperature fluctuations and stabilize water supply (Sato et al. 2019).

In this chapter, we examine some of the transitions in the land use and coastal zone management sector by focusing on forests, peatlands, and coastal wetlands. The transitions required in the agriculture sector are addressed separately in Chapter 9. Specifically, for forests, we focus on reduced deforestation (indicator 1), restored tree cover (indicator 2), and, relatedly, increased carbon sequestration through these tree cover gains (indicator 3). For peatlands, we look at reduced destruction (indicator 4) and increased restoration (indicator 5), and similarly, for coastal wetlands, we examine reduced conversion (indicators 6) and increased restoration (indicator 7).

Of the seven indicators, only three have historical rates of change that are headed in the right direction, but these are also well below levels required for 2030; one is heading in the wrong direction, and a step change in action is needed; and, for the remaining three, data are insufficient to assess the rate of historical change and current gap in action (Table 12). In particular, while

TABLE 12. Summary of progress toward 2030 land use and coastal zone management targets

Indicator	Most recent historical data point (year)[a]	2030 target[b]	2050 target[b]	Trajectory of change	Status	Acceleration factor
Deforestation rate (Mha/yr)	6.77 (2020)	2.01	0.33	Exponential change unlikely		n/a, U-turn needed
Reforestation (cumulative Mha)	80.60 (cumulative gain from 2000–2012)	259	678	Exponential change unlikely	!	3.2x
Rate of carbon removal from reforestation ($GtCO_2$/yr)	0.71 (annual sequestration rate as of 2012)	3	7.85	Exponential change unlikely	!	4.2x
Peatlands conversion rate (Mha/yr)	0.78 (1990–2008 annual average)	0.23	0.04	Exponential change unlikely	?	Insufficient data
Peatlands restoration (cumulative Mha)	No data	22	46	Exponential change unlikely	?	Insufficient data
Coastal wetlands conversion rate (Mha/yr)	0.63 (1990–2005 annual average)[c]	0.19	0.03	Exponential change unlikely	?	Insufficient data
Coastal wetlands restoration (cumulative Mha)	0.43 (cumulative gain, 2015–16)[d]	7	29	Exponential change unlikely	!	2.7x

Note: n/a = not applicable; $MtCO_2$/yr = million tonnes of carbon dioxide per year; $GtCO_2$/yr = gigatonnes (billion tonnes) of carbon dioxide per year; Mha/yr = million hectares per year.

a For indicators with limited data availability, we use the average annual rate of change across the most recently available time period (e.g., 2000–2012) to estimate the annual rate of change during the target's baseline year (2018 for all indicators in this table). We calculate the future rate of change required to reach the 2030 target against this estimated baseline year rather than the most recent year of data.

b Targets for 2030 and 2050 are derived from Roe et al. (2019) and Griscom et al. (2017), which define them against the baseline year of 2018. But for some targets, data are not available for 2018. We, therefore, use the most recently available data point (e.g., 80.6 Mha in 2012) or the most recently available annual average (e.g., an average of 0.78 Mha of peatlands lost per year from 1990–2008) to estimate the indicator's value in 2018.

c Historical data are assessed over a 15-year period for mangrove forests (1990–2005) but over significantly longer periods for salt marshes and seagrass meadows. Annual data for all three ecosystems are not available.

d Due to data limitations, historical data are assessed for mangroves only.

Sources: Historical data from GFW (2021b; 2021d); Cook-Patton et al. (2020); Griscom et al. (2017); Siikamäki et al. (2013); Giri et al. (2011); Pendleton et al. (2012); and Bunting et al. (2018). Targets derived from Roe et al. (2019); Griscom et al. (2017); and Cook-Patton et al. (2020).

gross tree cover gain is increasing, an abrupt halt to deforestation is required simultaneously. Reforestation is not a substitute for protecting forests (especially for the world's remaining tropical primary forests), as discussed further in this chapter.

Actions to protect and restore these carbon-rich ecosystems come with tremendous co-benefits and are often linked with the achievement of several SDGs. For example, forests support the livelihoods of millions of people across the globe, through the use and sale of firewood, nontimber products, timber, fruits, and raw materials for medicine (Sato et al. 2019). Forests also help ensure water availability by capturing rainfall and stabilizing water supplies for drinking and irrigation (Sato et al. 2019).

At the same time, some difficult trade-offs can emerge in the land sector, which must be considered and managed responsibly (FAO 2018; Searchinger et al. 2019). With an increasing global population, there is a growing demand for food, fuel, and fiber, which has resulted in the ongoing expansion of agricultural land at the expense of forests (e.g., it is estimated that nearly 500 million hectares of forests and woody savannas were cleared for agriculture between 1962 and 2010). Recent work conducted by WRI, the World Bank, UN Environment, and the UN Development Programme (UNDP) concludes that it is possible to feed 10 billion people by 2050 while halting deforestation and reducing GHG emissions in line with a 1.5°C pathway, but this will require a range of actions, from changes in food production and consumption patterns (see Chapter 9) to the types of ecosystem protection and restoration measures addressed in this chapter (Searchinger et al. 2019).

LAND INDICATOR 1:
Deforestation rate

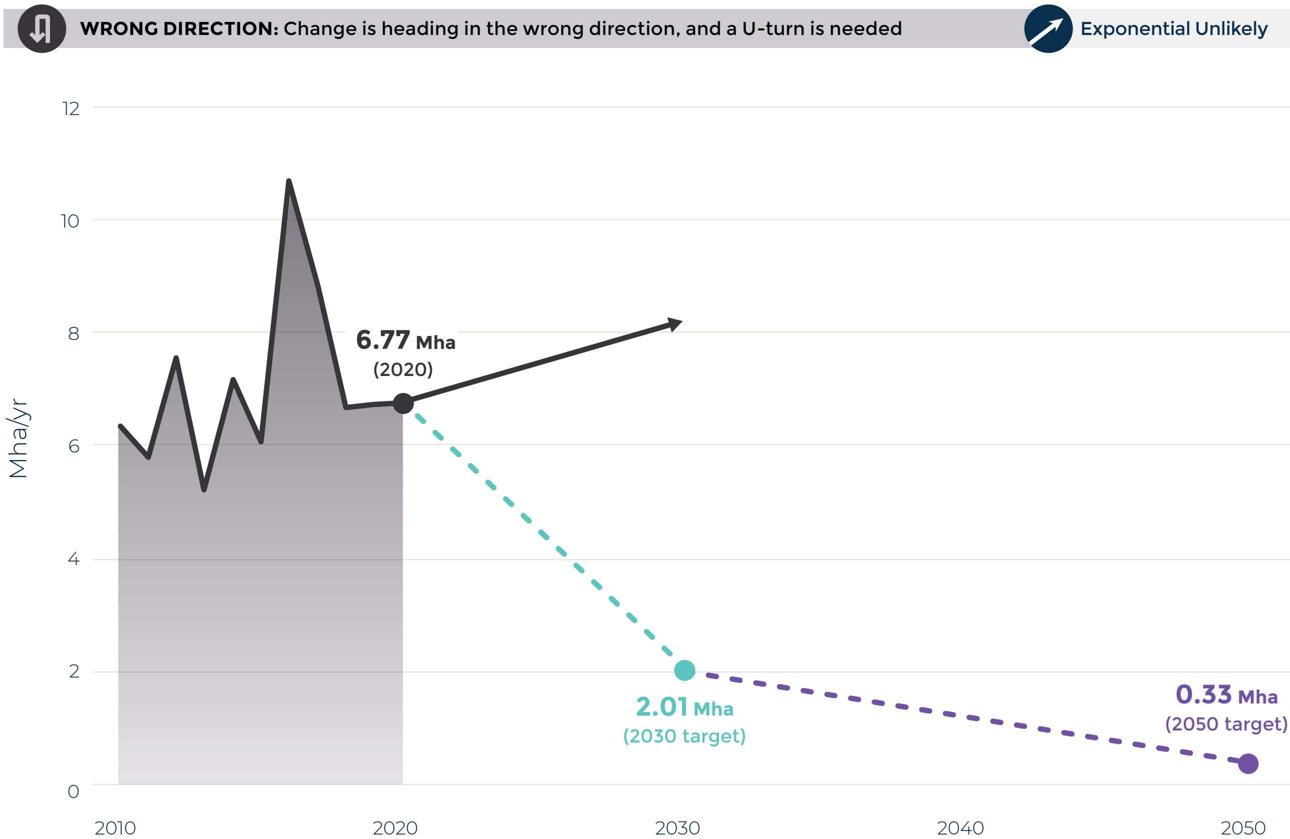
Targets: The global deforestation rate declines 70 percent by 2030 and 95 percent by 2050, relative to 2018.

The world's forests are a net carbon sink (Harris et al. 2021), but that fact obscures the gross emissions that occur as a result of deforestation, or the conversion of forest to another land cover or land use. A recent report on humid primary tropical forests, for example, found that losses in these forests resulted in 2.64 Gt of CO_2e in the year 2020 alone (WRI 2021d). Reducing deforestation, then, offers an immediate opportunity to reduce emissions.

Our targets are set according to the Roe et al. (2019) land sector roadmap for 1.5°C,[71] and highlight the need to quickly lower the rate of annual deforestation (Figure 54). This largely aligns with existing goals and commitments around forests that aim to rapidly reduce deforestation, such as the New York Declaration on Forests Goal 1 to end natural forest loss by 2030.

Unfortunately, the global rate of deforestation has not declined in accordance with these ambitions. Annual deforestation and associated emissions have risen since 2010 and increased slightly from 6.75 million hectares (Mha) in 2019 to 6.77 Mha in 2020.[72] More than 96 percent of deforestation since 2001 has occurred in the tropics, where the vast majority of forest loss is driven by conversion to agriculture, with much of the production destined for international markets (WRI 2021c). As a result, reducing deforestation is closely linked to simultaneously achieving the agricultural targets explored in Chapter 9, such as improving agricultural productivity, reducing food loss and waste, and—in countries where meat consumption is high—shifting dietary patterns toward plants.

FIGURE 54. Historical progress toward 2030 and 2050 targets for deforestation rate



Note: Mha = million hectares. Deforestation is defined here as tree cover loss due to commodity-driven deforestation, urbanization, or shifting agriculture where it overlaps with tropical primary forests (Hansen et al. 2013; Curtis et al. 2018; Turubanova et al. 2018). The spike in deforestation in 2016 and 2017 is related to anomalous fires in Asia and South America (Weisse and Goldman 2017); our method to determine the rate of change results in a positive trend over time despite these data points, and the historical data indicate an upward trend as well. The data used in this indicator have faced several changes over time that may result in temporal inconsistencies before and after 2015 (Weisse and Potapov 2021), which is another reason we use the last five years to determine the trend for this indicator.

Source: Historical data from GFW (2021b); 2030 and 2050 targets from Roe et al. (2019).

Humid tropical primary forests, some of the world's most important landscapes for biodiversity and carbon (Barlow et al. 2007; Gibson et al. 2011; Berenguer et al. 2014; Harris et al. 2021), have similarly been lost at an alarming rate. The rate of losses in these primary forests has remained around 3 Mha per year since record keeping began in 2002 and increased by 12 percent between 2019 and 2020 (WRI 2021d). Some countries, such as Indonesia, have succeeded in reducing their rate of humid tropical primary forest loss in recent years, while the majority of other countries, such as Brazil and the Democratic Republic of the Congo, have experienced stable or even increasing rates of loss (WRI 2021d) (see Figure 55).

Enablers of climate action

Efforts to reduce deforestation are hampered by a number of powerful economic and political barriers, including allocation of forests for political gain, the economic gains from forest conversion (linked to growing demand for commodities), lack of finance for conservation, lack of land tenure, unaligned management strategies, and unchecked illegality (Chaturvedi et al. 2019). Despite this complex situation, the following supportive measures have shown success in reducing deforestation in certain contexts and regions.

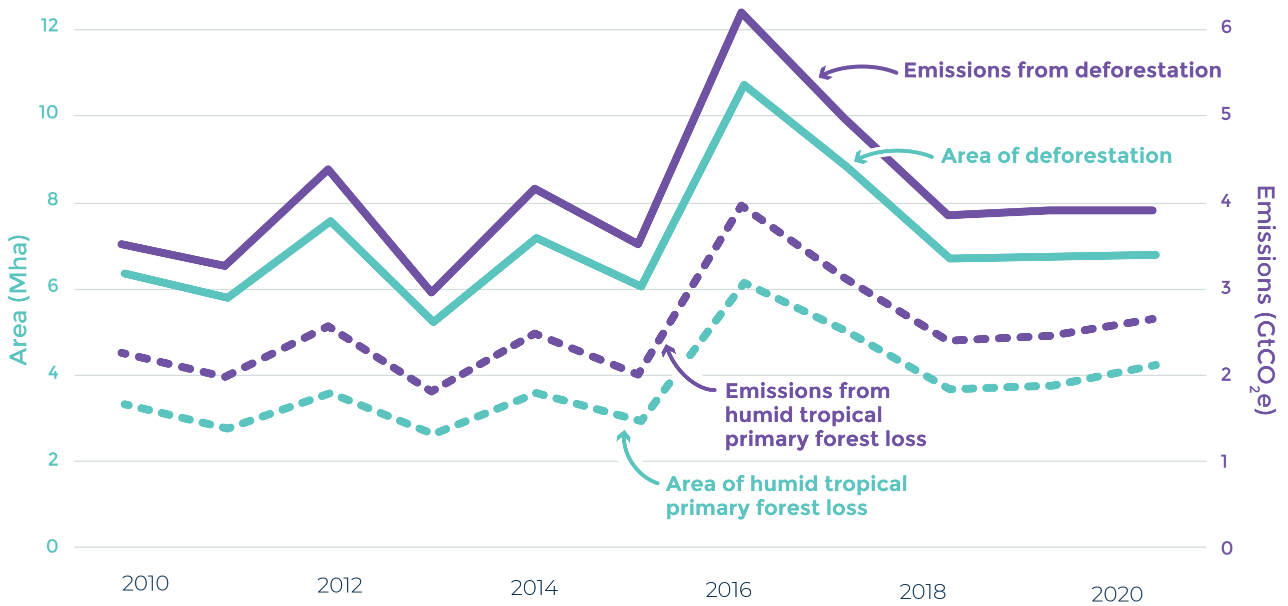
Strengthening forest policies and enforcement

Two of the most recognized examples of reducing deforestation in recent years, in Brazil and Indonesia, are due in part to improvement and enforcement of policies around forests. In Indonesia, new policies limiting fires and deforestation in sensitive areas and a moratorium on the granting of oil palm concessions in the wake of the devastating 2015 fires has resulted in four years in a row of declines in primary forest loss (WRI 2021d). In Brazil, increased coordination around enforcement, expansion of protected areas, blacklisting of municipalities with high rates of deforestation, and reinstatement of the Forest Code contributed to the dramatic reduction of deforestation in the Brazilian Amazon in the early 2000s (Nepstad et al. 2014). However, recent increases in deforestation in Brazil show how fragile these reductions can be if the political will to conserve forests is not maintained (Seymour 2021).

Boosting public finance for forests

The potential for tropical countries to reduce deforestation and associated emissions at relatively low cost (Griscom et al. 2017) has prompted interest in programs to reduce emissions from deforestation and degradation (REDD+), whereby industrialized countries compensate forest-rich countries for preserving their forests. While many tropical countries are engaged in REDD+ programs, the concept has still not fully been tried at scale due to its complexity and lack of international finance to date (Seymour et al. 2018). However, we may soon see

FIGURE 55. Deforestation and loss of humid tropical primary forests, and associated emissions



Note: Mha = million hectares; $GtCO_2e$ = gigatonnes (billion tonnes) carbon dioxide equivalent.
Source: GFW (2021a, 2021b, 2021c).

a turning point as interest increases; for example, the newly announced LEAF (Lowering Emissions by Accelerating Forest finance) Coalition will mobilize over $1 billion in results-based finance for the protection of tropical forests.

Increasing supply chain interventions

Conversion to agriculture remains the leading driver of deforestation, but commodities like oil palm and soy have begun to decouple from forest conversion since 2000 (Figure 56) (WRI 2021a). While some of the decline in rates of forest conversion is linked to lower prices for these commodities, supply chain interventions such as corporate sustainability commitments and the industry-led "soy moratorium" in the Brazilian Amazon are also likely playing a role (Macedo et al. 2012; Gibbs et al. 2015; Gaveau et al. 2019; Austin et al. 2018). These efforts to reduce deforestation within supply chains are generally voluntary and driven by consumer demand in importing countries, but there are also discussions underway in the European Union and the United States to legally restrict the import of commodities from recently deforested land (Taylor 2021; Korte 2021).

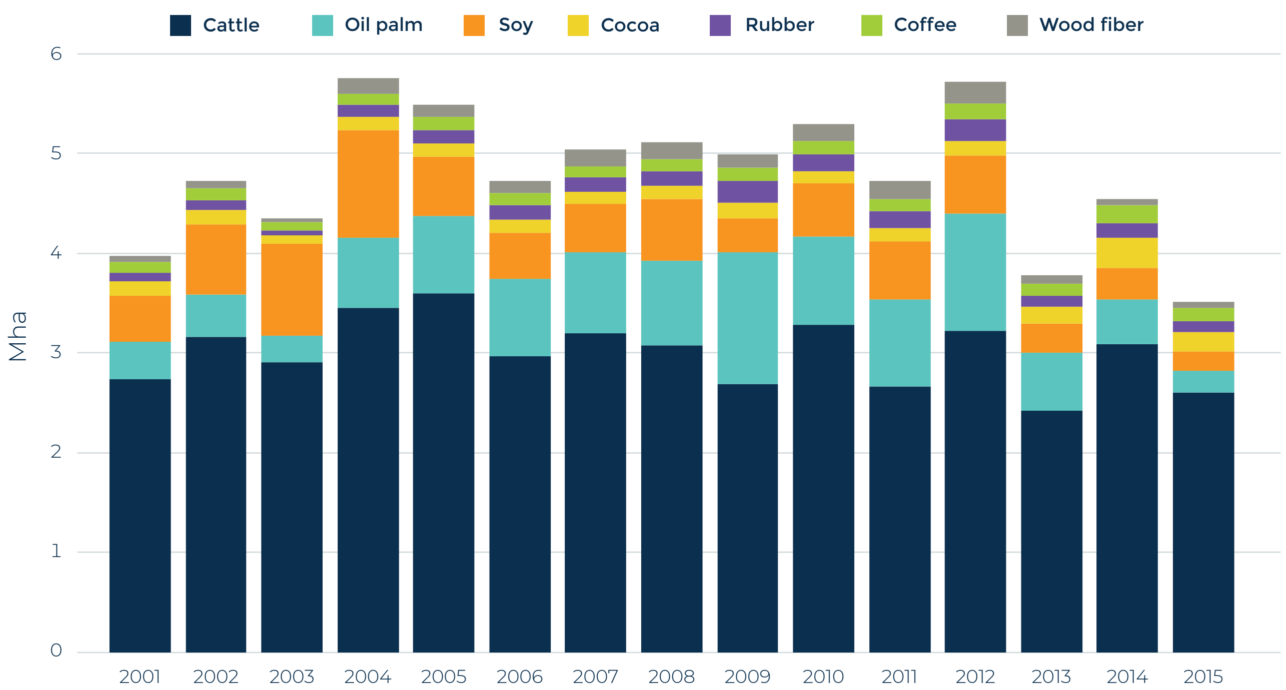
Securing Indigenous land tenure

Slowing deforestation will entail continuing to conserve the world's remaining areas of intact forests, at least 36 percent of which are located within Indigenous lands (Fa et al. 2020). Numerous studies have shown that Indigenous territories in the Amazon significantly reduce deforestation rates, in some cases as well as or better than strictly protected areas (Nolte et al. 2013; Ding et al. 2016; Schleicher et al. 2017; Baragwanath and Bayi 2020). Securing Indigenous tenure in forested lands and building capacity for Indigenous Peoples to manage existing forests are low-cost investments with significant potential for carbon mitigation and reduced deforestation, in addition to social and human rights benefits (Ding et al. 2016; Slough et al. 2021).

Improving forest monitoring

Forest monitoring is an important tool to understand where deforestation is happening in order to slow it and understand the effectiveness of the above interventions. The past two decades have seen major advancements in monitoring, at the global scale and within individual countries, with monitoring occurring operationally on annual and up to daily scales (Petersen et al. 2018). Several studies have

FIGURE 56. Forest area replaced by commodity production



Note: Mha = million hectares
Source: WRI (2021a).

shown that the use of near-real-time forest monitoring products can be successful in reducing deforestation (Assunção et al. 2013; Weisse et al. 2019; Slough et al. 2021; Moffette et al. 2021). Forest monitoring is also a critical component of results-based payments.

LAND INDICATOR 2:
Reforestation

Targets: Reforestation, as measured by gross tree cover gain,[73] occurs across a total of 259 million hectares by 2030, reaching 678 million hectares by 2050, relative to 2018.[74]

Reforestation[75] is not a substitute for protecting forests, particularly the world's remaining humid tropical primary forests. However, limiting global temperature rise to 1.5°C will require both halting deforestation and regrowing forests to remove carbon from the atmosphere. Many IPCC pathways with no or limited overshoot of 1.5°C rely on large-scale reforestation, with some calling for global forest cover to expand by upward of 950 Mha by 2050 relative to 2010 (IPCC 2018). Yet reforesting such vast areas will likely prove difficult as global population growth and rising incomes intensify competition over land for food, feed, fiber, and fuel, as well as for cities and other infrastructure. When considering biodiversity, food security, and fiber production safeguards, and excluding areas in which tree planting could unintentionally increase warming, Griscom et al. (2017) estimate a total maximum reforestation potential of 678 Mha globally (an area more than twice the size of India).[76] Regrowing forests across this area, while feeding a population of nearly 10 billion people, is theoretically possible provided that sustainable intensification of ruminant meat production and dietary shifts toward plant-based foods release millions of hectares of existing grazing lands (see Agriculture Targets 3 and 6).

Countries have already committed to restoring forest cover across 349 Mha within their NDCs and under the Bonn Challenge, which includes regional initiatives like the African Forest Landscape Restoration Initiative (AFR100) and Latin America's Initiative 20×20 (Figure 57) (Cook-Patton et al. 2020). Yet the limited data available show that gross tree cover gain increased by an average of just 6.7 Mha per year from 2000 to 2012, with the world gaining a total of 80.6 Mha over that 12-year period (GFW 2021d). A systematic review of the literature suggests that a fraction of these recent increases in tree cover were made within historically forested landscapes—just 20.5 Mha were reforested from 2000 to 2019. Additional tree cover gains likely occurred across agricultural lands (Box 7) or within

FIGURE 57. Targets and pledges compared to actual reforestation

Note: FLR = forest landscape restoration; Mha = million hectares; NDCs = nationally determined contributions.

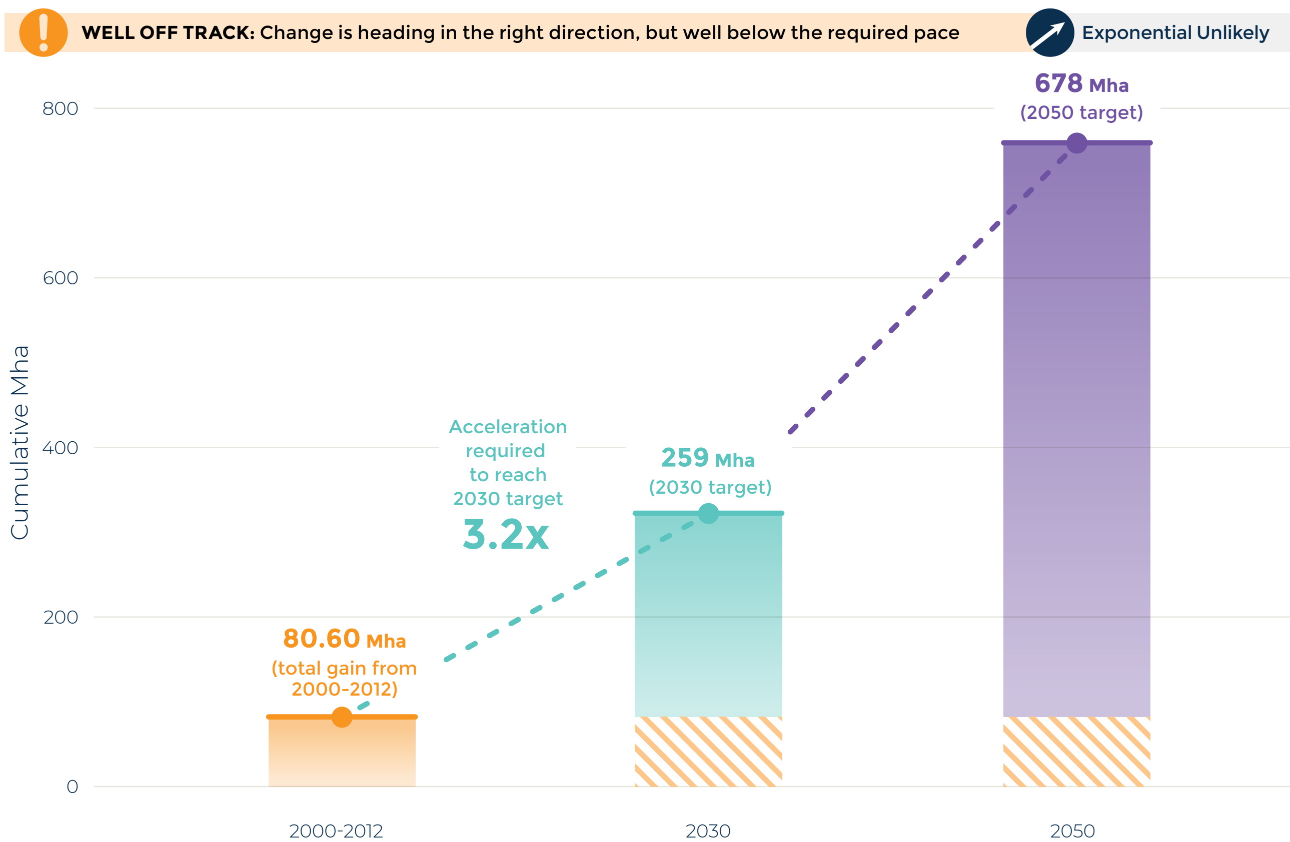
Source: GFW (2021d); Cook-Patton et al. (2020); Roe et al. (2019); Griscom et al. (2017).

BOX 7. The importance of trees outside forests

Trees outside the world's forests—those growing across farmlands, throughout cities, and alongside rivers and roads—also have a critical role to play in limiting global temperature rise to 1.5°C, especially as competing pressures on land for food, fiber, livestock feed, and urban infrastructure intensify (Roe et al. 2019; IPCC 2019). Through agroforestry systems, such as farmer-managed natural regeneration, alley cropping, and windbreaks, farmers could integrate trees into an estimated 608 million hectares of croplands worldwide without reducing yields or harming biodiversity—a climate mitigation strategy that could remove 1.0 gigatonnes (billion tonnes) of carbon dioxide per year (Griscom et al. 2017). Done well, planting trees across these agricultural landscapes can also deliver a wide range of co-benefits to farmers and rural communities, including diversifying livelihoods, increasing agricultural productivity, improving croplands' resilience to climate impacts, and stabilizing soils to combat land desertification and degradation (IPCC 2019).

Yet limited data on trees outside forests constrain efforts to set and track progress toward climate mitigation targets. The world's current global-scale forest monitoring systems rely on medium-resolution satellite data, from which trees outside forests are often difficult to identify. It is difficult, for instance, to detect trees under five meters tall and in areas where the initial cover is less than 10 percent per pixel. While this indicator may capture some dense agroforestry systems, such as shaded coffee, it generally does not allow scientists to measure more dispersed or shorter trees. Similarly, national governments' forest resource assessments often exclude trees outside forests. For example, in its global estimate of trees outside forests, the Food and Agriculture Organization of the United Nations (FAO) aggregates data submitted by national governments, but less than half of countries reported this information during FAO's most recent assessment in 2020 (WRI 2021e). Due to these data limitations, this report does not establish a target focused on increasing trees outside of forests, despite their significance in mitigating climate change and delivering important benefits to local communities.

FIGURE 58. Historical progress toward 2030 and 2050 targets for reforestation



Note: Mha = million hectares. The average historical rate of change is calculated over 12 years rather than 5 years due to data availability; 2030 and 2050 targets are defined against a baseline year (2018). Due to limited data availability, we use the most recently available data point (80.6 Mha in 2018) to estimate the indicator's value in 2018. We also use the average annual rate of change across the most recently available time period (2000–2012) to estimate the annual rate of change during the baseline year (2018), and we calculate the future rate of change required to reach the 2030 target against this estimated baseline year rather than the most recent year of data.

Sources: Historical data from GFW (2021d); 2030 and 2050 targets from authors' analysis of Griscom et al. (2017); Roe et al. (2019); Cook-Patton et al. (2020).

other natural landscapes with no recent history of forest cover (NYDF Assessment Partners 2019). Reforesting 678 Mha by 2050 will instead require gross tree cover gains of 21.6 Mha per year from 2018 to 2030 and 21 Mha from 2030 to 2050—rates that are more than three times faster than the historical pace of change (Figure 58).

LAND INDICATOR 3:
Rate of carbon removal from reforestation

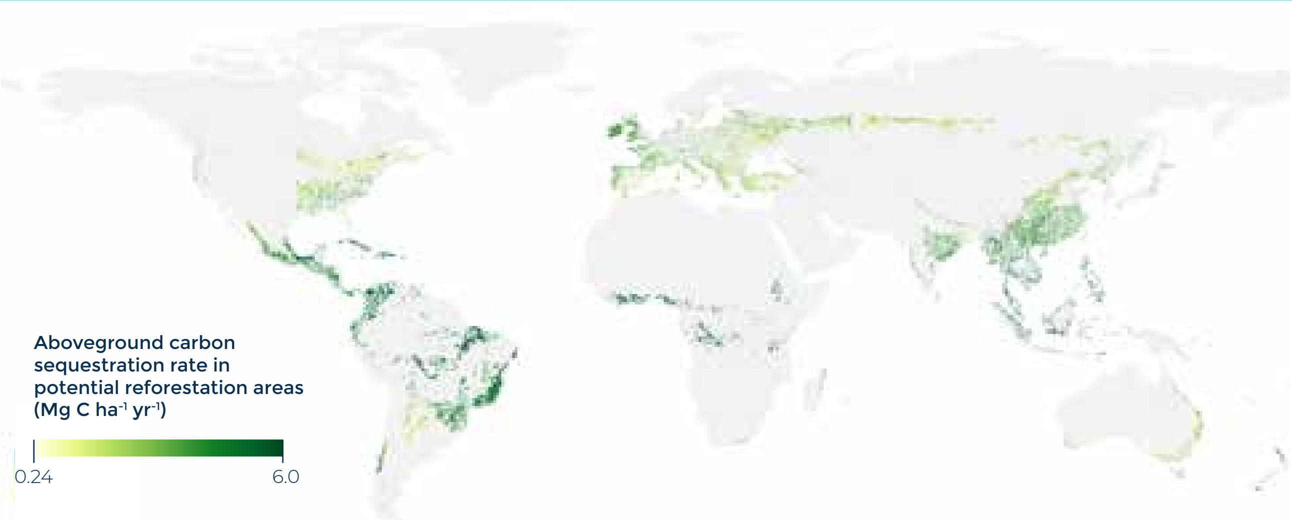
Target: Reforested lands begin removing 3.0 $GtCO_2$ annually by 2030 and 7.8 $GtCO_2$ annually by 2050.[77]

The IPCC finds that all pathways limiting global warming to 1.5°C with no or limited overshoot rely on carbon removal. Recent analysis suggests that achieving this temperature goal will likely entail removing 8–10 $GtCO_2$ annually by midcentury and up to 20 $GtCO_2$ per year by 2100 through both natural and technological CDR (IPCC 2018c; UNEP 2017; National Academies of Sciences, Engineering, and Medicine 2019). When compared to technological CDR approaches, such as direct air capture or mineralization (see Technological Carbon Removal Indicator 1), increasing forest cover is currently a more affordable and readily available approach that, done right, can also deliver significant climate resilience, biodiversity, and sustainable development co-benefits (UNEP 2017).

Reforesting 259 Mha could remove 3.0 $GtCO_2$ annually by 2030, which Roe et al. (2019) estimate is needed to help limit global temperature rise to 1.5°C (Griscom et al. 2017; Cook-Patton et al. 2020). Additional forest cover gain across 419 Mha (678 Mha in total) may be required by 2050 should technological CDR strategies encounter challenges during scale-up or delays in reducing emissions across other key sectors (see Power, Buildings, Industry, Transport, and Agriculture Targets) increase the magnitude of temperature overshoot beyond 1.5°C.[78] Reforesting 678 Mha (see potential reforestation area and variations in aboveground carbon sequestration rates in Figure 59) could remove an estimated 7.8 $GtCO_2$ per year by 2050—more than the combined emissions of the United States and Japan in 2018 (Griscom et al. 2017; Cook-Patton et al. 2020; ClimateWatch 2021)—provided that changes in food production and consumption also reduce agricultural land demand accordingly (see Agriculture Targets 2–6). Reaching both targets entails the removal of an additional 0.25 $GtCO_2$ annually through 2030 and 0.24 $GtCO_2$ annually from 2030 to 2050—rates of change more than quadruple the historical pace of progress (Figure 60).

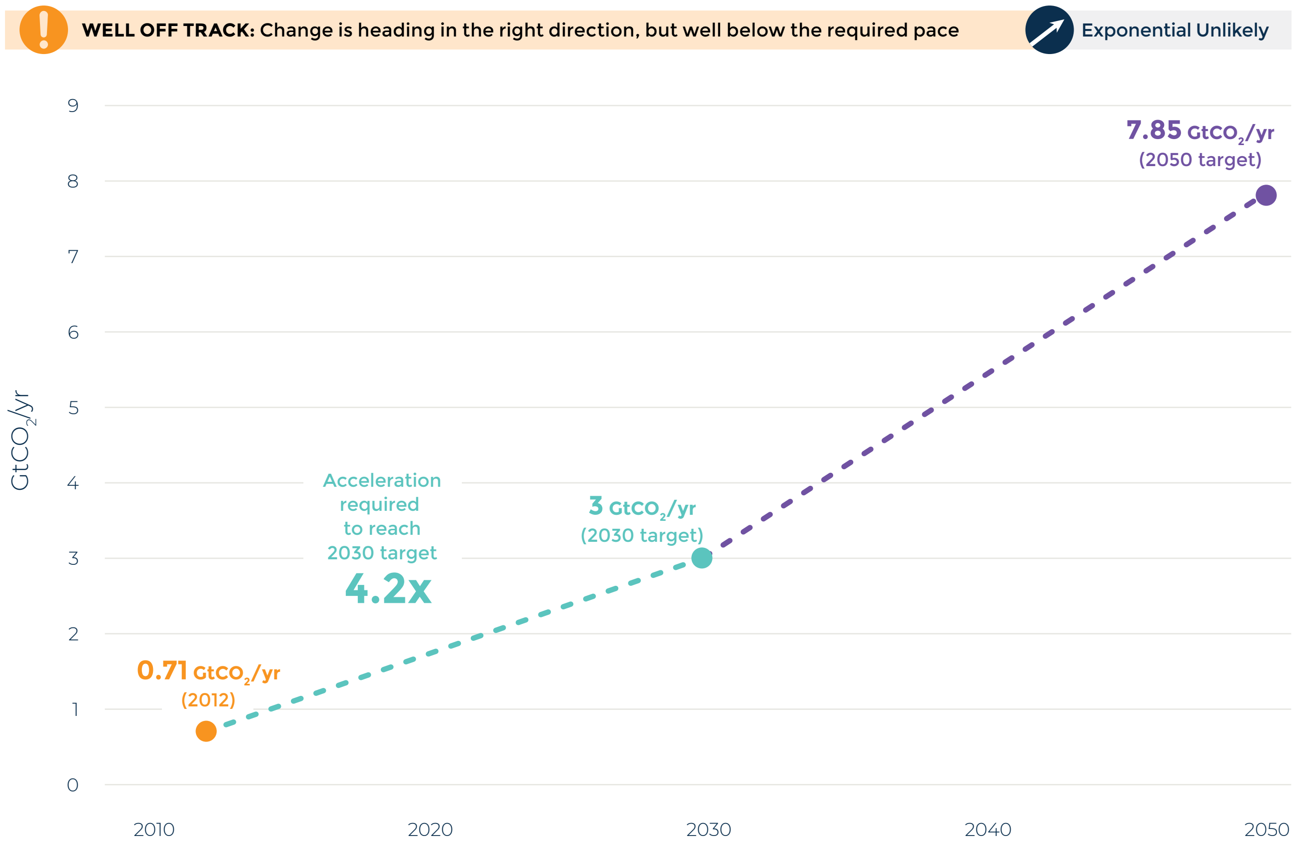
But carbon sequestration rates from reforestation will not continue indefinitely; eventually, they will saturate.

FIGURE 59. Map of aboveground carbon sequestration rates across the potential reforestation area of 678 million hectares



Note: MgC ha-1 yr-1 = megagram (tonne) of carbon per hectare per year. This map provides one potential roadmap for reforesting 678 million hectares and highlights where aboveground carbon sequestration gains are highest (dark green).
Source: Cook-Patton et al. (2020).

FIGURE 60. **Historical progress toward 2030 and 2050 targets for the rate of carbon removal from reforestation**



Note: $GtCO_2$ = gigatonnes (billion tonnes) of carbon dioxide.

The average historical rate of change is calculated over 12 years rather than 5 years, and only the carbon sequestration rate for 2012 is shown, due to data limitations; 2030 and 2050 targets are defined against a baseline year (2018). Due to limited data availability, we use the average annual rate of change across the most recently available time period (2000–2012) to estimate the annual rate of change during the baseline year (2018), and we calculate the future rate of change required to reach the 2030 target against this estimated baseline year rather than the most recent year of data.

Sources: Historical data from GFW (2021d); Cook-Patton et al. (2020); 2030 and 2050 targets from authors' analysis of Griscom et al. (2017); Roe et al. (2019); Cook-Patton et al. (2020).

Also, as with all land-based CDR strategies, the carbon stored within forests remains vulnerable to reversal, as wildfires or clear-cutting trees for farmlands would release sequestered carbon back into the atmosphere. Protecting these ecosystems from such disturbances will depend partly on their ability to support local livelihoods and ecological functions, so that they are valued by nearby communities rather than perceived as carbon sinks created solely to mitigate global emissions.

Enablers of climate action

Despite their tremendous benefits, reforestation efforts still encounter a wide range of political and economic barriers in many countries. Incentives to degrade or clear forests still outweigh those to restore them; insecure land rights prevent those charged with reestablishing trees from accruing the benefits of their labor; weak institutions struggle to implement reforestation commitments; failure to meaningfully engage local communities threatens long-term success; and limited finance constrains forest recovery efforts (Chaturvedi et al. 2019; NYDF Assessment Partners 2019; Hanson et al. 2015; FAO and UNEP 2020; Meyfroidt and Lambin 2011). But analyses of past instances of successful forest landscape restoration[79]—a process that includes reforestation, as well as increasing tree cover across agricultural lands or in ecosystems with naturally occurring trees—indicate that supportive policies, strong institutions, engagement with local communities, and readily available finance can help overcome these obstacles.

Adopting policies to help reduce competing pressures on land that prevent reforestation

Past forest restoration experiences suggest that decision-makers should not only establish national reforestation commitments but also translate these pledges into policies that reduce competing demands

for degraded forestland (Hanson et al. 2015). Measures designed to sustainably intensify agricultural production, such as reforming perverse agricultural subsidies or incentivizing the adoption of more efficient technologies, can help reduce many of these pressures on forested areas, as well as liberate farmland for forest restoration (Searchinger et al. 2020). Productivity increases, for instance, have helped enable significant forest regrowth across Europe and the United States since the 1990s (Chaturvedi et al. 2019; Hanson et al. 2015). But to ensure that these yield gains do not trigger local rebound effects,[80] countries should pair efforts to sustainably intensify agricultural productivity with policies that prevent forest loss by safeguarding Indigenous lands, establishing protected areas, and placing moratoriums on the conversion of forests into agricultural lands. To complement such actions undertaken in producer countries, consumer nations can enact policies to lower consumption of land-intensive agricultural commodities (see Agriculture Target 6), and all countries can reduce food loss and waste (see Agriculture Targets 4 and 5) that unnecessarily increase agricultural land demand (Hanson et al. 2015; Chaturvedi et al. 2019; Meyfroidt and Lambin 2011; Searchinger et al. 2019; Folberth et al. 2020).

Clarifying land tenure regimes and simplifying processes to secure land rights

Following in the footsteps of Costa Rica, China, and the United States, governments can further incentivize reforestation through direct payments (e.g., payment for ecosystem service schemes), tax credits, or concessional loans. Yet the success of these measures often depends on clear, secure tenure regimes—another driver of successful forest restoration (Chaturvedi et al. 2019; FAO and UNEP 2020; Hanson et al. 2015). Insecure, ambiguous, or contested land rights discourage investments in long-term land uses, such as reforestation. Without assurances that they will accrue the benefits of forest restoration, local communities may have little incentive to invest their time, labor, and resources into reestablishing trees (Meyfroidt and Lambin 2011; Reid et al. 2017; Gregersen et al. 2011). But land tenure regimes across much of the developing world remain complex, particularly for collectively held lands, characterized by overlapping claims and expensive land rights formalization processes that impose disproportionately high burdens on Indigenous Peoples and local communities (Notess et al. 2018; RRI 2015). Clarifying land tenure regimes, as well as simplifying processes to secure land rights, could go a long way in supporting reforestation efforts.

Strengthening institutions to improve enforcement

Over 60 countries have made forest restoration commitments under the Bonn Challenge, and nearly 130 nations included forest restoration-aligned activities in their first NDCs (IUCN 2020). While this immense showing of political will does represent a critical step forward, it has largely failed to spur action—just 26.7 Mha of the Bonn Challenge's 2020 goal of 150 Mha have been restored (NYDF Assessment Partners 2019). In some countries, corruption impedes forest restoration, while in others, resource constraints limit officials' ability to deliver ambitious pledges (FAO and UNEP 2020; Chaturvedi et al. 2019). Policy fragmentation across agencies and administrative scales can also hinder implementation, creating confusion among ministries that govern forests, incoherence in regulations, or even conflict among officials. Past successful forest restoration experiences underscore the importance of strengthening institutions to overcome these obstacles and improve enforcement (Hanson et al. 2015; FAO and UNEP 2020; Chaturvedi et al. 2019).

Meaningfully engaging communities in reforestation decision-making processes

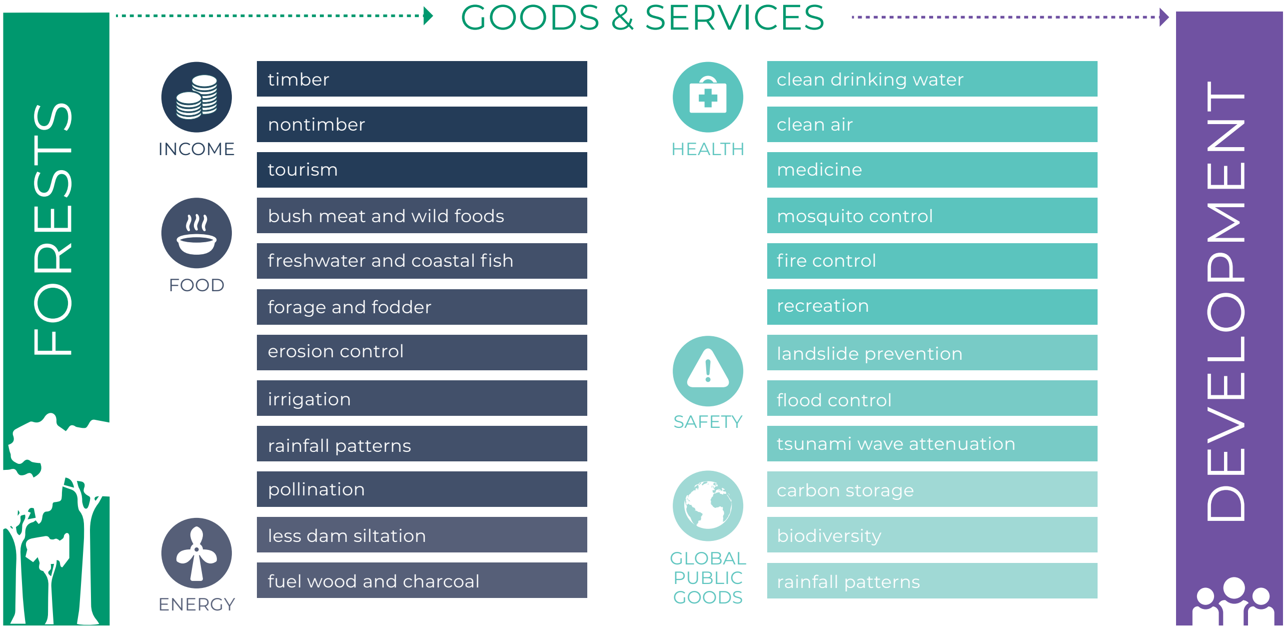
Ensuring that forest restoration initiatives deliver economic, environmental, and/or cultural benefits to local communities (Figure 61) and proactively communicating those benefits have underpinned past reforestation successes. Inclusive, participatory decision-making processes are another related hallmark of effective forest restoration. Done well, these forums enable local communities to actively shape reforestation goals and ensure that they address their priorities, such as alleviating poverty. This can increase local communities' investment in forest restoration, as well as their willingness to continue to care for reestablished trees after projects end (Hanson et al. 2015; FAO and UNEP 2020; Chaturvedi et al. 2019; Reid et al. 2017; Höhl et al. 2020). Long-term success also depends on the transfer of knowledge, technologies, and practices to those implementing and monitoring forest restoration. These efforts to build local capacity can take many forms—farmer-to-farmer peer networks, radio broadcasts, or trainings, for example—and should be bidirectional (Hanson et al. 2015).

Increasing public and private finance for reforestation

Readily available, accessible finance is a prerequisite for forest restoration. Achieving existing targets—restoring 350 Mha by 2030—may require up to $67 billion per year (FAO and UNCCD 2015; NCE 2018). Yet globally, public and private climate finance directed toward agriculture, forestry, land use, and natural resource management reached an annual average of just $18 billion in 2017 and 2018, with only a fraction of that amount going to restoration (Buchner et al. 2019). National public finance for forest restoration is especially limited in many developing countries, where revenues for such initiatives are often confined to the relatively small budgets of environmental ministries. These same states have also struggled to fill forest restoration funding gaps with private sector finance. Underdeveloped capital markets constrain access to loans; private sector lenders tend to perceive restoration investments as too risky; and tree-planting projects are often too small to attract funding from institutional investors (Ding et al. 2017; Chaturvedi et al. 2019).

Increasing subsidies for forest restoration, redirecting even a small fraction of agricultural subsidies (currently valued

FIGURE 61. The benefits of healthy forests to development



Sources: Chaturvedi et al. (2019); Seymour and Busch (2016).

at $600 billion annually), and integrating forest restoration initiatives into the budgets of better-funded ministries (e.g., agriculture or energy) could increase public funding for restoration, while constructing mechanisms that lower risks (e.g., tax credits, insurance guarantees, or first-loss capital structures) could help attract private sector capital. Similarly, intermediary financial mechanisms that bundle smaller forest restoration projects together could also make these initiatives more attractive to investors (Ding et al. 2017; Chaturvedi et al. 2019; Löfqvist and Ghazoul 2019). Increasing access to microfinance, as well as smaller-scale grants, could also help ensure that restoration finance actually reaches those implementing tree-planting projects (FAO and UNCCD 2015).

LAND INDICATOR 4:
Peatlands conversion rate

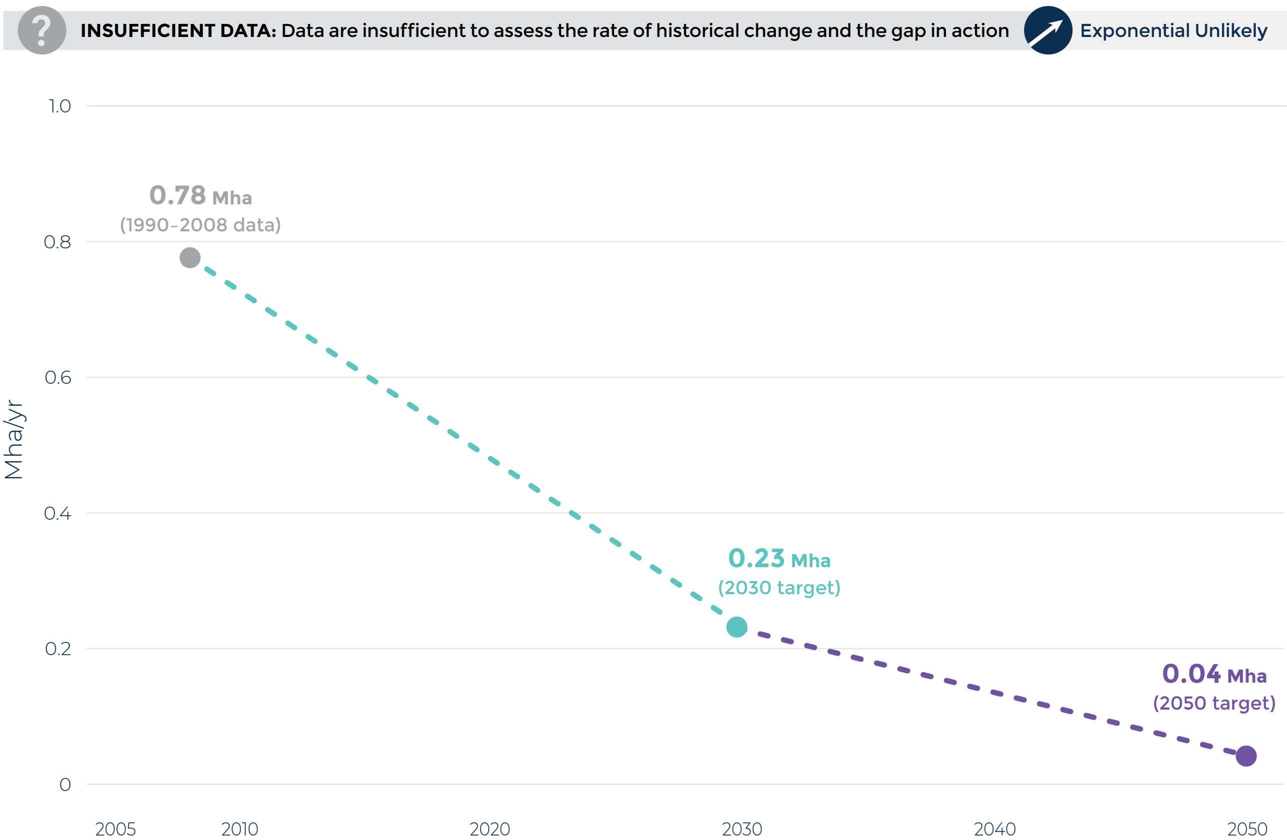
Targets: The degradation and destruction of peatlands drops 70 percent by 2030 and 95 percent by 2050, relative to 2018.

Peatlands are a type of wetland made up of accumulated organic matter that serve as a significant carbon sink. While peatlands cover only 3 percent of the global land surface across boreal, temperate, and tropical climates (roughly 380–460 Mha), they store more carbon than the global forest biomass, around 500–600 billion tonnes (Humpenöder et al. 2020; IUCN 2021). In terms of annual emissions flux, intact peatlands produce methane emissions due to decomposition of organic matter in anaerobic conditions, but they are still a moderate carbon sink, storing more carbon each year (Humpenöder et al. 2020). Peatlands also provide a number of important ecosystem services, like biodiversity and water regulation, that make them critical for more than carbon storage (Joosten et al. 2012).

An estimated 15 percent of peatlands have been drained for agriculture, plantation forestry, and other uses, with the most recent changes occurring in tropical regions (Griscom et al. 2017). Unlike emissions from deforestation, once peatlands are drained, they can emit 60–100 tCO_2/hectare each year for decades to centuries, as successive layers of organic matter are oxidized (Joosten 2010; Joosten et al. 2012). Globally, drained peatlands emit an estimated 1.3–1.9 $GtCO_2$/yr, or around 5 percent of global CO_2 emissions (Humpenöder et al. 2020). Dried peatlands are also prone to fires, which can lead to additional emissions.

Around 10 percent of peatlands are in the tropics, but these account for more than 80 percent of emissions associated with peatland degradation (Roe et al. 2019). While most peatland drainage in temperate and boreal regions happened centuries ago (Conchedda and Tubiello 2020),

FIGURE 62. Historical progress toward 2030 and 2050 targets for peatlands conversion rate



Note: Mha = million hectares. 2030 and 2050 targets are defined against a baseline year (2018). Due to limited data availability, we use the most recently available annual average (0.78 Mha of peatlands lost per year from 1990-2008) to estimate the indicator's value in 2018. Indicator status and acceleration factor cannot be calculated due to lack of comprehensive time series data for the historical rate of peatlands conversion (the target is a reduced rate of change, so we need to know not only the historical rate of change, but whether that rate is increasing or decreasing over time, for which there are insufficient data).
Sources: For historical data, Griscom et al. (2017); for targets, Roe et al. (2019).

rising temperatures are now causing thawing and burning of permafrost, a type of peatland, which is releasing significant emissions, particularly in Russia (Patel 2020).

Protecting peatlands by keeping them wet is an effective way to prevent future increases in emissions and retain the ecosystem services peatlands provide (peatlands that are drained for agriculture become sources of CO_2 emissions). Because of their significant stores of carbon and the fact that recovering lost carbon storage could take centuries, protecting peatlands is critical to staying within our carbon budget (Goldstein et al. 2020).

While some data are available on the net change in peatland area over time, as with tree loss and tree restoration, it can be helpful to look at peatlands conversion and restoration separately. The most recent data available for peatlands conversion include a cumulative value for 1990–2008, or an average annual conversion rate of 0.78 Mha/yr across boreal, temperate, and tropical peatlands (Griscom et al. 2017). Nearly half of degraded peatlands are in the tropics, and more than one-third of peatlands are in Indonesia (EIU 2020). The degradation of peatlands, which is driven by demand for palm oil and pulpwood, as well as for other agricultural uses, needs to slow significantly for the world to be on track—this would mean reducing peatland degradation 70 percent by 2030 and 95 percent by 2050 (Figure 62). The maximum mitigation potential of this type of effort is estimated to be 0.7 $GtCO_2$/yr, about 4.7 percent of the total mitigation needed in the land sector (Griscom et al. 2017; Roe et al. 2019).

LAND INDICATOR 5:
Peatlands restoration

Targets: Worldwide, 22 Mha of peatlands are restored by 2030, reaching 46 Mha by 2050, relative to 2018.

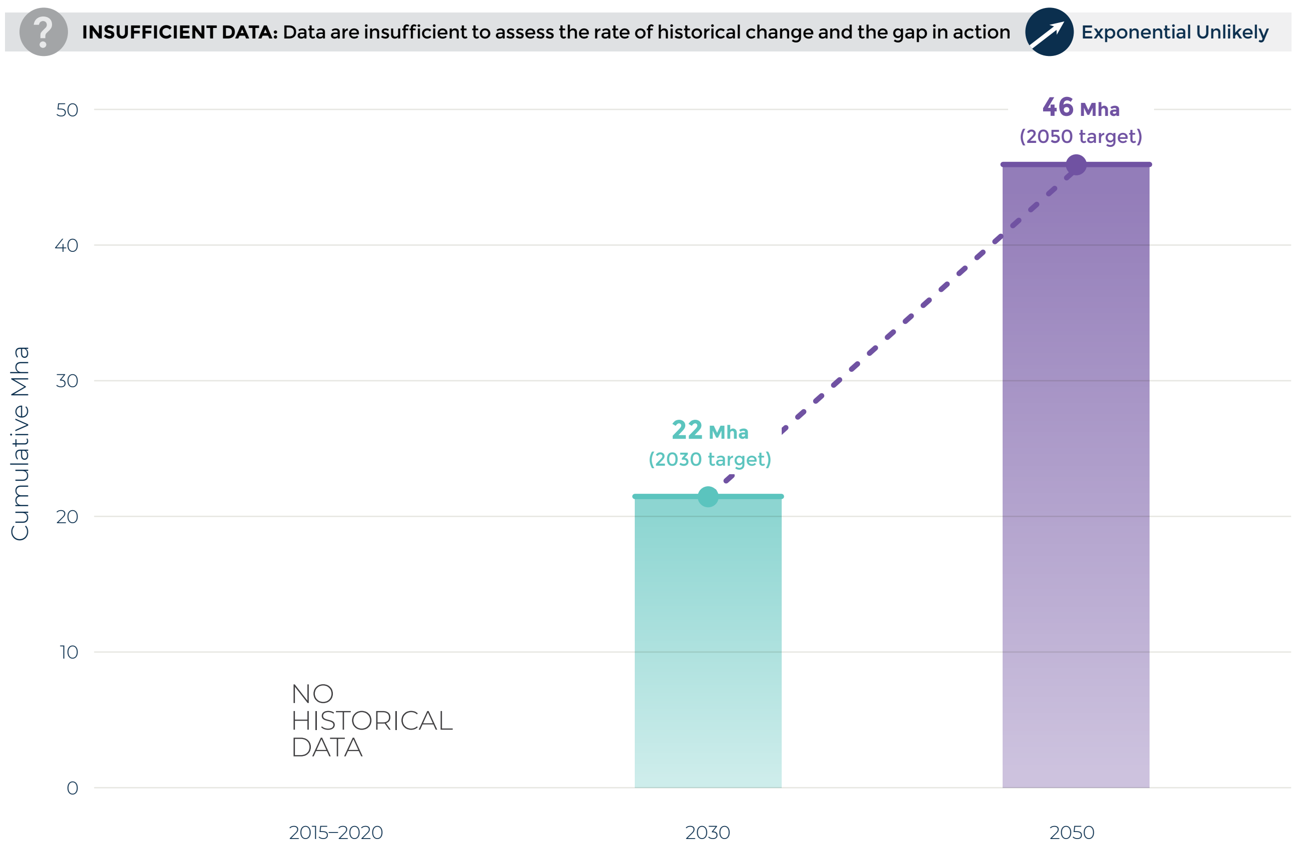
Although protection of existing peatlands is the highest priority, depending on how peatlands are degraded (e.g., drainage, burning, cutting, grazing), restoration may be possible to varying extents. If carbon is removed or destroyed through removing peat, for example, the carbon is irrecoverable on relevant timescales. However, if peatlands are drained, they may be rewetted to prevent further emissions and subsidence, and other restoration activities can help restore the original hydrology of the site (International Peatland Society 2021). If peatlands targeted for restoration are being used for agriculture, that lost food production will need to be made up elsewhere, ideally through yield increases so as not to just transfer land conversion and associated GHG emissions to another location.

Peatlands restoration across 22 Mha (roughly the area of Guyana) is estimated to be needed by 2030 to align with global climate goals and would sequester 0.4 $GtCO_2e$ per year (Griscom et al. 2017; Roe et al. 2019) (Figure 63). The maximum potential for peatlands restoration is estimated to be an additional 24 Mha (46 Mha total, or roughly the area of Papua New Guinea), which would provide an additional 0.4 $GtCO_2e$ annually in carbon sequestration (0.8 $GtCO_2e$ pear year by 2050 across the 46 Mha) (Griscom et al. 2017; Roe et al. 2019). If this were accomplished by 2050, it would provide continuous emissions benefits (as drained peatland would otherwise continue to produce emissions for decades) toward the 1.5°C temperature goal.

Enablers of climate action

Degradation and destruction of peatlands, particularly in the tropics, happens through drainage and sometimes fire that is driven by demand for agricultural products, mainly palm oil and pulpwood. In countries like Indonesia and Malaysia, which have seen the highest recent rates of peatland drainage, peatlands are drained to expand land availability for cultivation (Conchedda and Tubiello 2020; Harris and Sargent 2016). Key barriers to accelerated action on protection of and restoration of lost peatlands include lack of sufficient data, lack of national policies (and in some cases enforcement of policies that do exist), insufficient finance, and high demand for commodities like palm oil that can be cultivated in unsustainable ways.

FIGURE 63. Historical progress toward 2030 and 2050 targets for peatlands restoration



Note: Mha = million hectares. Indicator status and acceleration factor cannot be calculated due to lack of time series data for the historical rate of peatlands restoration.
Source: For targets, Roe et al. (2019).

Improving data availability

Consistent, comprehensive, and updated data on peatland extent and change over time (as well as emissions impacts) are scarce, which makes managing existing peatlands and preventing degradation difficult (Xu et al. 2018). Data availability is constrained: there are different definitions of what counts as "peatland" in different places; maps are often out of date and have coarse spatial resolution (in part because peatlands cannot be identified in satellite imagery); maps often don't include information on peat thickness, which is critical to understanding where priority conservation areas should be; and in some cases the peatland itself is not well-defined (Hamzah and Juliane 2016; Xu et al. 2018). Without accurate maps, conservation and restoration efforts are less effective. A recent meta-analysis of peatland distribution data shows peatland extent based on existing knowledge (Figure 64) (Xu et al. 2018). Other efforts like Indonesia's Peat Prize are working toward improved data availability (Packard Foundation 2018).

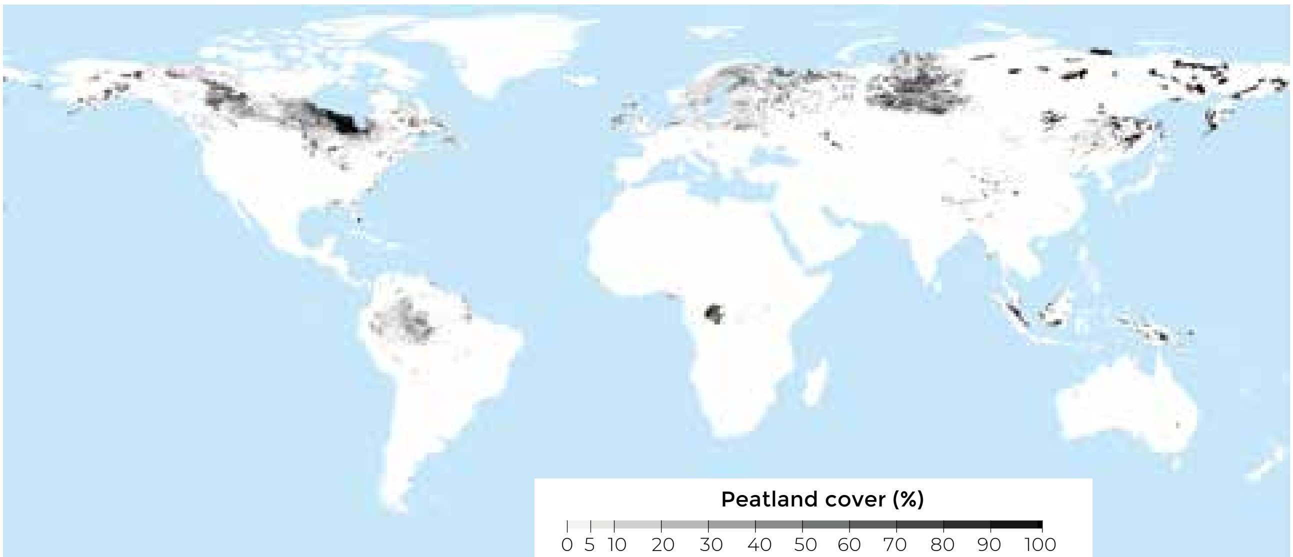
Adopting policies to protect and restore peatlands

Policies that protect existing peatlands are needed, including forbidding the conversion of peatland for cultivation of palm oil or logging, along with better enforcement. In 2015, Indonesia experienced particularly damaging fires across 2.6 Mha, one-third of which occurred on peatlands. The fires contributed to 42 percent of the country's emissions that year and cost the economy $16 billion (Hamzah and Juliane 2016; EIU 2020). After the fires the Indonesian government banned the use of fire in clearing peatlands, created a Peatlands Restoration Agency, and pledged to restore 2 Mha of peatlands by 2020 (UNEP 2018). A four-year extension was granted in 2020 to reach this restoration goal after delays caused by overlapping legal authorities across government agencies and data resolution that was too low (Astuti et al. 2020).

Reducing commodity production impact on peatlands

Peatlands have been drained for agricultural production, in particular palm oil, as well as pulpwood production from acacia trees. Palm oil is used in a number of consumer products, to cook food, and in biodiesel, and acacia feeds nearby pulp and paper mills. Both can be grown in areas that were forested, but as fertile land runs out, peatlands are drained for cultivation (Harris and Sargent 2016). Oil palms are up to 10 times more productive per hectare than other oil crops, which incentivizes producers to switch to growing palm rather than other oils. And acacia is fast-growing but requires deep drainage to be productive. Palm oil cultivation is driven by domestic and international demand and continues to increase—biofuel targets in the European Union and other countries have driven and continue to drive demand growth beyond what the human food supply requires (Lustgarten and Gilbertson 2018).

FIGURE 64. Global extent of peatlands based on meta-analysis of existing data sets



Source: Xu et al. (2019).

At the same time, demand for sustainably produced palm oil is growing. More than 130 companies that operate in the palm oil supply chain have made commitments to peatland protection (Supply Change 2021), and initiatives like the Roundtable on Sustainable Palm Oil (RSPO) and the Global Peatlands Initiative have been established. As the leading global certification scheme for palm oil, the RSPO brings together stakeholders across the supply chain and has developed criteria for sustainable palm oil production. While the RSPO has certified 19 percent of global production as sustainable (RSPO n.d.), a few recent studies have indicated the need for stronger enforcement of sustainability criteria (Morgans et al. 2018; Cazzolla Gatti and Velichevskaya 2020).

Scaling up finance for peatlands

Intact peatlands provide noneconomic services (i.e., public goods), while degraded peatlands can provide immediate cash flow through agricultural production or other means. For this reason government policy and funding are needed to protect and restore peatlands to ensure that short-term economic gain does not outweigh long-term benefit, including to compensate farmers and communities for not using the land and to carry out restoration activities (Searchinger et al. 2019). Aside from international development funding, financing peatlands restoration will depend on being able to monetize the benefits; for example, through cultivating native species that grow in the wet environment of intact peatlands or through carbon markets (EIU 2020).

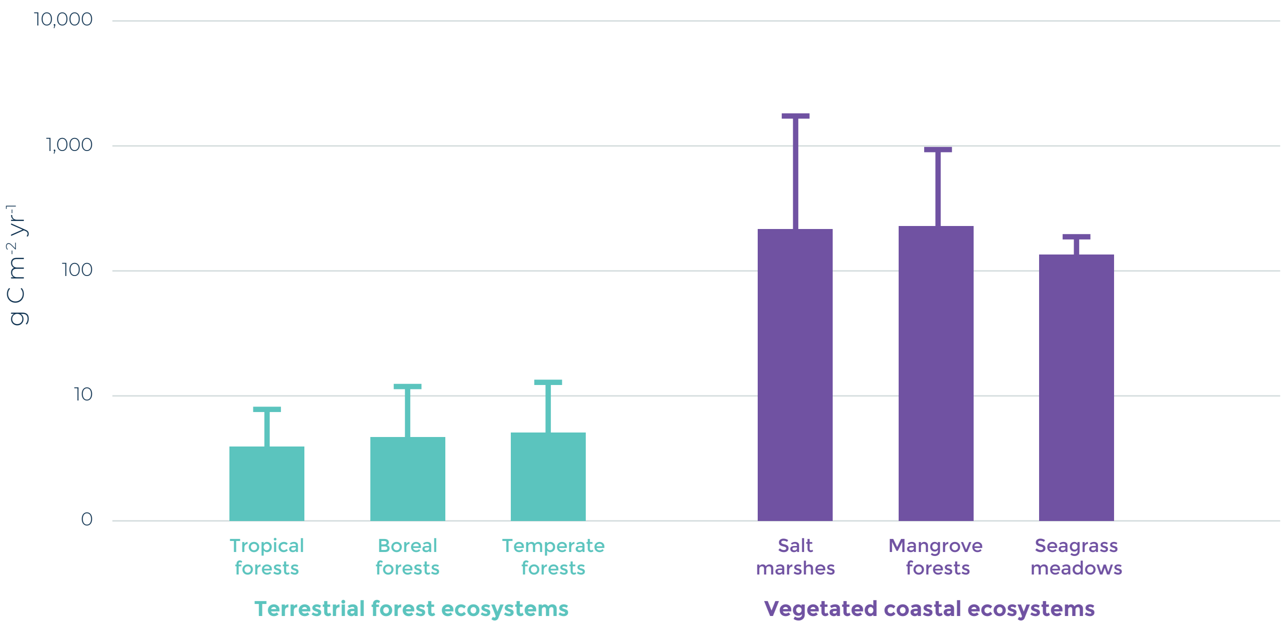
Halting peatland destruction and protecting existing peatlands will require a range of actions from different players and will be dependent on the location. However, across all areas, increasing policy ambition and enforcement will be critical, as will improving data availability and monitoring, reducing unsustainable demand, and increasing consumer education. Increasing the number of investors interested in peatlands restoration will also be critical to success.

LAND INDICATOR 6:
Coastal wetlands conversion rate

Targets: Coastal wetlands conversion falls 70 percent by 2030 and 95 percent by 2050, relative to 2018.[81]

Stretching across just 49 Mha (an area nearly the size of Spain), coastal wetlands—mangrove forests, salt marshes, and seagrass meadows[82]—are global carbon storage hotspots, with annual soil carbon burial rates that, on average, are 30–50 times greater per hectare than those of terrestrial forests (Figure 65) (Pendleton et al. 2012; Mcleod et al. 2011). Such high, long-term soil

FIGURE 65. Average long-term rates of soil carbon sequestration in tropical, temperate, and boreal forests, as well as in coastal wetlands



Note: g C m^{-2} y^{-1} = grams of carbon per square meter per year. The error bars show each ecosystem's maximum rates of accumulation
Source: Mcleod et al. (2011).

carbon sequestration rates enable these ecosystems to store between 50 percent and 90 percent of all carbon sequestered within their submerged marine sediments or waterlogged soils, where tidal inundation slows decomposition of organic matter and allows vast, relatively stable carbon stocks to accumulate over centuries to millennia (Howard et al. 2017; Pendleton et al. 2012). Global estimates of these deposits, which also include carbon stored within above- and belowground biomass, range from 111 tonnes of carbon per hectare in seagrass meadows to 265 tonnes of carbon per hectare in salt marshes to 502 tonnes of carbon per hectare in mangrove forests (Goldstein et al. 2020).[83] These figures, however, often underestimate the magnitude of coastal wetlands' carbon stocks, as many only measure carbon stored within the top meter of soil, and in some locations, these carbon-rich sediments can extend down to depths of 10 meters (Howard et al. 2017; Duarte et al. 2013; Mcleod et al. 2011; Pendleton et al. 2012).

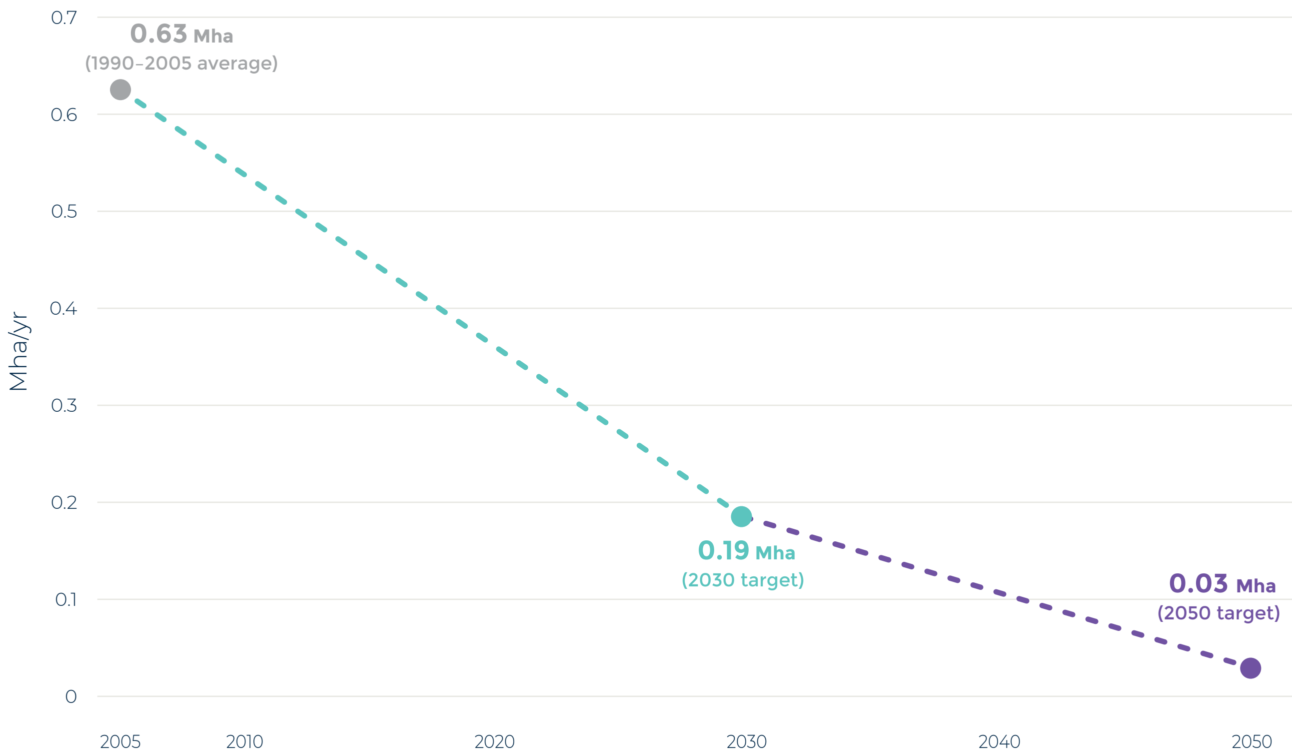
Not only does the conversion of coastal wetlands limit their capacity to sequester carbon, but for mangrove forests and salt marshes, specifically, exposure of their waterlogged soils to the air—for example, when drained to create croplands, extracted to constructed aquaculture ponds, or excavated to build port, marina, and harbor infrastructure—also oxidizes soil carbon and releases it as CO_2 (Hiraishi et al. 2014). Globally, the conversion and degradation of all three of these ecosystems emit an estimated 0.15–1.02 $GtCO_2$ annually (Pendleton et al. 2012). Once lost, this carbon can take decades to centuries to reaccumulate (Goldstein et al. 2020). Protecting these ecosystems, then, is among the most readily available mitigation strategies that can help avoid future emissions over the next three decades and play a critical role in limiting global temperature rise to 1.5°C. Roe et al. (2019) estimate that annual emissions of 0.3 $GtCO_2e$ can be avoided by reducing the conversion of coastal wetlands 70 percent by 2030 and 95 percent by 2050, relative to 2018 (Roe et al. 2019; Griscom et al. 2017).[84]

Yet, already, between 25 percent and 50 percent of these ecosystems have been lost since the 1940s. Although mangrove deforestation has slowed in recent years, the limited data available suggest that seagrass meadow degradation remains consistent and widespread, with losses still outweighing gains globally (Duarte et al. 2013; UNEP et al. 2020; Dunic et al. 2021). In aggregate, the world now loses 0.63 Mha of coastal wetlands annually (an area roughly half the size of Vanuatu) (Griscom et al. 2017).[85] Achieving these targets will require this historical rate of loss to drop sharply, reaching 0.19 Mha in 2030 and 0.03 Mha in 2050 (Figure 66).

FIGURE 66. Historical progress toward 2030 and 2050 targets for coastal wetlands conversion rate

INSUFFICIENT DATA: Data are insufficient to assess the rate of historical change and the gap in action

Exponential Unlikely



Note: Mha = million hectares. 2030 and 2050 targets are defined against a baseline year (2018). Due to limited data availability, we use the most recently available annual average (0.63 Mha of coastal wetlands lost per year from 1990-2005) to estimate the indicator's value in 2018. Griscom et al. (2017) derive this global estimate of the average annual rate of coastal wetlands conversion from Siikamäki et al. (2013) and Giri et al. (2011) for mangrove forests and Pendleton et al. (2012) for salt marshes and seagrass meadows. These global annual rates of loss were estimated over specific time periods, which varied considerably by ecosystem. For mangrove forests, the time period was 1990–2005 (as shown on the graph), but the time periods for salt marshes and seagrass meadows are significantly longer, stretching back to the 1800s in some instances. Due to this lack of consistent historical data on annual losses of coastal wetland extent, an acceleration factor could not be calculated.

Sources: The 2030 and 2050 targets are adopted from Roe et al. (2019) and Griscom et al. (2017). Historical data are taken from Griscom et al. (2017), Siikamäki et al. (2013), Giri et al. (2011), and Pendleton et al. (2012).

LAND INDICATOR 7:
Coastal wetlands restoration

Targets: A total of 29 Mha of coastal wetlands are restored by 2050, reaching 7 Mha by 2030, relative to 2018.[86]

Restoring coastal wetlands cannot replace efforts to protect intact mangrove forests, salt marshes, and seagrass meadows. Rather, both strategies will be needed to achieve the goals of the Paris Agreement. Reestablishing these ecosystems not only enhances their ability to sequester carbon but may also reduce GHGs that they would otherwise continue to release after certain disturbances (e.g., drainage). Mangrove forests and salt marshes, for example, can emit CO_2 and methane for decades after they have been degraded and, depending on the intensity of the disturbance, can shift from net carbon sinks to sources (Crooks et al. 2011). But restoring these ecosystems, in particular by reestablishing natural hydrological regimes, can help prevent the release of GHGs and improve their capacity to store carbon (Kroeger et al. 2017; Lewis et al. 2019). Once reestablished, all coastal wetland ecosystems can accumulate soil carbon for thousands of years, because, unlike terrestrial forests, they accrete sediment vertically, building new soils atop progressively carbon-saturated layers (Mcleod et al. 2011; Crooks et al. 2011).

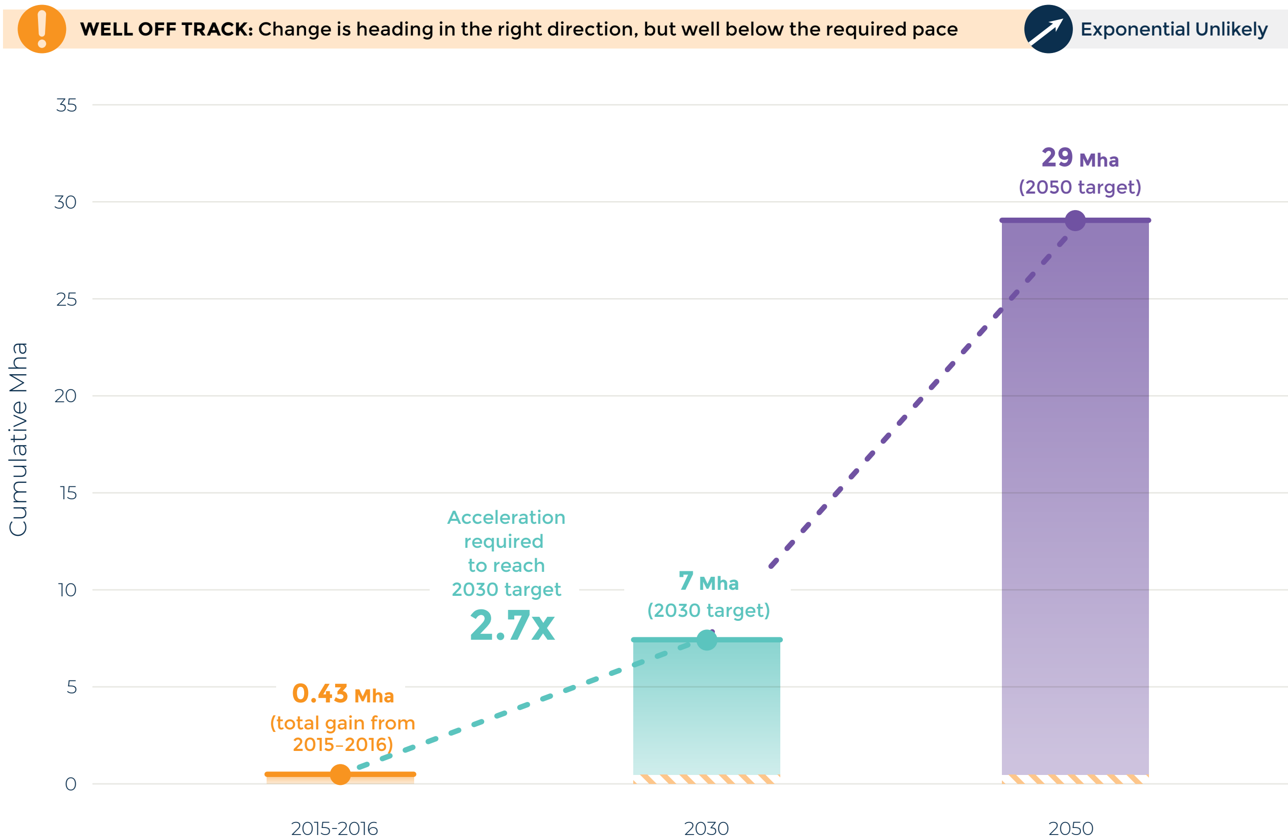
Restoring 7 Mha of coastal wetlands could enable these ecosystems to sequester 0.2 $GtCO_2$ annually by 2030, which Roe et al. (2019) suggest is required to limit global temperature rise to 1.5°C (Griscom et al. 2017). Additional restoration across 22 Mha (29 Mha in total) may be needed by 2050 should emissions reductions across other systems stall or the deployment of technological CDR approaches face delays. Recovered mangrove forests, salt marshes, and seagrass meadows across 29 Mha (an area roughly the size of Italy) could begin removing an estimated 0.8 Gt CO_2 annually by 2050, with mangrove restoration accounting for over 70 percent of this mitigation potential (Griscom et al. 2017).[87] Reaching these targets will require the restoration of 0.6 Mha per year through 2030 and 1.1 Mha per year from 2030 to 2050 (Figure 67).

Although efforts to recover coastal wetlands are increasing in number, size, and effectiveness, they remain mostly small-scale. Notable exceptions include replanting 18,000 hectares of mangroves in Vietnam and restoring 58,900 hectares of tidal marshes along the U.S. coastline (Hoegh-Guldberg et al. 2019; Buckingham and Hanson 2015). While advances in mapping methods and remote sensing techniques are improving global estimates of coastal wetland extent, particularly for mangroves, data are insufficient to assess the rate of historical change for all ecosystems (Duarte et al. 2013; Ramsar Convention on Wetlands 2018).

Enablers of change

Although political awareness of these "blue carbon" ecosystems is increasing, efforts to protect and restore coastal wetlands still face a number of challenges (Thomas et al. 2020). Across many countries, limited data constrain efforts to include these ecosystems in climate mitigation targets, competing pressures on coastal wetlands coupled with a general lack of awareness of their benefits have given rise to the perception that conversion equates to economic gain, and a substantial finance gap persists (Macreadie et al. 2019; Steven et al. 2020; Crooks et al. 2011; Duarte et al. 2008; Ramsar Convention on Wetlands 2018; Hoegh-Guldberg et al. 2019; Sumaila

FIGURE 67. Historical progress toward 2030 and 2050 targets for coastal wetlands restoration



Note: Mha = million hectares. 2030 and 2050 targets are defined against a baseline year (2018). Due to limited data availability, we use the most recently available data point (0.43 Mha in 2016) to estimate the indicator's value in 2018. Historical data shown for mangrove forest gain only, given data limitations for salt marshes and seagrass meadows, and the average historical rate of change is calculated over 2 years rather than 5 years due to data availability. Similarly, an acceleration factor is calculated for mangroves only. Also, 2030 and 2050 targets are defined against a baseline year (2018). Due to limited data availability, we use the average annual rate of change across the most recently available time period (e.g., 2015–2016) to estimate the annual rate of change during the baseline year (2018), and we calculate the future rate of change required to reach the 2030 target against this estimated baseline year rather than the most recent year of data.

Sources: Historical data from Bunting et al. (2018); 2030 and 2050 targets from Roe et al. (2019); Griscom et al. (2017).

et al. 2020). While the drivers of successful coastal wetland conservation remain complex and likely vary across contexts, the following measures can help nations surmount these obstacles.

Improving coastal wetlands data

Accurate estimates of coastal wetlands' global extent, as well as annual gains and losses in area, are prerequisites for assessing their contributions to climate change, including GHGs emitted once degraded or carbon removed when restored. Without comprehensive, consistent, and timely data, decision-makers can neither establish mitigation targets to conserve these ecosystems nor track progress toward achieving these goals (Crooks et al. 2011). Although scientists have made significant gains in using remote sensing to map mangrove forests, uncertainties remain; for example, in measuring the extent of scrub mangroves (Bunting et al. 2018; Macreadie et al. 2019). Worldwide distribution of salt marshes is also poorly understood, with estimates ranging from 2.2 to 40 Mha (Pendleton et al. 2012). To date, these ecosystems have been mapped in 43 countries, representing just 14 percent of the total potential area (Macreadie et al. 2019). Available data on seagrass meadows face similar challenges of geographic bias due to uneven mapping and monitoring efforts among regions, with approximately one-tenth of the potential area suitable for this ecosystem mapped with moderate to high confidence (Macreadie et al. 2019; McKenzie et al. 2020; Jayathilake and Costello 2018).

Additional research is also needed to construct a more accurate global carbon budget for coastal wetlands, to effectively account for non-CO_2 GHG emissions in estimates of carbon sequestration rates, to better understand how climate impacts will affect carbon accumulation, and to identify management actions that will enhance carbon sequestration (Macreadie et al. 2019). Improving data across all 151 countries with coastal wetlands, as well as prioritizing these research questions within the scientific community, will prove critical to developing effective, evidence-based conservation programs, as well as to underpin efforts to include these ecosystems within national GHG inventories, establish mitigation targets within NDCs, and secure results-based payments for reducing emissions or increasing carbon removals (Northrop et al. 2021; Herr and Landis 2016; Hoegh-Guldberg et al. 2019).

Strengthening coastal wetland protection and restoration policies

Competition for land along the world's shorelines is intensifying, with coastal wetlands facing increased pressures from agriculture, aquaculture, industry, tourism, and urbanization. To protect and restore these ecosystems, governments can pair policies that limit the supply of public lands available for conversion with those that increase the costs associated with illegal degradation (Chaturvedi et al. 2019; Steven et al. 2020). Establishing, expanding, or strengthening limitations on harmful human activities within marine protected areas,[88] prohibiting coastal wetlands conversion, and recognizing that other effective conservation measures, like locally managed marine areas, can help reduce loss of these ecosystems. At the same time, strengthening institutions, ensuring policy coherence, and reducing corruption can improve enforcement (Sala and Giakoumi 2018; Gill et al. 2017; Steven et al. 2020).

To disincentivize land uses that compete with mangroves, in particular, governments can also

support "land-sparing" measures that sustainably intensify aquaculture and agriculture production, which together accounted for nearly half of global mangrove deforestation from 2000 to 2016 (Goldberg et al. 2020). Specific policies vary by context and commodity, but they broadly include using spatial planning to optimize aquaculture siting, incentivizing productivity gains through tax credits and subsidies, investing public funds in sustainable agricultural research and development, strengthening shrimp and rice pond regulations, and developing monitoring systems to reduce harmful impacts to nearby ecosystems (Searchinger et al. 2019).

Similarly, rapid urbanization along the coast has increased the opportunity costs of protecting and restoring coastal wetlands, particularly for salt marshes (Steven et al. 2020). Urban planning practices that limit the outward expansion of cities, coupled with policies that encourage residents to retreat from the shoreline, can also help relieve the pressure of competing demands on these ecosystems. For example, zoning regulations—such as establishing no-build zones, requiring setbacks from the shoreline, or allowing landowners to transfer their development rights from one "managed retreat" zone that contains coastal wetlands to another "accommodation zone"—can help shift urban development away from intertidal zones (City of Coral Gables 2016; South Florida Regional Planning Council 2013). Doing so could also enable inward mangrove forest and salt marsh migration—one process by which these ecosystems adapt to sea level rise (Kirwan et al. 2016; Schuerch et al. 2018).

Because coastal wetlands sit at the intersection of land and sea, conserving these ecosystems will also require policymakers to go beyond reducing direct habitat loss to addressing the underlying drivers of degradation—nutrient pollution, overfishing, and sediment loading in seagrass meadows (Waycott et al. 2009; Heithaus et al. 2014; Maxwell et al. 2017), as well as sea level rise, shoreline hardening (e.g., building seawalls or jetties), and declining sediment delivery due to damming rivers for mangroves and salt marshes (Crooks et al. 2011; Leo et al. 2019). Absent comprehensive actions to address these indirect drivers of coastal wetlands loss and to manage coastal wetlands holistically, even highly protected areas that limit direct human disturbances within their borders may still experience significant levels of degradation.

Raising the public's awareness of the benefits coastal wetlands provide to shoreline communities

Efforts to ensure that policymakers, the private sector, and local communities recognize the overlooked, often undervalued benefits that ecosystems provide have often underpinned the success of large-scale restoration projects (Hanson et al. 2015). Historically perceived as worthless, coastal wetlands deliver a wide range of ecosystem services that extend far beyond carbon sequestration to include improving water quality, protecting shorelines from erosion, safeguarding coastal communities from sea level rise and storm surges, and providing nursery grounds for fisheries. Site-specific economic valuations of these individual benefits range widely, from roughly $20 to $8,000 per hectare per year, while Costanza et al. (2014) estimate the global annual value of these ecosystems services to be nearly $29,000 per hectare for seagrass meadows and $194,000 per hectare for mangroves and salt marshes (Barbier et al. 2011; Costanza et al. 2014).[89]

Although recognition of these benefits is growing, particularly among policymakers, with more than 30 countries including coastal or marine nature-based solutions in their new or updated NDCs (as of June 2021), these ecosystems' contributions to human well-being, economic development, and climate change are still largely overlooked (Ramsar Convention on Wetlands 2018; Lecerf et al. 2021). Seagrass meadows, salt marshes, and mangrove forests are underrepresented in global ecosystem assessments that influence conservation policy priorities and funding, while some species of mangroves are excluded from national forest inventories that inform countrywide accounting of emissions from deforestation (Brown et al. 2021). Similarly, less media attention, a proxy for measuring levels of public awareness, has been paid to these coastal wetlands relative to more charismatic marine ecosystems like coral reefs (Duarte et al. 2008). Increasing our collective understanding of the many benefits that mangrove forests, salt marshes, and seagrass meadows provide, as well as ensuring that these benefits accrue to nearby communities and those charged with protecting and restoring these ecosystems, can help incentivize and sustain conservation efforts. In Vietnam, for example, clear benefits of mangroves, namely storm protection, food security, and livelihood diversification, helped motivate the government to reforest 18,000 hectares (Buckingham and Hanson 2015). Meaningful engagement with local communities has also proved critical to such restoration successes, particularly when inclusive, participatory decision-making processes enable those living near protected coastal wetlands or those tasked with the long-term management of these ecosystems to shape conservation goals (Hanson et al. 2015; FAO and UNEP 2020; Chaturvedi et al. 2019; Reid et al. 2017).

Increasing finance for coastal wetland protection and restoration

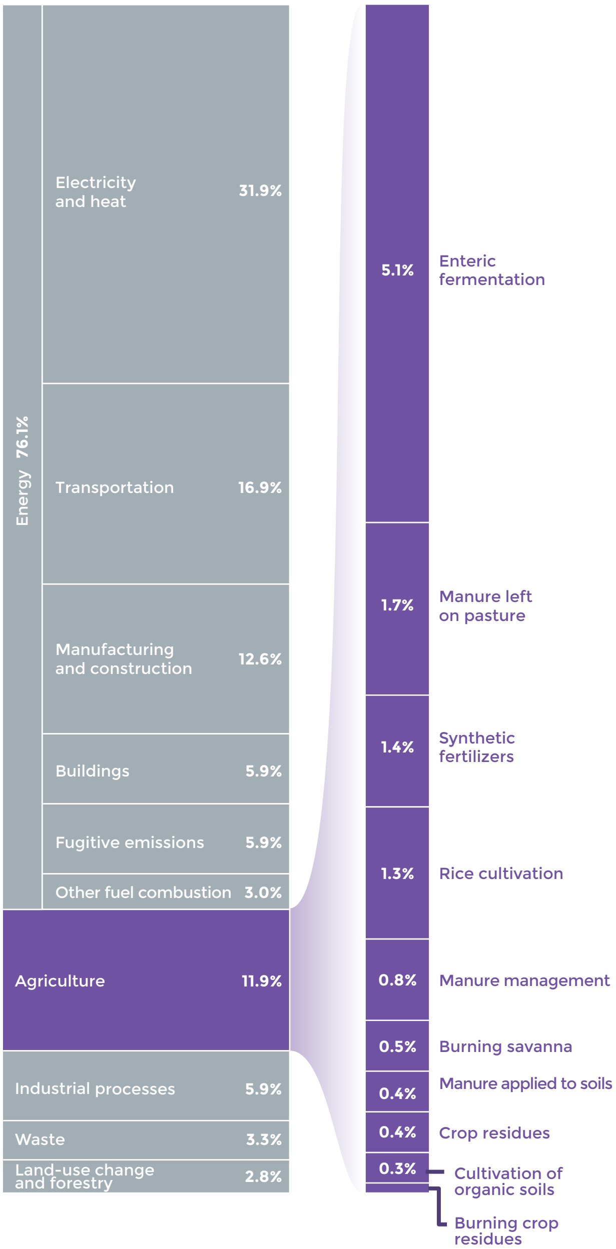
Although it varies widely across countries, the average cost of coastal wetlands restoration per hectare is relatively high, particularly when compared to forest landscape restoration—approximately $19,000 for mangroves, $67,000 for salt marshes, and $107,000 for seagrass meadows (Ding et al. 2017; Konor and Ding 2020; Bayraktarov et al. 2016). Still, the benefits of healthy, restored coastal wetlands far outweigh these high price tags. A recent cost-benefit analysis, for example, estimates that every $1 invested in mangrove restoration generates $2 in benefits. Protecting this ecosystem is even more cost-effective, with the cost-benefit ratio rising to 1:88 (Konar and Ding 2020).

Despite these significant benefits, public and private finance lag behind need. An estimated $300 billion global gap in conservation finance exists across all biomes, but the proportion of this gap that speaks specifically to the protection and restoration of mangrove forests, salt marshes, and seagrass meadows has not yet been quantified. However, analyses of existing flows to the ocean, including climate finance to coastal protection, suggest low levels of investment in these wetland ecosystems (Buchner et al. 2019; Sumaila et al. 2020). Increasing public funding for coastal wetlands—for example, by redirecting revenues from harmful fisheries subsidies that incentivize overfishing to the conservation of these ecosystems—is needed but on its own will likely not meet estimated needs. Private finance will also be required, with some experts expecting it to grow quickly, as methodologies to quantify GHG emissions reductions and carbon removals increasingly include the conservation of coastal wetlands (Jones 2021). To mobilize additional private sector funding across a wide range of sources, governments should explore new innovative approaches, including derisking private investments in coastal wetlands (e.g., through first-loss capital structures or tax credits), issuing blue bonds, or restructuring debt into funding for marine protection initiatives (Sumaila et al. 2020). Success in marshaling revenues for coastal wetlands will likely depend partially on improvements in data collection, supportive policies, and recognition of the many benefits that these ecosystems provide.

9 AGRICULTURE

The world's population will likely reach nearly 10 billion by 2050 (UN DESA 2019). Population and income growth are projected to lead to a 45 percent increase in food demand between 2017 and 2050 (Searchinger et al. 2021; FAO 2018).

FIGURE 68. Role of the agricultural sector in global greenhouse gas emissions



Note: Estimates of greenhouse gas emissions from forestry are subject to high uncertainties. Data featured in this figure are from ClimateWatch (2021), which relies on 2018 forestry emissions data from FAOSTAT. This differs from IPCC (2019), which includes older forestry emissions data from FAOSTAT, as well as data from a number of other global models, to estimate emissions from agriculture, forestry, and other land use.

Source: ClimateWatch (2021).

AND WHILE THE WORLD WORKS TO eliminate hunger—which affected between 720 million and 811 million people in 2020 (FAO et al. 2021)—the world must also strengthen the livelihoods of people working in agriculture and across food supply chains, while at the same time reducing the food system's impacts on the climate, forests (see Land Indicators 1–3), and freshwater supplies.

From 2007 to 2016, GHG emissions from agriculture and land-use change accounted for about one-quarter of global emissions annually, with agricultural production alone contributing 11.9 percent in 2018 (Figure 68) (IPCC 2019; FAO et al. 2021; ClimateWatch 2021). While reducing fossil fuel emissions remains critical for limiting warming to 1.5°C, meeting the Paris Agreement goals will also require major changes to food production and consumption (Clark et al. 2020).

With increasing global demand for food, feed, and fiber, large-scale reductions in deforestation and increases in reforestation will only be possible if the world greatly improves the efficiency of land use. This will require increasing crop yields, as well as meat and milk output per hectare of pasture, at higher than historical rates, while protecting soil health and freshwater resources. Across the board, the agricultural sector will also need to reduce emissions from each of its key sources, including from livestock, fertilizers, rice production, and energy use. At the same time, given the scope of the challenge, it will be essential to further slow the rate of growth in food and agricultural land demand by reducing food loss and waste, shifting diets away from high levels of meat (especially beef and other ruminant meat) consumption, and avoiding further expansion of bioenergy production. Taken together, a nearly 40 percent reduction in agricultural production emissions, coupled with carbon removals from large-scale reforestation (Land Indicator 3), could theoretically achieve a net-zero-emissions land sector by 2050, even while feeding a growing world population (Searchinger et al. 2019).

Across the six Agriculture Targets, three are moving in the right direction but not yet at the right speed (crop yield growth, ruminant meat productivity growth, and declining ruminant meat consumption in high-income regions). Trend data are not yet globally available for the two food loss and waste targets. And emissions from agricultural production, which need to peak as soon as possible and decline between now and 2050, are still rising (Table 13). For each indicator, we draw from the *World Resources Report: Creating a Sustainable Food Future* (Searchinger et al. 2019) to detail the main technical mitigation options as well as high-priority policies, technologies, and investments to accelerate progress toward the 2030 and 2050 targets.

There are numerous potential synergies among agricultural mitigation strategies. Boosting crop and livestock productivity can increase the efficiency of resource use, leading to less land and water needed per unit of food produced. Similarly, strategies to reduce methane emissions from rice production can save water and boost yields. Efforts to improve soil health can sustain productivity while also building resilience to climate change—and there are many other opportunities to practice mitigation and adaptation at the same time. Demand-side strategies can further reduce the challenge of feeding a growing population with a finite land base and a need to greatly reduce emissions. Supply- and demand-side strategies can also potentially improve health and nutrition outcomes. And there are crucial synergies with the forest sector: large-scale forest protection and restoration will only be possible if the world can peak and then reduce agricultural land demand, even while feeding a growing population, through the measures discussed in this section. Importantly, it will be necessary to link agricultural intensification with establishment and enforcement of strong forest protection measures to achieve the agriculture and forest targets simultaneously.

There are also potential trade-offs. The Green Revolution combination of synthetic fertilizers, irrigation, and scientifically bred seeds led to enormous production and productivity gains, but it also brought serious issues such as water scarcity, pollution, and excessive reliance on chemical and fossil-based inputs. A major challenge will be to further accelerate productivity gains, in a changing climate, while minimizing such detrimental effects. And while the global prevalence of hunger declined from 2005 to 2014, it slowly rose between 2014 and 2019 and ticked sharply upward in 2020 under COVID-19 to an estimated 768 million people (FAO et al. 2021). Furthermore, without complementary measures to protect forests, yield gains can create a "rebound effect" due to the increased profitability of agriculture, and lead to additional land clearing. And another trade-off looms in the other direction: without productivity gains (or with shifts to lower-input, lower-output forms of agriculture), agricultural land demand will continue to grow along with global food demand, increasing pressure on forests and potentially pushing zero-deforestation and climate goals out of reach.

TABLE 13. Summary of progress toward 2030 agriculture targets

Indicator	Most recent historical data point (year)	2030 target	2050 target	Trajectory of change	Status	Acceleration factor
Agricultural production GHG emissions ($GtCO_2e$/yr)	5.35 (2018)	4.17	3.27	Exponential change unlikely		n/a, U-turn needed
Crop yields (t/ha/yr)	6.64 (2019)	7.67	9.44	Exponential change unlikely		1.9x
Ruminant meat productivity (kg/ha/yr)	27.07 (2018)	33.42	41.57	Exponential change unlikely		1.6x
Share of food production lost (%)	14 (2016)	7	7	Exponential change unlikely		Insufficient data
Food waste (kg/capita/yr)	121 (2019)	60.50	60.50	Exponential change unlikely		Insufficient data
Ruminant meat consumption in the Americas, Europe, and Oceania (kcal/capita/day)	93.55 (2018)	78.98	60	Exponential change unlikely		1.5x

Note: n/a = not applicable; $GtCO_2e$/yr = gigatonnes (billion tonnes) of carbon dioxide equivalent per year; t/ha/yr = tonnes per hectare per year; kg/ha/yr = kilograms per hectare per year; kg/capita/yr = kilograms per capita per year; kcal/capita/day = kilocalories per capita per day.

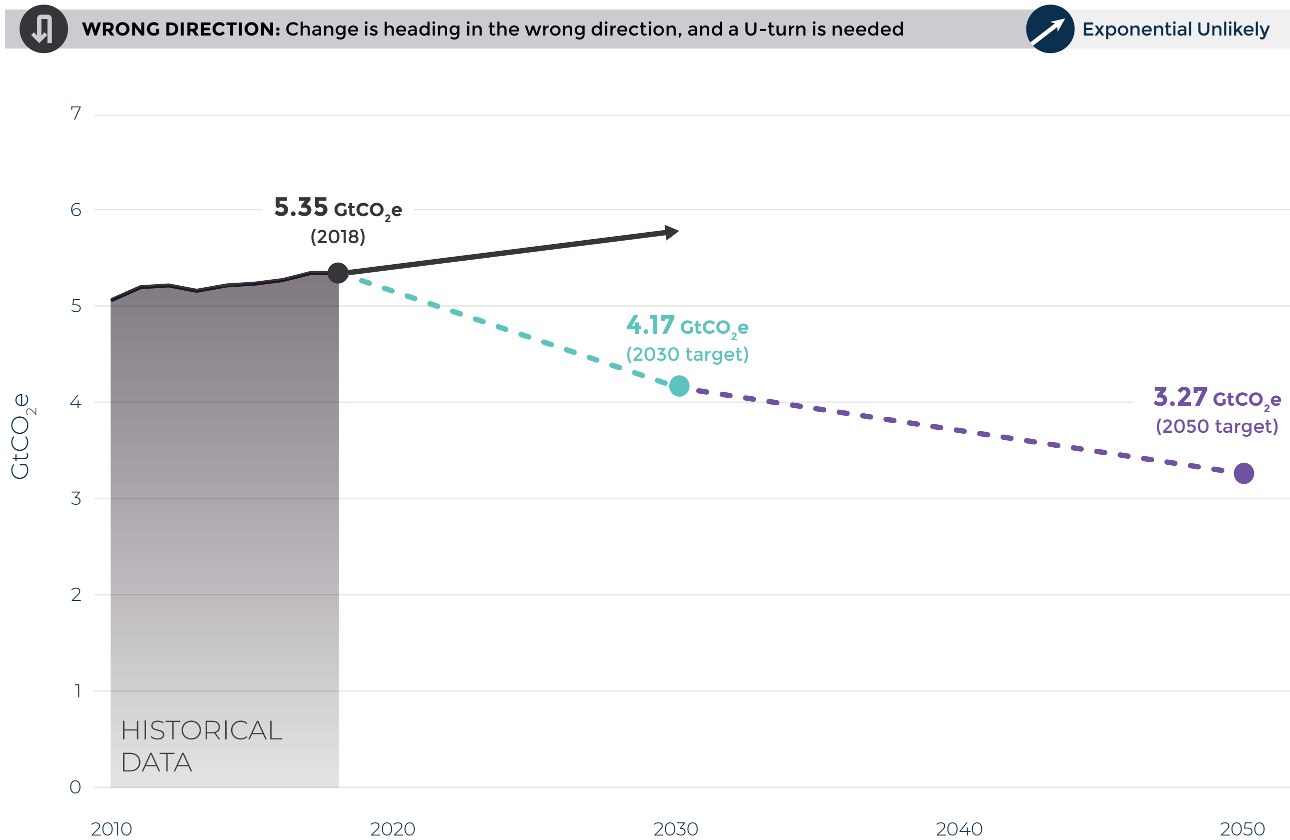
Sources: Historical data from FAOSTAT (2021); FAO (2019); and UNEP (2021); targets adapted from Searchinger et al. (2019); Searchinger et al. (2021); and United Nations (2015).

AGRICULTURE INDICATOR 1:
Agricultural production GHG emissions

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

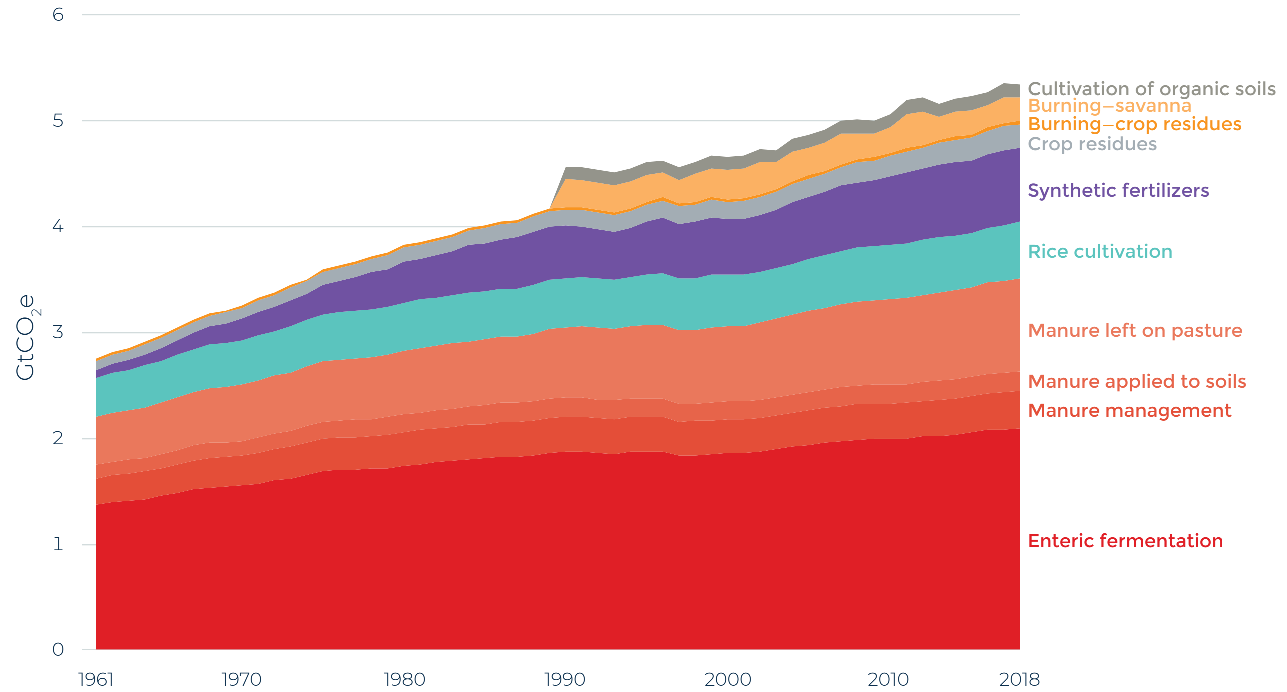
At roughly 12 percent of global GHG emissions, and growing steadily for decades (FAOSTAT 2021) (Figure 69), peaking and then lowering emissions from agricultural production is an important ingredient in keeping warming below 1.5°C. Without reducing emissions from agriculture and deforestation, emissions from global food systems alone could put the Paris Agreement temperature goals out of reach (Clark et al. 2020; Searchinger et al. 2019). This indicator measures annual emissions of GHGs (expressed in terms of CO_2e) from agricultural production, including fossil fuel use, livestock and rice production, and use of synthetic fertilizers and manure (Figure 70). It excludes emissions from land-use change caused by agriculture, which are covered in Chapter 8, "Land use and coastal zone management."

FIGURE 69. Historical progress toward 2030 and 2050 targets for agricultural production greenhouse gas emissions



Note: $GtCO_2e$ = gigatonnes (billion tonnes) of carbon dioxide equivalent.
Sources: Historical data from FAOSTAT (2021); 2030 and 2050 targets adapted from Searchinger et al. (2019).

FIGURE 70. Breakdown of agricultural production emissions



Note: $GtCO_2e$ = gigatonnes (billion tonnes) of carbon dioxide equivalent. Data for "Burning—savanna" and "Cultivation of organic soils" only available since 1990.
Source: FAOSTAT (2021).

Global agricultural production emissions have roughly doubled since 1961 (Figure 70) (FAOSTAT 2021), and under a business-as-usual scenario are projected to grow by another 27 percent between 2017 and 2050. However, to limit global temperature rise to 1.5°C, emissions in 2050 would need to move in the other direction, falling by 39 percent relative to 2017 (Searchinger et al. 2019) (Table 14). Emissions reductions would be required across all world regions and all emissions sources relative to 2017 but would be less stringent in regions with high projected population and food demand growth, such as sub-Saharan Africa. Both supply-side (e.g., improvements in livestock feed and manure management, improvements in nitrogen use efficiency, improvements in rice management and breeds) and demand-side (e.g., reductions in food loss and waste and dietary shifts) actions are important to achieve the necessary level of emissions reductions.

Global agricultural production emissions stayed relatively steady between 2017 and 2018 (FAOSTAT 2021), and only grew by 6 percent between 2010 and 2018, perhaps suggesting that a peak is near, even as food production continues to grow (Figure 69).

TABLE 14. Disaggregated targets by major agricultural production emissions sources

Emissions source	Historical trend (2013-18)	Target (2017-30)	Target (2017-50)
Enteric fermentation	+4%	−17%	−29%
Manure management	+4%	−21%	−38%
Manure on pasture	+6%	−13%	−19%
Soil fertilization	+2%	−19%	−36%
Rice cultivation	+1%	−24%	−46%
Total	+4%	−22%	−39%

Sources: FAOSTAT (2021) for historical trend; Searchinger et al. (2019) for 2030 and 2050 targets.

Enablers of climate action

While agricultural production emissions have nearly doubled since 1961, total agricultural output has roughly tripled during that time frame, whether measured by value or by total calories in the human food supply (FAOSTAT 2021). Therefore, the emissions intensity of agriculture is steadily falling even while absolute agricultural production emissions continue to rise. The question is how to accelerate emissions intensity improvements so that overall emissions peak as soon as possible—and then decline toward the 2030 and 2050 targets. Low levels of funding for agricultural research and development in general—and for agricultural mitigation in particular—reduce the likelihood of the world's meeting these mitigation targets, as well as the likelihood of meeting the agricultural productivity targets described below (indicators 2 and 3). Increasing investment in research, development, and deployment—which can be further stimulated through flexible regulations to incentivize innovation—could help accelerate progress (Searchinger et al. 2019).

Investing in innovative technologies and approaches

A number of promising technological innovations and other approaches on the horizon could help the agricultural sector drive down each major source of GHG emissions while feeding a growing world population:

- **Improved feed conversion efficiency.** The majority of agricultural production emissions are from livestock (the bottom four layers in Figure 70), with roughly two-thirds of livestock emissions from cattle (Gerber et al. 2013). Improving animal feeds and breeding can increase efficiency, reducing emissions per kilogram of meat or milk. Such efficiency improvements are largely responsible for previous improvements in livestock emissions intensity, although overall emissions have continued to climb.
- **Enteric methane inhibitors.** The largest source of agricultural production emissions come from "enteric fermentation" (cow burps)—and researchers and companies are working on feed compounds that reduce enteric methane emissions while maintaining or increasing productivity. These include chemical feed additives such as 3-nitrooxypropan (3-NOP) (Hristov et al. 2015), as well as seaweeds (Roque et al. 2020).

- **Improved manure management.** "Managed" manure, which originates from animals raised in intensive production systems, accounts for 6–9 percent of agricultural production emissions. Separating liquids from solids, capturing methane in digesters, and other approaches can help reduce these emissions (Searchinger et al. 2019).
- **Improved nitrogen management.** Fertilizers, including synthetic and organic (manure), account for about 20 percent of emissions from agricultural production. And about half of all nitrogen applied to crops is not taken up by the plants, resulting in excess emissions and water pollution. Compounds called "nitrification inhibitors" that prevent formation of nitrous oxide—a powerful GHG—can reduce both emissions and water pollution. Cover crops can also trap nitrogen in the soil, reducing the need for fertilizers and reducing soil erosion and water pollution. Overall, better nutrient management

will continue to play an important role in reducing fertilizer emissions by curbing overuse (Cui et al. 2018), including through emerging precision farming systems (Rees et al. 2020).

- **Lower-methane rice production**. Paddy rice production produces methane and is responsible for 10–15 percent of agricultural production emissions. Management practices that draw down water during the growing season can help reduce methane emissions, and some researchers have identified rice varieties that emit less methane.
- **Reduce fossil fuel use in agricultural production.** Energy emissions from fossil fuel use account for about 20 percent of global agricultural production emissions and include emissions from heat and electricity use in farm buildings, fuel for tractors and other heavy equipment, as well as nitrogen fertilizer manufacturing. As in other sectors, increasing energy efficiency and shifting to renewable energy sources can mitigate these emissions.

While some of the above approaches have been applied in many places (e.g., improving feed conversion efficiency over time; drawing down water in rice production in China, Japan, and South Korea), others need to be scaled up through additional investments and supportive policies (e.g., cover crops) or further developed and then deployed (e.g., enteric methane inhibitors and nitrification inhibitors).

Strengthening government action to reduce agricultural GHG emissions

Reasons for previous declines in emissions intensity include advances in efficiency driven by improvements in technology and management practices, and increased uptake of such technologies and practices. For example, improvements in feed quality—leading to faster animal growth per unit of feed, and less feed needed per liter of milk produced—are one key reason why dairy emissions intensities (in terms of kilograms of CO_2e per liter of milk) are 80 percent lower in the most efficient countries than in the least efficient (Gerber et al. 2013). Approaches to increase adoption of better practices and technologies include securing farmers' property rights, investing in agricultural extension services, and redirecting agricultural subsidies to focus more on the synergies between boosting food production and simultaneously reducing agricultural emissions (Searchinger et al. 2020; Searchinger et al. 2019; Gerber et al. 2013). Countries should also fully integrate ambitious agricultural mitigation targets and actions into their NDCs that are tailored to each country's unique circumstances and needs (Ross et al. 2019).

However, expanding adoption of current best practices and technologies will not be enough. Across the board, the size of the necessary GHG emissions reductions and the fact that not all mitigation approaches immediately increase farm profitability or "pay for themselves" suggest a strong need for government action and investment to spur additional technological development and deployment and drive down costs. Flexible regulations can help give incentives to the private sector to develop needed innovations (Searchinger et al. 2019). This can help the agricultural sector "catch up" to the energy sector where low-emissions technologies (e.g., solar and wind) are more mature.

AGRICULTURE INDICATOR 2:
Crop yields

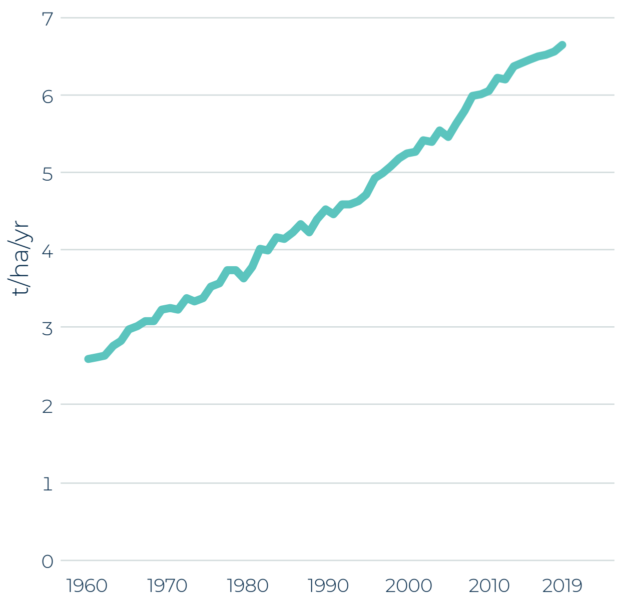
Targets: Crop yields increase by 18 percent by 2030 and 45 percent by 2050, relative to 2017.

Even as crop yields are expected to increase in the coming decades (FAO 2018), models tend to project continued cropland expansion out to 2050 as the global population grows (Schmitz et al. 2014; Bajželj et al. 2014; Searchinger et al. 2019), implying continued encroachment of cropland onto forests. Therefore, yields must increase even faster than historical rates over the next 30 years in order to boost crop production on existing agricultural land and avoid additional expansion. Increasing productivity is the single most important step toward simultaneously meeting food production and environmental goals—and underpins the forest protection and restoration goals in Chapter 8, "Land use and coastal zone management"—but it must be done in ways that protect soil health, as well as water quantity and quality.

Globally, if the world boosted crop yields by 45 percent by 2050 relative to 2017, productivity would keep pace with projected crop demand growth (Searchinger et al. 2021), and it would eliminate the need for further cropland expansion. Worldwide, crop yields have grown steadily by about 70 kilograms per hectare per year (kg/

ha/year) since the 1960s, although yield growth was lower (46 kg/ha/year) since 2014 (Figure 71). To boost yields another 18 percent by 2030 and 45 percent by 2050, annual crop yield growth will need to be nearly twice as high—at 90 kg/ha/year (0.09 t/ha/year)—than it was between 2014 and 2019 (Figure 72).

FIGURE 71. Historical change in crop yields

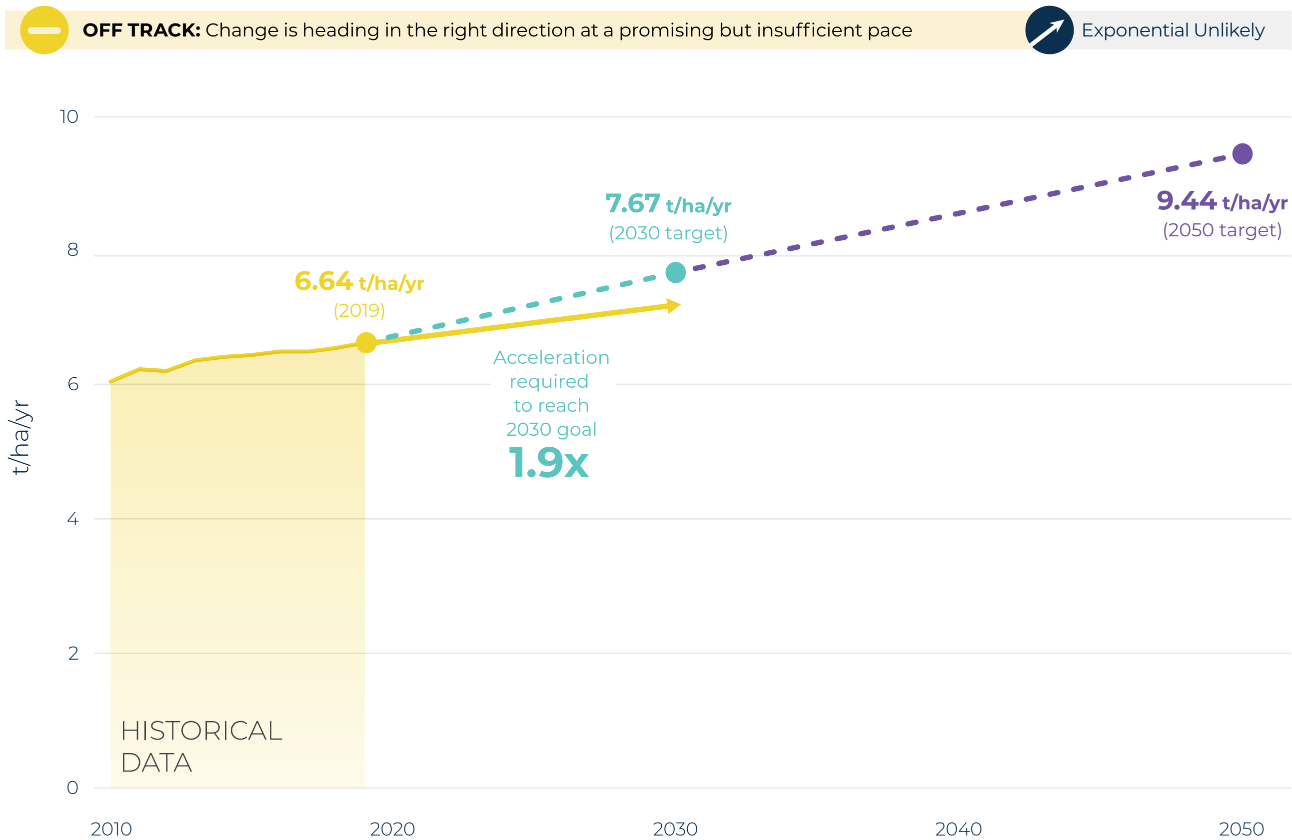


Note: t/ha/yr = tonnes per hectare per year. Crop yields are calculated using harvested production (fresh weight), across all crops, and weighted by harvested area.
Source: FAOSTAT (2021).

Enablers of climate action

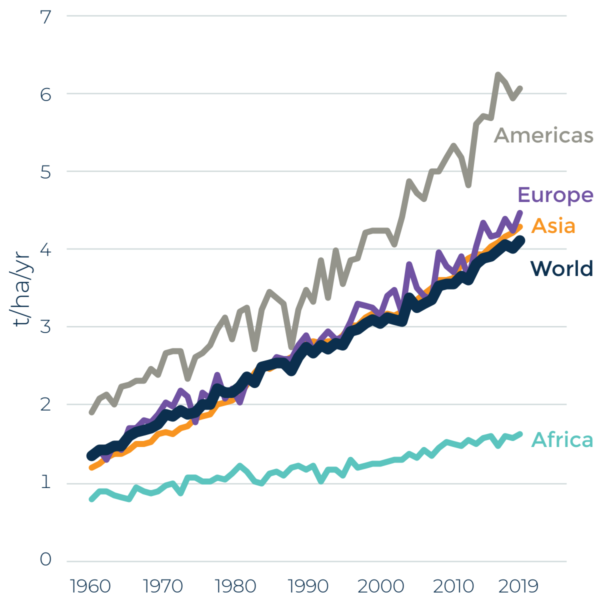
While the steady progress on this indicator for the past six decades is encouraging, two caveats are necessary. First, this global growth represents an enormous amount of effort by farmers, agricultural researchers, and others, meaning that accelerating crop yield growth over the next three decades, in a changing climate with increasing resource constraints, will be a major undertaking. In addition, in many parts of the world, most of the "easier" approaches to increase yields (such as adding irrigation, using chemical inputs, and introducing basic machinery) have already occurred. Second, the global growth in yields masks wide variation among regions, and yields in sub-Saharan Africa remain far below the global average and have grown more slowly than elsewhere (Figure 73). While yield gains are necessary across all world regions, particular attention is warranted in areas like sub-Saharan Africa where current yields

FIGURE 72. Historical progress toward 2030 and 2050 targets for crop yields



Note: t/ha/yr = tonnes per hectare per year.
Sources: Historical data from FAOSTAT (2021); 2030 and 2050 targets adapted from Searchinger et al. (2021).

FIGURE 73. Variation in cereal crop yields across world regions



Note: t/ha/yr = tonnes per hectare per year. Cereal crop yields are calculated using harvested production (fresh weight) and weighted by harvested area.
Source: FAOSTAT (2021).

are low and where climate change without adaptation is expected to significantly depress yields (Porter et al. 2014; Verhage et al. 2018).

Advancing innovative technologies and approaches

Two major approaches have helped to improve crop yields in previous decades and have the potential to further boost productivity:

- **Improved crop breeding.** Breeding improvements have historically driven about half of all yield gains (Evenson and Gollin 2003; Tischer et al. 2014). Breeding can both increase the maximum potential yield of a crop and also help farmers achieve better yields through characteristics that resist sources of crop stress (e.g., drought, flooding, diseases), which is particularly relevant in a changing climate. New technologies are also helping breeders improve crops faster than before, such as genomics and gene editing.
- **Improved soil and water management.** Soil degradation, particularly in the drylands of sub-Saharan Africa, can keep yields low and threaten food security. Approaches such as agroforestry (integrating trees and shrubs on farmland), rainwater harvesting (practices that block water runoff), and "microdosing" of fertilizer can help increase soil fertility and moisture, boosting yields and increasing resilience to climate change while keeping input costs low. More research is needed to systematically understand the full range of conditions under which agroforestry systems are successful, in order to scale up their adoption.

Boosting public, private, and civil society action to sustainably intensify crop production

Increasing public and private crop breeding budgets—particularly in developing countries and focusing on "orphan crops" that are important for food security but have not historically been researched as much as maize, wheat, rice, and soybeans—can help accelerate needed improvements. Breeding programs should take advantage of new technologies, such as those listed above. University researchers, research partnerships like CGIAR (formerly the Consultative Group for International Agricultural Research), ministries of agriculture, and agribusinesses all have a role to play in accelerating improvements in crop breeding.

In addition, increasing support for improved soil and water management practices is essential, especially in regions where progress is slower. Strengthening agricultural extension can help spread awareness and uptake of these practices. Building the capacity of local institutions, like village development committees, to formulate and enforce rules around natural resource use and access, can help ensure protection of trees on and around farms. And policy reforms—including overhauling forest codes that discourage farmers from growing trees on farms, and securing smallholders' land tenure and management rights over trees—can further accelerate uptake (Reij and Garrity 2016).

AGRICULTURE INDICATOR 3:
Ruminant meat productivity

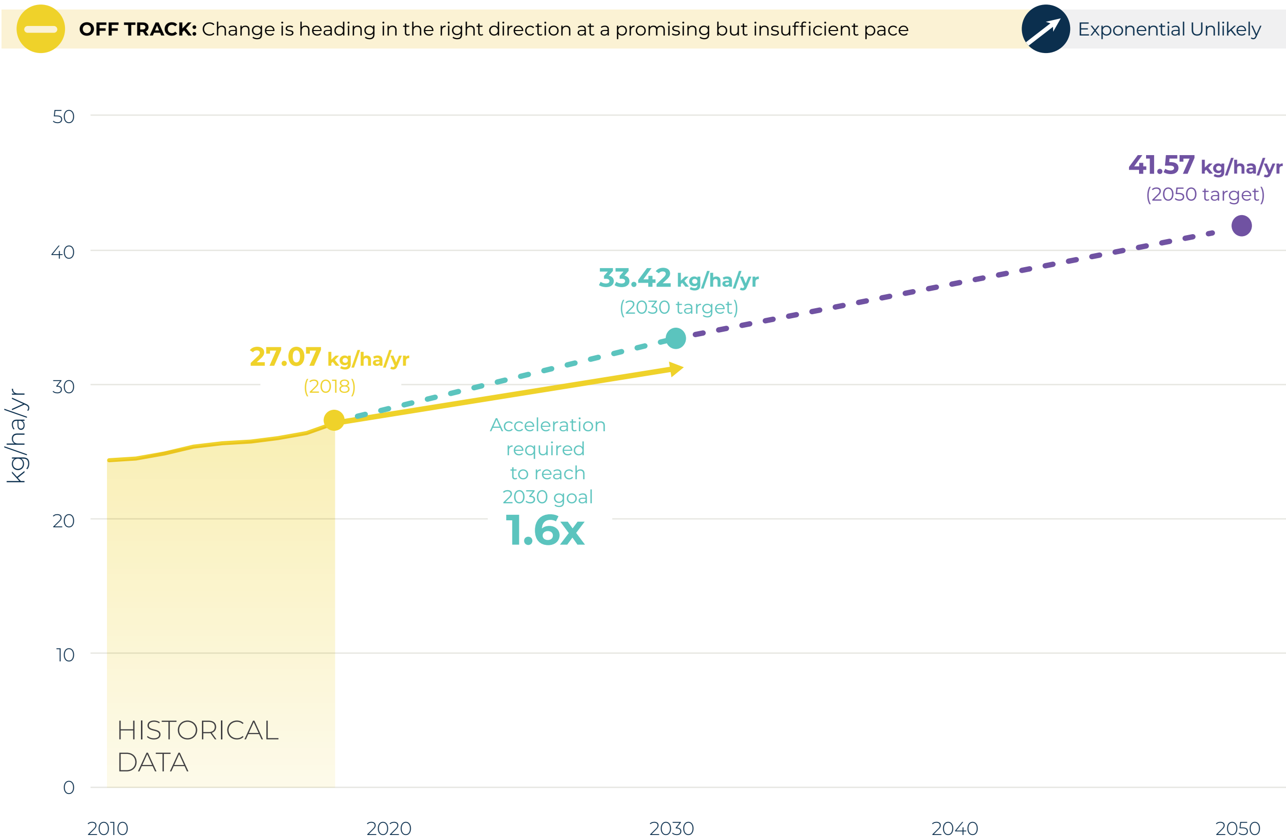
Targets: Ruminant meat productivity per hectare rises 27 percent by 2030 and 58 percent by 2050, relative to 2017.

Between now and 2050, population and income growth are likely to be concentrated in the developing world, where meat consumption levels currently are relatively low. These population and income trends suggest that global demand for ruminant meat (and dairy products) is likely to increase even more than demand for crops, at nearly 70 percent growth between 2010 and 2050 (Searchinger et al. 2019). While it will be important to moderate meat consumption in high-income countries (see indicator 6 below), the fact that billions of people are likely to enter the global middle class in coming decades suggests that boosting the productivity of animal agriculture will also be necessary to reduce pressures on land and the climate.

Pastureland—where ruminant animals such as cattle, sheep, and goats graze—currently accounts for more than 3 billion hectares, or about two-thirds of all agricultural land (FAO 2011b). Searchinger et al. (2019) estimated that in a business-as-usual scenario, pasture could increase by roughly 400 million hectares between 2010 and 2050. Such an area of pastureland expansion (larger than the size of India) would put forest protection and restoration goals out of reach. And in contrast to poultry and pork production, where concentrated production systems are approaching biological limits in terms of efficiency and reaching or exceeding limits on humane conditions for raising animals, there is still ample technical potential to increase the productivity and efficiency of meat and milk production from ruminants (Gerber et al. 2013).

Improving the productivity of ruminant meat production by 58 percent by 2050 relative to 2017 could help eliminate the need for further pastureland expansion (Searchinger et al. 2019). While productivity has grown over the past six decades, including by 0.35 kg/ha/year since 2013, hitting the 2030 productivity target would require accelerating progress 1.6 times faster than from 2013 to 2018 (Figure 74), and hitting the 2050 target would require accelerating progress 1.2 times faster

FIGURE 74. Historical progress toward 2030 and 2050 targets for ruminant meat productivity



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

Sources: Historical data from FAOSTAT (2021); 2030 and 2050 targets adapted from Searchinger et al. (2019).

than from 2013 to 2018. Because much of the world's pastureland is dry or sloped, achieving a global goal of a nearly 60 percent increase in ruminant meat production per hectare by 2050 would require improvements on nearly every suitable hectare of wetter pastureland.

Enablers of climate action

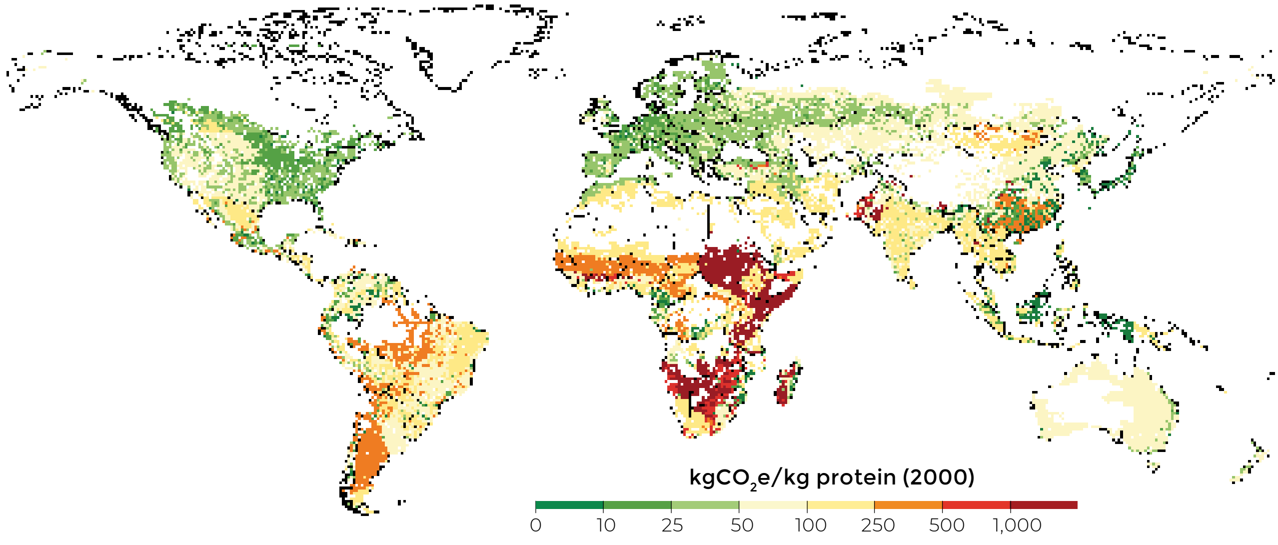
The wide range in ruminant productivity across countries—as evidenced by large variations in the amount of land use or amount of GHG emissions per kilogram of beef (Figure 75)—suggests great potential for improvements. And while some of the most GHG-efficient systems in developed countries are due to establishment of concentrated feedlots, large productivity gains are possible on pastureland in developing countries without a shift to feedlot systems. For example, in Colombia, farmers across 4,000 hectares have established intensively managed "silvopastoral" systems that integrate improved grasses, shrubs, and trees—boosting productivity while also resisting drought (Murgueitio et al. 2011). And in Brazil's Cerrado, improving grasses and adding legumes and fertilizers has doubled productivity or more (Cardoso et al. 2016). However, even though pastureland covers twice the area of cropland globally, attention to sustainable livestock intensification (as compared to boosting crop yields) has lagged.

Accelerating adoption of innovative technologies and approaches

The main opportunities to boost pasture productivity, which can also build resilience to climate change, are well known:

- **Improve feeds.** Improved breeds of pasture grasses, and integrating legumes and shrubs or trees into pastures, can increase the amount of meat produced per hectare. Improving feed compositions to improve digestibility can increase feed efficiency (i.e., the amount of meat or milk produced per kilogram of feed). Supplementing grass-based feeds in dry or cold seasons with crops and/or crop residues can further improve feed efficiency, although dedicating additional cropland to animal feed increases land-use competition.
- **Improve animal breeds and health care.** Animals bred for faster weight gain can boost productivity per hectare, and improving veterinary services can reduce disease and increase production.
- **Improve grazing and other management practices.** For example, rotational grazing, which moves animals through different parts of a pasture area, can help animals consume grass when it is most nutritious and also maximizes grass growth.

FIGURE 75. Greenhouse gas emissions efficiency and productivity of beef production vary widely across countries



Note: $kgCO_2e$/kg protein = kilograms of carbon dioxide equivalent per kilogram of protein.
Source: Herrero et al. (2013).

Linking government support for productivity improvements with ecosystem protection measures

The greatest potential to improve productivity of ruminant meat production is across the tropics (Figure 75). Governments should set productivity targets—which would help focus attention on the need for sustainable livestock intensification—and support farmers to improve production through technical and financial assistance. Countries should also develop monitoring systems to understand current and potential performance, in terms of productivity and GHG emissions, from the level of the farm to that of the nation. Such systems could help governments and private researchers understand how to target assistance and identify knowledge gaps to guide future research. Productivity improvements should be achieved in ways that ensure humane conditions for raising animals.

Programs to support productivity improvements—whether of cropland (described above) or pastureland—should be linked whenever possible to policies that support ecosystem protection. This is because just boosting yields can increase profitability, encouraging further conversion of forests or other natural ecosystems. Conversely, policies to protect forests (described in Chapter 8, "Land use and coastal zone management") that do not also seek to boost productivity can lead to forest conversion elsewhere ("leakage"). Development assistance, agricultural loans, corporate supply chain commitments, and land-use planning all provide opportunities for actors to explicitly link "produce and protect," that is to produce more food per hectare of agricultural land and simultaneously protect forest or other natural lands.

AGRICULTURE INDICATORS 4 AND 5: Share of food production lost and food waste

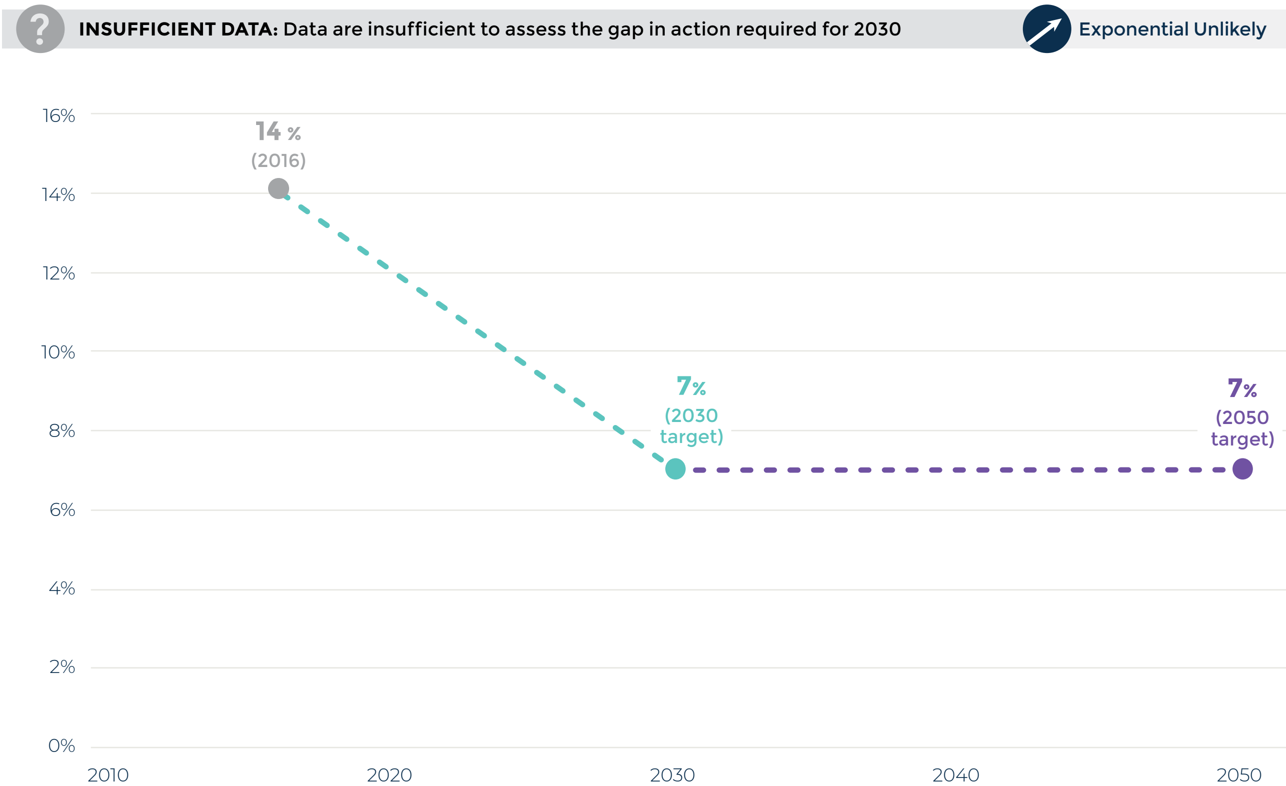
Targets: The share of food production lost declines 50 percent by 2030, relative to 2016, and these reductions are maintained through 2050.

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

Roughly one-third of all food produced in the world each year (by weight) is lost or wasted between the farm and the fork (FAO 2011a), resulting in high economic losses, contributing to food insecurity in lower-income countries, adding to GHG emissions, and representing a "waste" of agricultural land and water resources. SDG Target 12.3 calls for reducing per capita global food waste at the retail and consumer levels by 50 percent by 2030, and reducing food losses (including post-harvest losses) where possible along production and supply chains (United Nations 2015).

FAO has estimated that in 2016, 14 percent of food produced was lost from the farm up to, but excluding, the retail stage of the supply chain (FAO 2019) (Figure 76). UNEP's first Food Waste Index report estimates that in 2019, 17 percent of food available at retail, or 121 kilograms per person, was wasted (including 74 kilograms in households, 32 kilograms in food service, and 15 kilograms in retail) (UNEP 2021a). To stay in line with SDG Target 12.3, the 2030 food waste target should be half of that level, or 60.5 kilograms per person per year (kg/capita/yr) (Figure 77). Food loss and waste targets for 2050 have

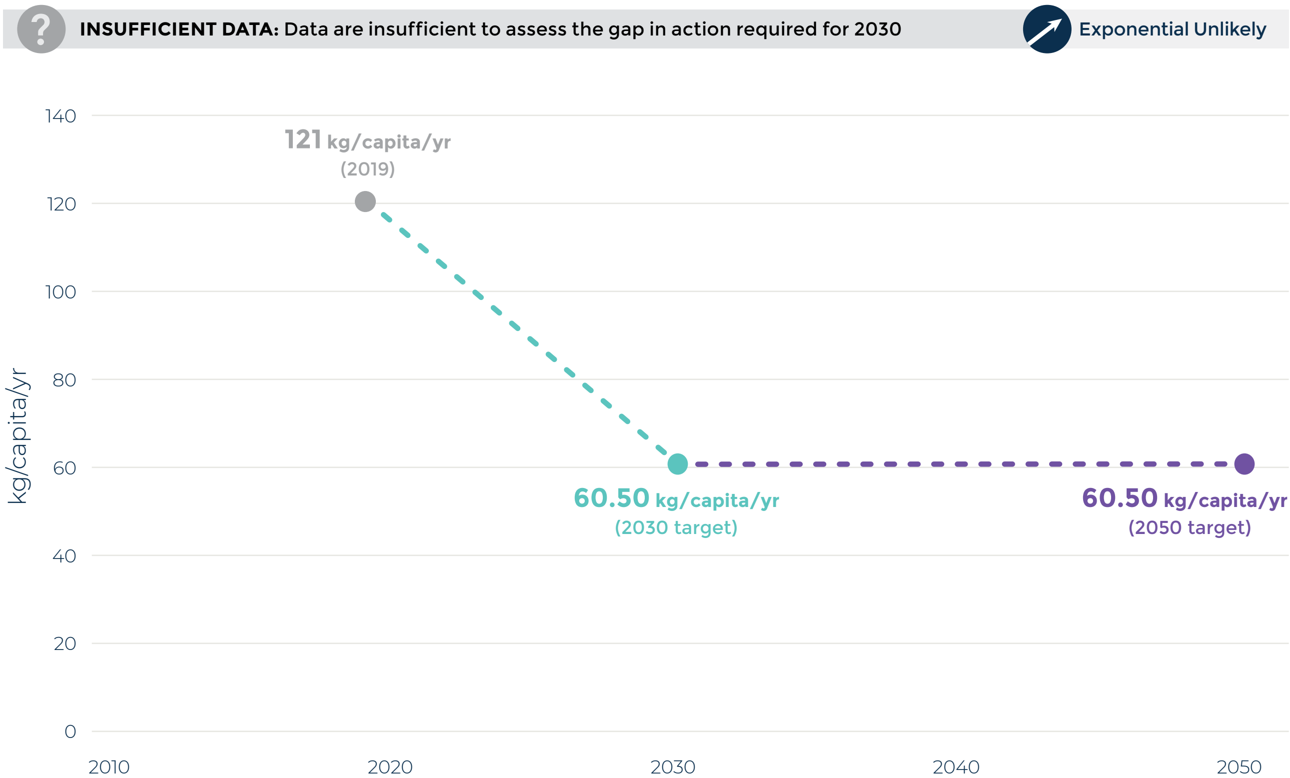
FIGURE 76. Historical progress toward 2030 and 2050 targets for share of food production lost



Note: Data are unavailable to establish a historical rate of change or acceleration factor. Targets for food loss are based on Sustainable Development Goal Target 12.3, which is to reduce food waste 50 percent by 2030, with reductions in food loss where possible. We therefore set 50 percent targets for both food loss and food waste for 2030 to be ambitious. The same targets are maintained for 2050 recognizing the need to maintain that progress and that further progress beyond 50 percent becomes increasingly difficult.

Sources: Historical data from FAO (2019); 2030 and 2050 targets adapted from United Nations (2015).

FIGURE 77. Historical progress toward 2030 and 2050 targets for food waste



Note: kg/capita/yr = kilogram per capita per year. Data are unavailable to establish a historical rate of change or acceleration factor. Targets for food waste are based on Sustainable Development Goal Target 12.3, which is to reduce food waste 50 percent by 2030, with reductions in food loss where possible. We therefore set 50 percent targets for both food loss and food waste for 2030 to be ambitious. The same targets are maintained for 2050 recognizing the need to maintain that progress and that further progress beyond 50 percent becomes increasingly difficult.

Sources: Historical data from UNEP (2021a); 2030 and 2050 targets adapted from United Nations (2015).

not been quantitatively defined, so here we have set targets of 50 percent reduction in the rate of food loss and food waste by 2030, and maintaining that 50 percent reduction by 2050 (Figures 76 and 77). Reducing food loss and waste could have large benefits in terms of reducing agricultural land demand and GHG emissions. Searchinger et al. (2019) estimated that a 50 percent reduction in food loss and waste by 2050 would reduce land needs (and deforestation) by about 310 Mha and annual agriculture and land-use change emissions by roughly 3 $GtCO_2e$, relative to "business as usual." However, while the theoretical opportunity is large, barriers to reducing food loss and waste loom as well. Loss and waste occur in every country and every food supply chain, and across supply chains from agricultural production, to handling and storage, processing, distribution and marketing, consumption, and disposal. They can be unintentional (e.g., due to inadequate infrastructure or refrigeration) or due to wasteful behaviors (e.g., poor stock management, buffet overproduction, neglect). Sizable reductions therefore require efforts by many actors across supply chains, and must be carefully targeted and monitored.

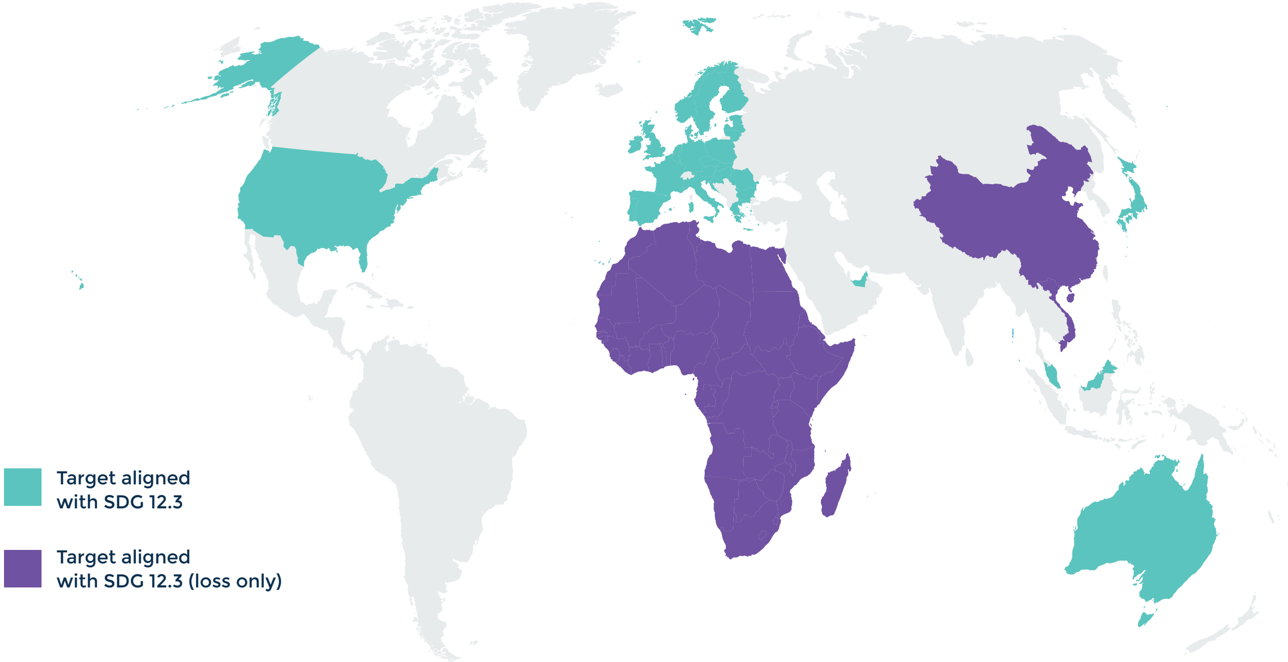
Enablers of climate action

Adopting and implementing a "Target-Measure-Act" approach

Countries and companies have been using a Target-Measure-Act approach to reduce food loss and waste since the adoption of the SDGs in 2015:

- **Target.** Governments and companies have been setting targets in line with SDG Target 12.3 for the year 2030. As of September 2020, countries and regions representing about half of the world's population had set targets in line with the SDG target (Figure 78) (Lipinski 2020).
- **Measure.** Quantifying food loss and waste within borders, operations, or supply chains can help countries understand where "hotspots" are and design effective strategies to reduce food loss and waste. Measurement is also necessary to understand progress against targets. The United

FIGURE 78. National and regional governments with food loss and/or food waste reduction targets aligned with Sustainable Development Goal Target 12.3 (as of September 2020)



Note: SDG = Sustainable Development Goal.
Source: Lipinski (2020).

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 2021a) to monitor progress at the global level and help standardize national government measurement efforts. As the data improve, it should become easier to understand situations across regions and countries and trends over time, as with the other indicators in this Agriculture chapter.

- **Act.** Countries and companies can take a variety of actions to reduce food loss and waste across food supply chains. Figure 79 lists some of the most promising near-term actions. In developing countries, food loss and waste tend to occur in the production, handling, and storage stages, and improved harvesting techniques, storage and cold chain technologies, and infrastructure can help reduce losses. In developed countries, food loss and waste tend to occur toward the consumption end of the supply chain, and changes in retail and food service environments, as well as in households, can reduce waste. "Early mover" countries are starting to see results. For example, the United Kingdom reduced food loss and waste per capita by 27 percent between 2007 and 2018, making it the first country to be more than halfway to the 2030 target of halving waste. 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).

While awareness and ambition are rising, food loss and waste measurement is still relatively new in many places, and the progress demonstrated by a handful of major actors must now be scaled across the entire world. In addition, the COVID-19 pandemic exposed the fragility of food supply chains to large shifts in demand, labor shortages, and fluctuations in income—leading to increases in food loss and waste in some areas in 2020. More governments and companies need to adopt the Target-Measure-Act approach to ensure action to reduce food loss and waste at the necessary scale.

FIGURE 79. Potential approaches to reduce food loss and waste

PRODUCTION	HANDLING & STORAGE	PROCESSING & PACKAGING	DISTRIBUTION & MARKET	CONSUMPTION
During or immediately after harvesting on the farm	After leaving the farm for handling, storage, and transport	During industrial or domestic processing and/or packaging	During distribution to markets, including at wholesale and retail markets	In the home or business of the consumer, including restaurants and caterers
• Convert unmarketable crops into value-added products • Improve agriculture extension services • Improve harvesting techniques • Improve access to infrastructure and markets	• Improve storage technologies • Introduce energy-efficient, low-carbon cold chains • Improve handling to reduce damage • Improve infrastructure (e.g., roads and electricity access)	• Reengineer manufacturing processes • Improve supply chain management • Improve packaging to keep food fresher for longer, optimize portion size, and gauge safety • Reprocess or repackage food not meeting specifications	• Provide guidance on food storage and preparation • Change food date labeling practices • Make cosmetic standards more amenable to selling "imperfect" food (e.g., produce with irregular shape or blemishes) • Review promotions policy	• Reduce portion sizes • Improve consumer cooking skills • Conduct consumer education campaigns (e.g., general public, schools, and restaurants) • Consume "imperfect" produce

- Improve forecasting and ordering
- Facilitate increased donation of unsold food
- Increase financing for innovation and scaling of promising technologies
- Create partnerships to manage crop flushes
- Increase capacity building to accelerate transfer of best practices

Source: Hanson and Mitchell (2017).

AGRICULTURE INDICATOR 6: Ruminant meat consumption

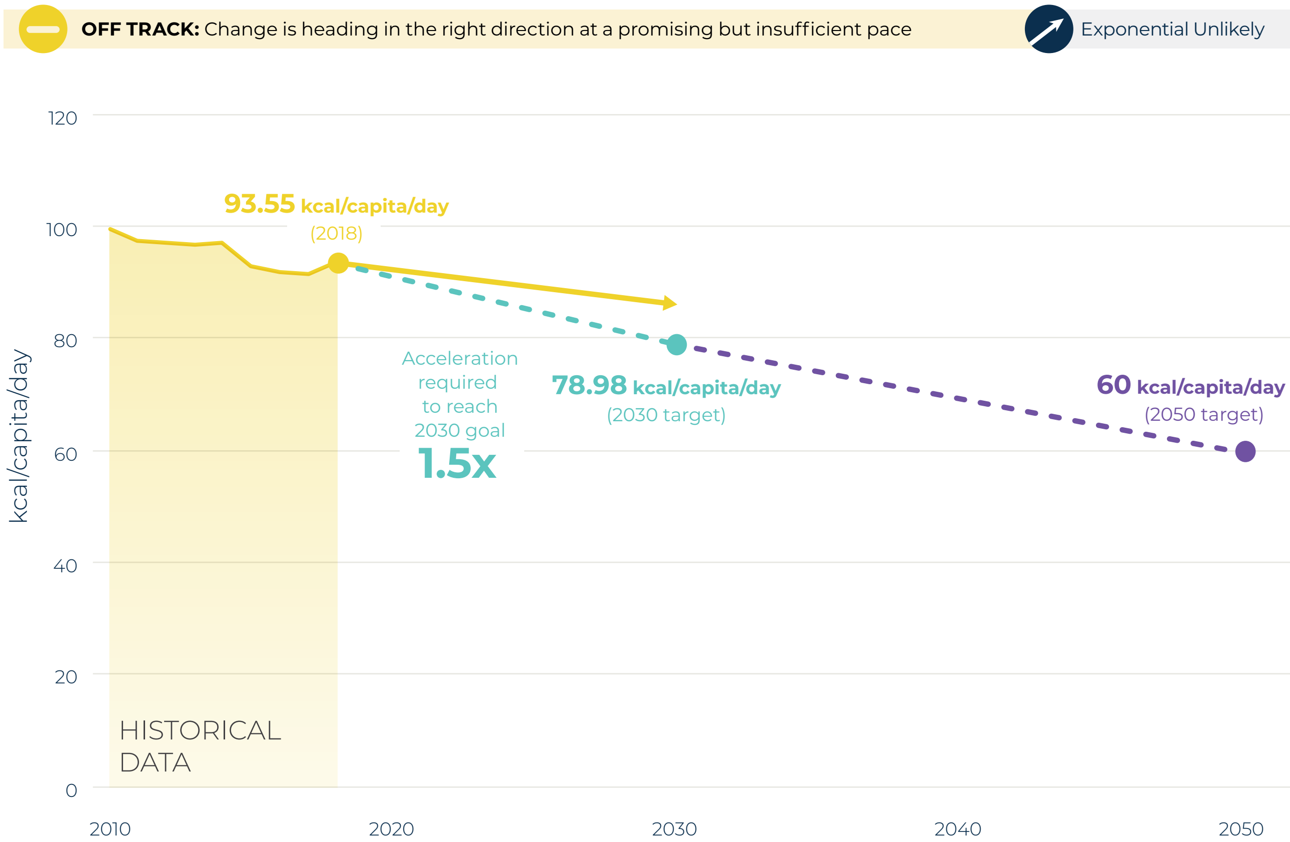
Targets: Across high-consuming regions (the Americas, Europe, and Oceania), daily per capita ruminant meat consumption decreases to 79 kilocalories by 2030 and to 60 kilocalories by 2050.

As incomes rise and people move to cities, diets tend to become more varied and higher in resource-intensive foods like meat and dairy. Consumption of animal-based foods is projected to grow by nearly 70 percent between 2010 and 2050 on an absolute basis (Searchinger et al. 2019), an estimate roughly in line with several other researchers' estimates (e.g., Willett et al. 2019; Tilman and Clark 2014; Springmann et al. 2016). This projected growth makes climate mitigation goals, particularly those related to forest protection (see Chapter 8, "Land use and coastal zone management"), more challenging; for instance, beef production requires 20 times more land and leads to 20 times more GHG emissions per gram of protein than beans. Beef and other ruminant meat production is also roughly seven times as land- and GHG emissions-intensive as poultry and pork production (Ranganathan et al. 2016).

Modest increases in consumption of animal-based foods can boost nutrition in low-income countries. However, in high-income countries, where protein consumption is well above dietary requirements and substitutes for animal protein are widely available, shifting diets toward plant-based foods and especially away from beef and other ruminant meats can reduce agricultural land demand and GHG emissions. If ruminant meat consumption in high-consuming countries declined by 2050 to 60 kilocalories per person per day, or about 1.5 burgers per person per week, it would reduce agricultural land demand by more than 500 Mha, and decrease agriculture and land-use change emissions by more than 5 $GtCO_2e$, relative to "business-as-usual" (Searchinger et al. 2019).

Across the Americas, Europe, and Oceania—all regions with consumption above the 60 kcal/person/day target—per capita ruminant meat consumption has already receded by about 30 percent from its peak in 1990 (FAOSTAT 2021). However, to reach the target by 2050, consumption would need to fall by another 35 percent—accelerating 1.5 times the rate of decline observed between 2013 and 2018. This faster rate of decline will

FIGURE 80. Historical progress toward 2030 and 2050 targets for ruminant meat consumption in the Americas, Europe, and Oceania



Note: 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 (2021); 2030 and 2050 targets adapted from Searchinger et al. (2019).

also be needed to achieve the more immediate 2030 target of reducing daily, per capita consumption to 79 kilocalories (Figure 80).

Enablers of climate action

Much of the shift away from ruminant meat consumption in Europe and the United States has been toward consumption of poultry meat (FAOSTAT 2021), likely due to a combination of cheaper and more convenient chicken products on the market, and health concerns around red meat (Bentley 2017; Tonsor et al. 2009). While a shift from beef toward chicken consumption greatly reduces diet-related GHG emissions (Ranganathan et al. 2016), it can also increase animal welfare concerns, due to more animals being eaten overall and often raised in more crowded conditions. A shift toward plant-based foods would avoid this trade-off and further increase environmental benefits (Searchinger et al. 2019). Three approaches can help shift consumption patterns toward lower-impact diets: product innovation; promotion and marketing; and policy and pricing.

Directing investments toward innovation in plant-based and blended products

Consumers make food purchasing decisions based on factors such as taste, price, and convenience. Therefore, products such as plant-based meats, and blends of meat and plants, can help satisfy consumers' tastes while reducing GHG intensity. In the United States, retail sales of plant-based meats grew by 72 percent between 2018 and 2020, but they still only represent 1.4 percent of sales in the meat category (Good Food Institute 2021). Therefore, the plant-based industry will need to accelerate growth in order to have a significant effect on meat consumption at global or national levels. Food service outlets are also innovating blended beef-mushroom burgers that reduce beef content per burger by 20–35 percent and can outcompete 100 percent beef burgers on taste (Myrdal Miller et al. 2014). If costs can come down, cell-cultured or "cultivated" meat could also be an important innovation. Businesses should continue to invest in developing meat substitutes and drive down their prices until they are competitive with conventional meats.

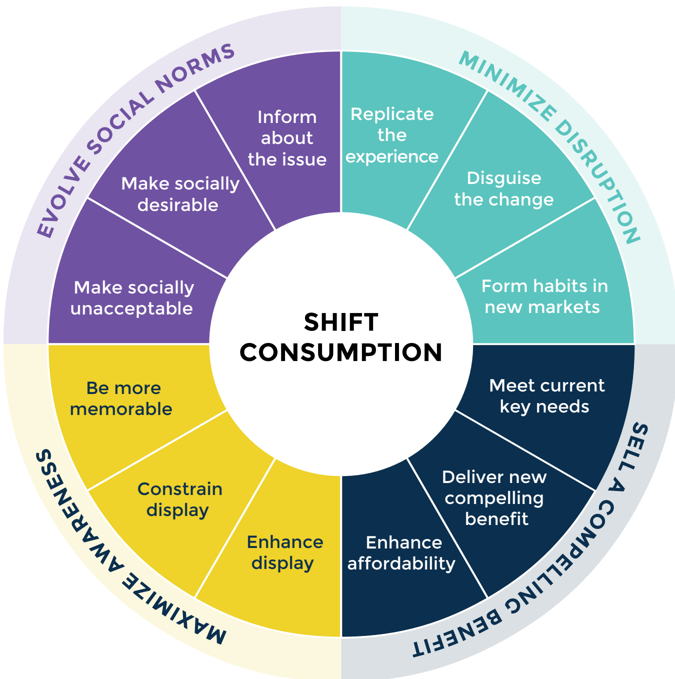
Using behavioral science to promote and market climate-friendly meals

Moving beyond consumer education campaigns to improving presentation and marketing of plant-based foods and plant-rich dishes can help make the more sustainable choice the more desirable choice. Behavioral science is showing that "nudges" that change the placement, presentation, and promotion of plant-centered meals can increase sales of climate-friendly options (Attwood et al. 2020). Businesses and civil society can both be more sophisticated in helping guide consumers toward more sustainable choices. Retailers and food service providers can use strategies from the "Shift Wheel" (Ranganathan et al. 2016) to minimize disruption to consumers who enjoy meat, better sell the benefits of plant-based or plant-rich products, maximize awareness and availability of the products, and evolve social norms over time (Figure 81).

Pairing supportive policies with financial incentives to shift diets

Governments can use the power of procurement to support shifts toward lower-impact diets. For example, national school lunch programs feed tens of millions of students each day in the United States and Brazil, and incorporating more plant-rich meals into school menus can have a large impact. At the city level, Milan, Italy, reduced its GHG emissions related to food procurement by 20 percent between 2015 and 2019 by changing menus in schools and other public places (Moore 2020). Governments can also advance policies that incentivize businesses to make the above changes. Incorporation of environmental sustainability into national dietary guidelines can also support development of policies to help consumption shift toward healthier and more sustainable patterns (Fischer and Garnett 2016). Changes to taxes and subsidies—ones that would favor consumption of lower-emitting foods over higher-emitting foods—are politically more difficult, but if meat substitutes compete with conventional meats on price and taste, these changes may become easier in the future.

FIGURE 81. The Shift Wheel's four strategies to shift food consumption patterns



Source: Ranganathan et al. (2016).

10 FINANCE

Finance is a key means to enable climate action. As other chapters have shown, investment and aligning financial incentives is often a critical driver itself for achieving other sectoral transformations covered in this report.

IN THIS SECTION, WE EXAMINE KEY indicators for how finance can unlock greater climate action: scaling up climate finance (both public and private); measuring, reporting, and managing climate risks; and properly pricing emissions. For four indicators, historical rates of change are headed in the right direction but are below levels required for 2030; for the carbon-pricing indicator, progress has stagnated, with a near flat historical rate of change; and, for the climate risk disclosure indicator, data are insufficient to assess the historical rate of change and the gap in required action (see Table 15).

FINANCE INDICATOR 1: Total climate finance

Targets: Global climate finance flows reach $5 trillion per year by 2030 and are sustained through 2050.

Mobilizing investment is vital for implementing climate action. These are investments that will pay dividends in reduced climate damages and more efficient, inclusive, and sustainable economies (NCE 2014; UNCTAD 2019). Both public and private finance can play important, and complementary roles. There is substantial debate about what should and should not be counted as

TABLE 15. Summary of progress toward 2030 finance targets

Indicator	Most recent historical data point (year)	2030 target	2050 target	Status	Acceleration factor
Total climate finance (billion US$)	640 (2020)	5,000	5,000	!	13x
Public climate finance (billion $)	300 (2020)	1,250	1,250	!	5x
Private climate finance (billion $)	340 (2020)	3,750	3,750	!	23x
Corporate climate risk disclosure	No data	Jurisdictions representing three-quarters of global emissions mandate TCFD-aligned climate risk reporting and all of the world's 2,000 largest public companies report on climate risk in line with TCFD recommendations by 2030.	No target defined	?	Insufficient data
Share of global emissions covered by a carbon price of at least $135/tCO_2e (%)	0.08 (2021)	51% of global emissions at a price of at least $135/tCO_2e	51% of global emissions at a price of at least $245/tCO_2e	×	n/a; historical data flat
Total public financing for fossil fuels[a] (billion $)	725 (2019)[b]	0	0	–	1.1x

Note: n/a = not applicable; TCFD = Task Force on Climate-Related Financial Disclosures; tCO_2e = tonnes of carbon dioxide equivalent.

a Public financing for fossil fuels includes production and consumption subsidies for 81 economies, public fossil fuel finance from multilateral development banks and G20 countries' export credit agencies and development finance institutions, and state-owned entity fossil fuel investment for G20 countries.

b Data for public fossil fuel finance from multilateral development banks and G20 countries' export credit agencies and development finance institutions were unavailable for 2019, so this figure comprises only production and consumption subsidies for 81 economies and fossil fuel investment by state-owned entities for G20 countries.

Sources: Historical data from Buchner et al. (2019); Macquarie et al. (2020); CPI (2021); World Bank (2021a); OECD (2021a); Doukas et al. (2017); Tucker and DeAngelis (2020); and Geddes et al. (2020). Targets derived from IPCC (2018); IEA (2021c); OECD (2017); UNEP (2016; 2021b); and G20 (2009) and G7 (2016) commitments.

climate finance, both in terms of sectors and types of financial flows. For the purposes of this section, we use the operational definition of the UNFCCC's Standing Committee on Finance: "Climate finance aims at reducing emissions, and enhancing sinks of GHGs and aims at reducing vulnerability of, and maintaining and increasing the resilience of, human and ecological systems to negative climate change impacts" (UNFCCC Standing Committee on Finance 2014). The majority of data on climate finance flows used here come from Climate Policy Initiative's (CPI) *Global Landscape of Climate Finance* reports, which track "primary capital flows directed toward low-carbon and climate-resilient development interventions with direct or indirect GHG mitigation or adaptation benefits," including grants, project-level debt and equity, and balance sheet financing, drawing on data from a variety of bilateral and multilateral public financial institutions, private sector analysts, and civil society organizations (Buchner et al. 2019).

It is also challenging to accurately project total climate financing needs due to continually improving understanding of climate science, rapidly falling technology costs, and societal shifts. Based on different assessments of climate investment needs for energy, transportation, water and sanitation, nature-based solutions, and adaptation by the IPCC (2018), IEA (2021c), OECD (2017), and UNEP (2021b, 2016), we suggest that climate finance flows will need to reach at least $5 trillion per year by 2030 and sustain this level through 2050 (see Table 16).

TABLE 16. Estimates of annual climate investment needs (trillion US$)

Sector, scope, and temperature pathway	Source	2030	2050
Energy, global, 1.5°C	IPCC (2018)[a]	$2.32	n/a
	IEA (2021c)[b]	$4.4	$4.2
Energy, transport, water, sanitation, and telecommunication infrastructure, global, 2°C	OECD (2017)[c]	$6.9	n/a
Mean of energy-focused assessments		$4.54	$4.2
Nature-based solutions, global	UNEP (2021b)[d]	$0.354	$0.536
Adaptation finance, developing countries	UNEP (2016)[e]	$0.14–$0.3	$0.28–$0.5
TOTAL[f]		$5.03–$5.19	$5.02–$5.24

Note: n/a = not applicable.

a The Intergovernmental Panel on Climate Change's (IPCC) review of integrated assessment models of global energy investment needs for a 1.5°C scenario found a mean value of $2.32 trillion annually between 2015 and 2035 (IPCC 2018).

b The International Energy Agency's (IEA) net-zero roadmap for 1.5°C projects that total energy investment needs will be $4.98 trillion per year by 2030, of which $4.4 trillion will be for clean energy systems, and $4.53 trillion by 2050, of which $4.2 trillion will be for clean energy (IEA 2021c).

c The Organisation for Economic Co-operation and Development (OECD) assessed global infrastructure investment needs across the energy, transport, water, sanitation, and telecommunication sectors for a 2°C scenario to be $6.9 trillion annually between 2016 and 2030, of which $0.6 trillion was incremental to a baseline scenario without additional climate action (OECD 2017).

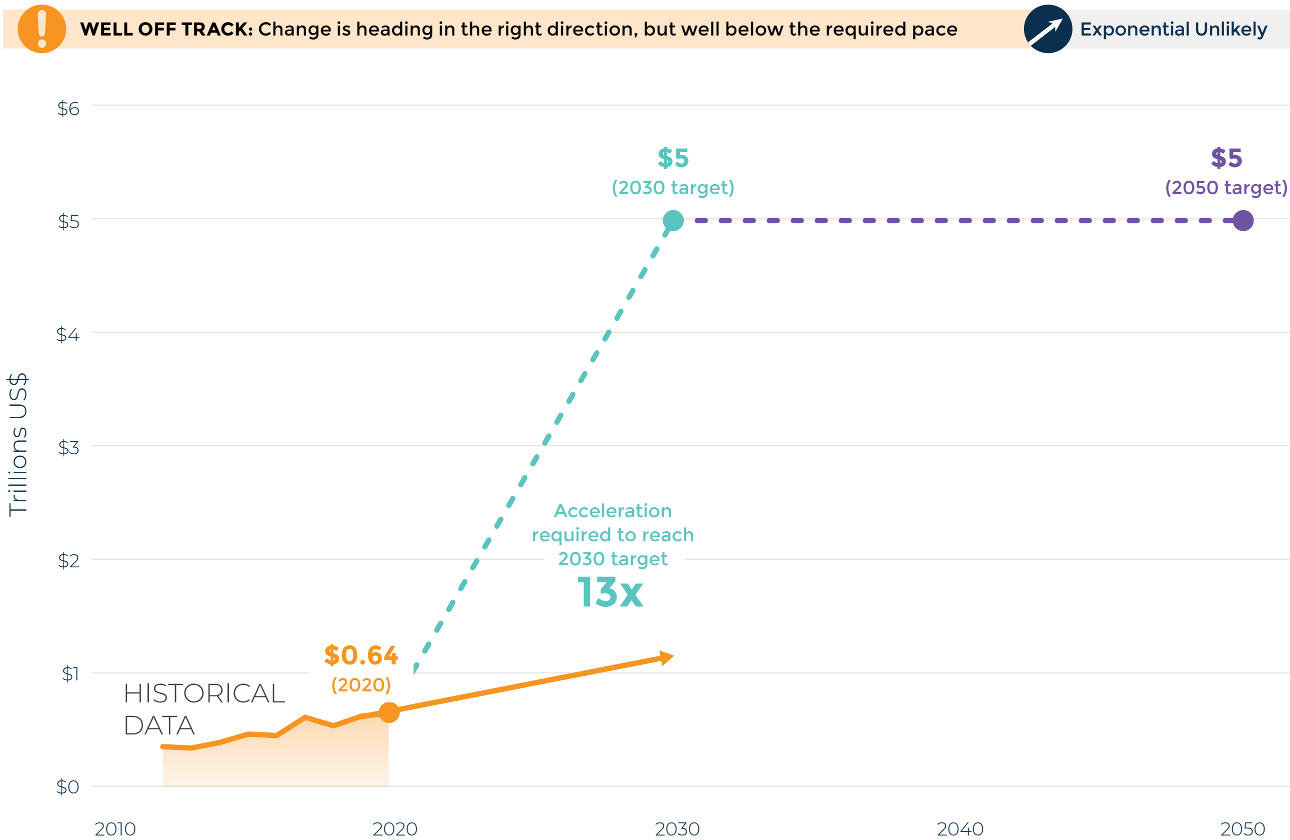
d The United Nations Environment Programme (UNEP) estimates finance needed for nature-based solutions to meet climate change, biodiversity, and land degradation targets to be $354 billion per year in 2030 and $536 billion per year in 2050 (UNEP 2021b).

e UNEP estimated annual adaptation finance needs in developing countries to be between $140 billion and $300 billion by 2030 and $280 billion to $500 billion by 2050 (UNEP 2016).

f Adding the nature-based solutions and adaptation finance estimates to the $4.54 trillion energy and infrastructure mean investment needs from the IPCC, IEA, and OECD would take the total investment needs to $5.03 trillion to $5.19 trillion per year in 2030. Only the IEA included a 2050 energy investment needs estimate of $4.2 trillion; adding the nature-based solution and adaptation finance needs estimates takes total investment needs to $5.02 trillion to $5.24 trillion per year in 2050.

Total global flows of climate finance as tracked by CPI, however, are still much lower, reaching $640 billion in 2020, an average increase of $33.6 billion per year over the preceding five years (CPI 2021). By comparison, total global investment in fossil fuels was estimated at $726 billion in 2020 (IEA 2021f), 13 percent more than total tracked climate finance. The amount of global climate finance would need to increase nearly eightfold to reach $5 trillion per year by 2030, an average increase of $436 billion a year between 2020 and 2030. This is 13 times the historical rate of increase. It should be noted that a number of gaps exist in the climate finance tracking data, and CPI takes a conservative approach to collecting and reporting data,[90] meaning actual climate-related finance flows may be higher (Buchner et al. 2019). Nonetheless, that gap between investment needs and climate finance flows remains large (see Figure 82), beyond what may be missed due to tracking issues, so a significant scale-up in both public and private finance will be necessary.

FIGURE 82. Historical progress toward 2030 and 2050 targets for total climate finance



Sources: Historical data from Buchner et al. (2019); Macquarie et al. (2020); and CPI (2021); 2030 and 2050 targets based on analysis of IPCC (2018); IEA (2021c); OECD (2017); and UNEP (2016; 2021b).

FINANCE INDICATOR 2:
Public climate finance

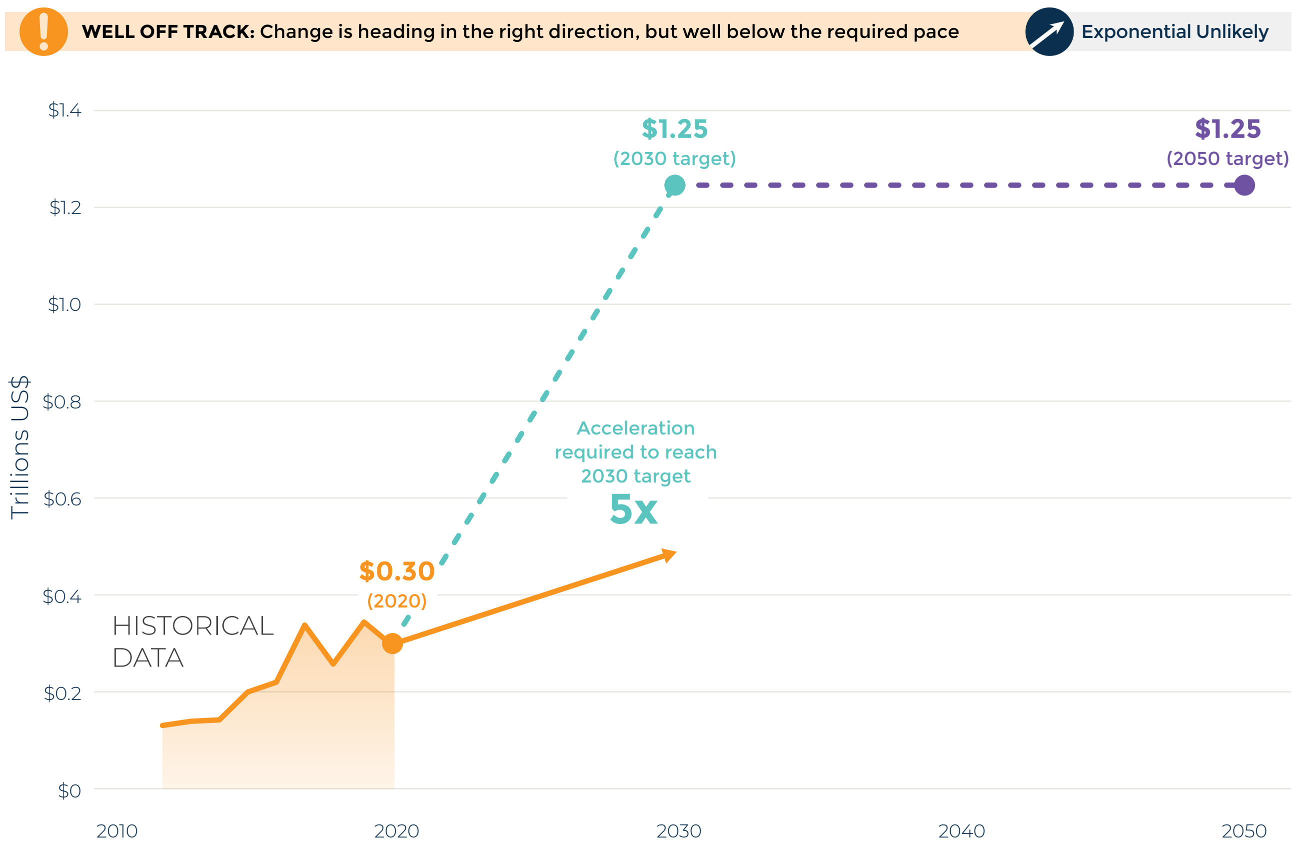
Targets: Global public climate finance flows reach at least $1.25 trillion per year by 2030 and are sustained through 2050.

Scaled up public finance 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, and 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, which markets alone do not guarantee (see Chapter 11, "Equity and just transition").

While it is difficult to determine the precise breakdown between public and private finance needed to meet climate goals, the IPCC cites the World Bank's projection that a quarter of global climate investment will come from public sources (IPCC 2018). Based on this, global public climate finance would need to be $1.25 trillion per year by 2030 (Figure 83). Global public climate finance flows as tracked by CPI amounted to $300 billion in 2020, an average growth of $19 billion per year between 2015 and 2020 (CPI 2021). 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. 2019), so total public climate finance may be higher than is currently tracked. Based on available data, public climate finance would need to quadruple to reach $1.25 trillion per year by 2030, growing at an average rate of $95 billion per year between 2020 and 2030. This represents a 5-fold increase compared to historical growth rates.

Smaller tax bases and sovereign creditworthiness limit lower-income countries' ability to raise domestic public expenditures, so these countries will require international public finance to meet some of their public climate investment needs. In 2009, developed countries

FIGURE 83. Historical progress toward 2030 and 2050 targets for public climate finance

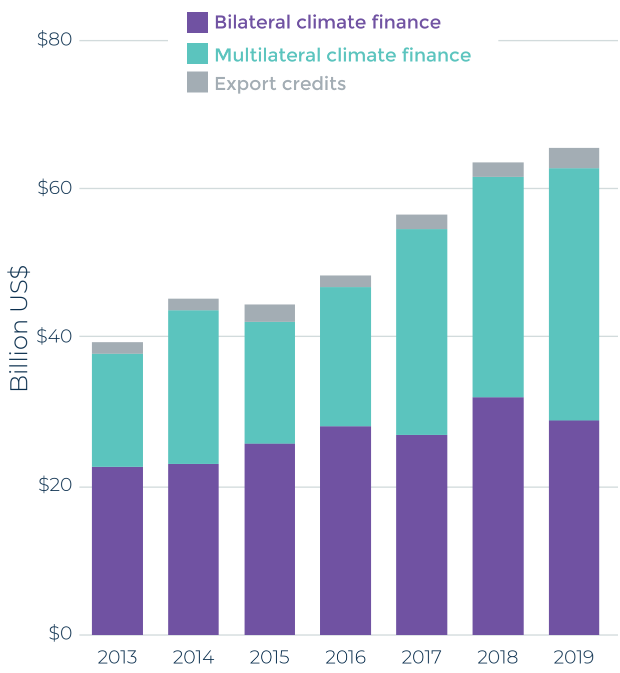


Sources: Historical data from Buchner et al. (2019); Macquarie et al. (2020); and CPI (2021); 2030 and 2050 targets based on analysis of IPCC (2018); IEA (2021c); OECD (2017); and UNEP (2016; 2021b).

committed to mobilizing $100 billion annually in climate finance from public, private, and alternative sources for developing countries by 2020 (UNFCCC 2010, para. 8). In 2015, developed countries agreed to maintain this mobilization goal until 2025, by which point a new collective quantified goal from a floor of $100 billion per year would be agreed upon (UNFCCC 2016, para. 53).

The Organisation for Economic Co-operation and Development (OECD) estimated that public climate finance from developed to developing countries reached $65.5 billion in 2019 (see Figure 84),[91] an average growth of $4.3 billion per year since 2013 (OECD 2021c). This represents a fifth of global tracked public climate finance in 2019 of $343 billion (CPI 2021). These figures are based on developed countries' self-reporting, and other analyses have suggested that climate finance may be flowing at lower rates (Carty et al. 2020). Developed countries did not likely meet their commitment of $100 billion by 2020 (Battacharya et al. 2020). So as not to prejudge the outcomes of negotiations on the new collective quantified goal under the UNFCCC, we do not set a specific 2030 or 2050 target for developed to developing country public climate finance, but it will be extremely important to establish an ambitious goal to ensure sufficient public finance for developing countries to make the needed investments in climate action.

FIGURE 84. Developed to developing country public climate finance flows



Source: Adapted from OECD (2021c).

Enablers of climate action

There are several key barriers to scaling up public finance: institutional arrangements that restrict governments' ability to raise public spending, lack of political leadership to make ambitious public spending commitments, and social norms that may be averse to greater levels of public spending. The following measures can help overcome these obstacles.

Increasing fiscal space for government spending on climate action

Increased government spending generally requires fiscal space, either through more tax revenues, more debt issuance, or reductions in spending in other areas. Raising taxes on wealthy individuals and major corporations are the most politically popular and equitable approaches to increasing government tax revenues. Efforts within the OECD and G20 to establish a global minimum corporate tax rate, which have been backed by the G7, can help tackle tax evasion and are estimated to raise tax revenue by between $60 billion and $100 billion a year (OECD 2021b; G7 2021). Another form of progressive taxation is a financial transaction tax, a small levy on sales of stocks, bonds, and other financial contracts. Many jurisdictions already have some form of financial transaction tax (FTT), and the European Union and United States are currently considering proposals (Dowd 2020). Academics have estimated a globally applied FTT 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).[92] Proceeds from carbon pricing (carbon tax revenues and proceeds from auctions of emissions trading credits) could also be used to finance increased government spending on climate action;[93] carbon-pricing instruments generated $53 billion in revenue in 2020, the majority in European countries (World Bank 2021b). Researchers at the International Monetary Fund (IMF) estimated that a carbon tax on international transportation fuels of $75 per tonne in 2030 would raise $120 billion a year in revenue (IMF 2019). Finance Indicator 5 goes into more detail on carbon pricing. But even if a broad carbon price is not implemented, targeted modest taxation of fossil fuels could also raise substantial revenues. The International Institute for Sustainable Development (IISD) estimated that 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 (Sánchez et al. 2021).

International financial institutions could also 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). 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 can improve governments' ability to raise public finance through borrowing (Volz et al. 2020; Fresnillo 2020). Reducing public spending on fossil fuels and other emissions-intensive sectors can also free up resources to invest in climate action. The IISD estimated that ending consumer fossil fuel subsidies on transportation fuels and coal could raise $123 billion per year (Sánchez et al. 2021). Table 17 provides an overview of potential revenues from these different sources, while Finance Indicator 7 goes into more detail on the scale of fossil fuel subsidies and efforts to phase them out.

TABLE 17. Potential sources of revenue for increased public climate finance

Type of revenue-raising mechanism	Amount per year	Source
Global minimum corporate tax	$60 billion to $100 billion	OECD (2021b)
Global financial transaction tax	$238 billion to $419 billion	Pekanov and Schratzenstaller (2019)
Current carbon-pricing revenues	$53 billion	World Bank (2021b)
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	Sánchez et al. (2021)
Ending consumer fossil fuel subsidies	$123 billion	Sánchez et al. (2021)

Note: 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 have the potential to go a significant way toward meeting public climate finance targets.

Strengthening leadership from governments to invest more public money on climate

Scaled-up public spending can also be unlocked by governments showing leadership by increasing public investments, even if they may not be immediately politically popular. Developed countries also need to provide more clarity on how they will scale up public climate finance for developing countries, including individual pledges, in order to meet and exceed the $100 billion mobilization goal.

Shifting social norms to support government spending and policies

Shifting social norms toward greater public support for government spending can help drive increases in public climate finance by giving political leaders a mandate to show leadership by raising public spending. In a recent UNDP poll of 1.2 million people in 50 countries covering 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 (UNDP 2021).[94] Changing attitudes toward increased taxation or debt financing can also help open up political space for greater public spending. Responsive and representative governance institutions will be necessary for shifts in public opinion to translate into policy change.

FINANCE INDICATOR 3:

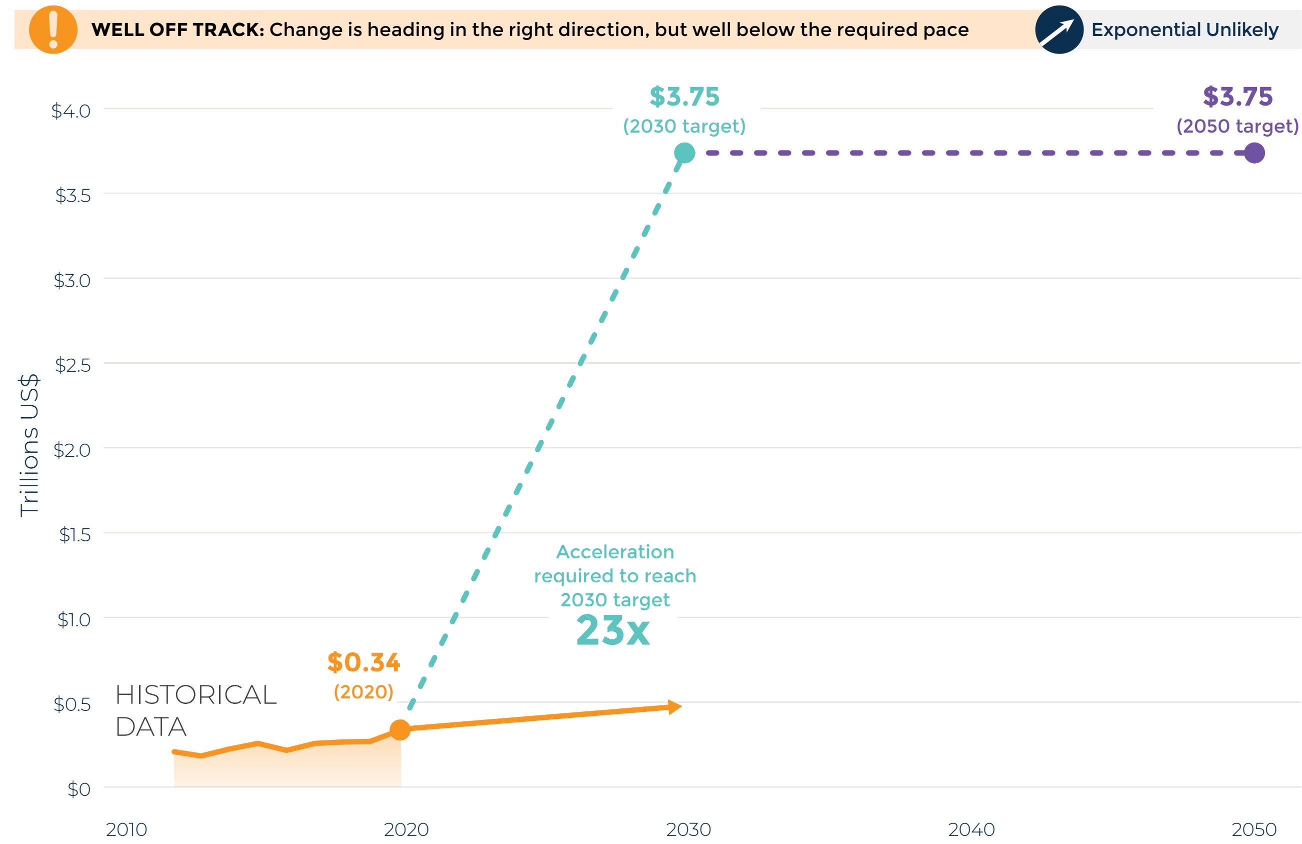
Global private climate finance

Target: Global private climate finance flows reach at least $3.75 trillion per year by 2030.

It is also 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 that are misaligned with the Paris Agreement will need to be scaled down, and if these are then shifted toward climate objectives, it could play a substantial role in contributing to the total climate finance needed. There is a lack of data on the degree to which private investments are misaligned, and Finance Indicator 4 on measuring, managing, and disclosing carbon risks can help address these gaps. Assuming public sources of climate finance will meet a quarter of the investment needed, as discussed in the preceding section on public climate finance (IPCC 2018), private climate finance flows of at least $3.75 trillion per year will be necessary by 2030 (Figure 85).

Global private climate finance flows from financial institutions, institutional investors, corporations, and households amounted to $340 billion in 2020, only 13 percent more than global public climate finance flows, although significant data gaps exist for private climate finance tracking data sets,[95] so actual climate-related finance flows may be higher (CPI 2021). Private climate finance grew by an average of $14.6 billion per year between 2015 and 2020, less than the growth in public climate finance over the same period. Based on available data, to date, businesses do not yet appear to be investing in climate at anywhere near the level required. The total amount of private climate finance will need to increase by more than 11 times by 2030 to reach the $3.75 trillion per year needed, requiring an average growth rate of $341 billion per year between 2020 and 2030. This is 23 times the historical growth rate.

FIGURE 85. Historical progress toward 2030 and 2050 targets for private climate finance



Sources: Historical data from Buchner et al. (2019); Macquarie et al. (2020); and CPI (2021); 2030 and 2050 targets based on analysis of IPCC (2018), IEA (2021c), OECD (2017), and UNEP (2016; 2021b).

Enablers of change

Significantly scaling up private climate finance faces complex challenges and requires actions from both the private and public sectors. Increasing private sector climate finance commitments and actions can help mainstream climate into decision-making within the private sector that, in turn, can help reallocate capital to climate finance. It's also important to have supportive government policies and regulations to provide a conducive environment for private investment in climate mitigation, as the social return on climate mitigation investments are often greater than financial return due to the negative externalities of climate change.

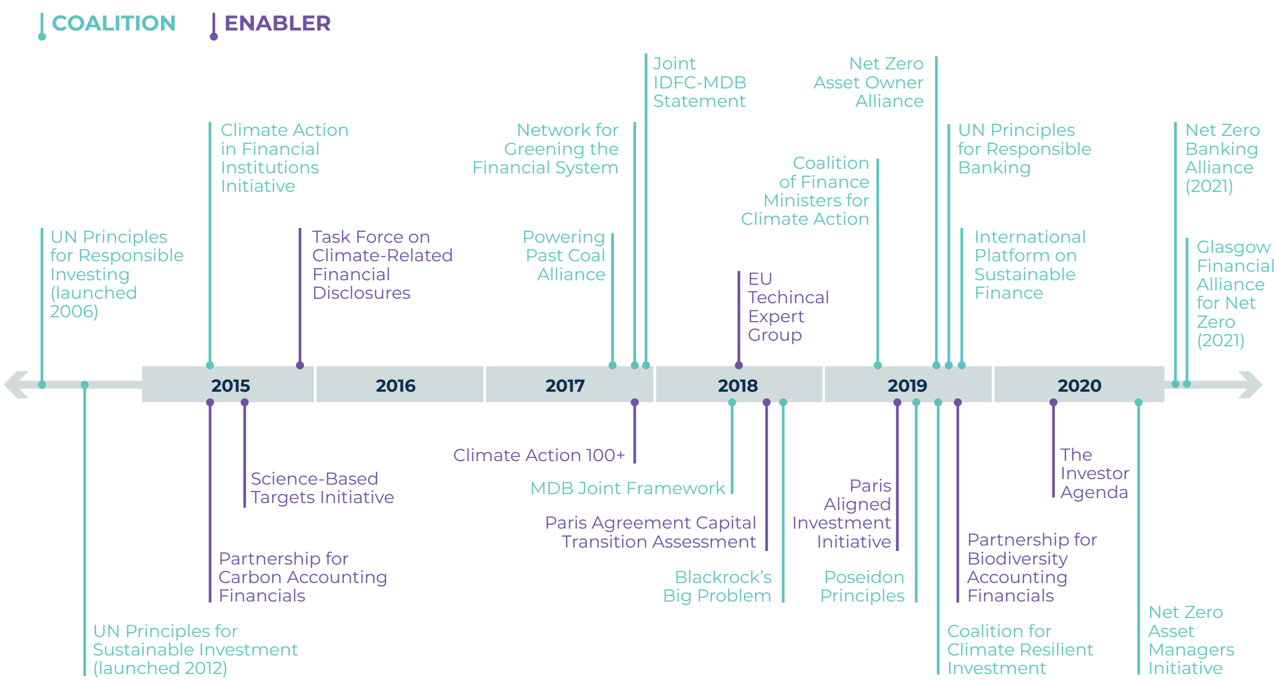
Increasing private sector climate finance commitments—and translating them into action

Many financial sector sustainability initiatives have been launched in recent years to encourage financial institutions to commit to increasing their climate-aligned finance (see Figure 86). Of the 50 largest private-sector banks globally, only 23 had a sustainable finance target as of July 2019 (WRI 2019a). The recent Glasgow Financial Alliance for Net-Zero brings together net-zero alliances of asset managers, asset owners, and banks, comprising over 250 firms collectively responsible for more than $80 trillion in assets. These actors have committed to science-aligned interim and long-term goals to reach net zero no later than 2050 (Carney 2021; UNFCCC 2021). Translating these commitments into concrete actions that reallocate capital away from high-emissions activities and toward climate-aligned investments will be important. To do this, climate needs to be mainstreamed into everyday decision-making throughout companies. Ensuring 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).

Adopting policies that encourage private investments in climate mitigation

Other sections of this chapter cover a number of ways to encourage and direct private investment toward climate objectives: financial policies and regulations influence private investment flows through force of law (see Finance Indicator 4); fiscal policy levers change price signals to influence private investment decisions (see Finance Indicators 5 and 6); and direct public financing can be used to reduce the financial risk for private investors (see Finance Indicator 2) (Whitley et al. 2018).[96]

FIGURE 86. Sustainability coalitions and initiatives in the financial sector



Note: IDFC-MDB = International Development Finance Club-Multilateral Development Bank. UN = United Nations; MDB = multilateral development bank; EU = European Union

Source: Adapted from Tonkonogy and Choi (2021).

FINANCE INDICATOR 4:

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), and all of the world's 2,000 largest public companies report on climate risk in line with TCFD recommendations by 2030.

Measuring, managing, and disclosing climate-related risks is a crucial component for the financial market to allocate resources efficiently to the assets and investments that are best positioned to mitigate and adapt to climate change. Accurate, timely, and comparable material information from companies, such as financial disclosures, provide a realistic picture of firms' past performance and future prospects. This type of information is essential for investors, creditors, regulators, and other market participants to correctly price assets and efficiently allocate capital (Glassman 2003). Climate change could have significant financial implications across economic sectors and industries (TCFD 2017). Measuring, managing, and disclosing climate-related risks in a way that is similar to financial reporting would be useful to decision-makers in understanding these risks.

The Financial Stability Board, an international body under the G20 that monitors and makes recommendations about the global financial system, created the TCFD to improve and increase reporting of climate-related risks. The TCFD divided climate-related risks into risks related to the transition to a lower-carbon economy and risks related to the physical impacts of climate change. It developed a comprehensive framework to help companies and other organizations more effectively disclose those risks in 2017 (TCFD 2017). It has become the standard framework for climate-related financial disclosures (Kröner and Newman 2021).

Many companies and financial institutions have endorsed or adopted the TCFD recommendations. Financial institutions—investors, banks, insurers, and pension funds—responsible for assets of $150 trillion have endorsed or adopted the TCFD recommendations and are demanding that companies they invest in assess and disclose climate-related risks. Larger companies are more likely to disclose information aligned with these recommendations: 42 percent of companies with a market capitalization (the value of a company that is traded on the stock market) greater than $10 billion did so, while only 15 percent of companies with a market capitalization less than $2.8 billion did, suggesting that smaller businesses may encounter greater challenges in complying with disclosure requirements or that they are under less pressure to address these issues. However, high-quality disclosure against all of the recommendations is still rare (TCFD 2020). As such, data are currently insufficient to assess the extent to which governments' and companies' risk reporting meets the indicator target.

Enablers of change

Efforts to measure, manage, and disclose carbon risks face many challenges. Net-zero GHG emission targets are important commitments for financial institutions to have real mitigation impact across the economy. Financial institutions should provide adequate disclosures that integrate interim targets (for example, 2030 targets) and strategic changes to allow investors and other stakeholders to evaluate their preparedness for a transition to a low-carbon economy. Voluntary standards and disclosures are encouraging, but only mandatory disclosure requirements can help achieve universal, consistent, and comparable disclosure.

Setting net-zero GHG emission targets

Because they have a wide range of impacts on every sector, financial institutions have a particularly important role to play in unlocking the systematic change needed to reach net-zero GHG emissions by 2050. Their exposure to the wider economy through lending and investment portfolios across industries means that they could be at a higher risk than other sectors, but this also means that they could play a more proactive role in supporting the real economy in line with climate goals. Reducing their operational carbon footprint, alongside decarbonizing their lending and investment portfolios, then could have cascading, economy-wide effects.

Establishing mandatory disclosure requirements

As 59 countries representing more than half of global GHG emissions, including China and the United States, have set net-zero emissions targets, many of them may also legislate mandatory disclosure of climate-related risks (ECIU 2021). In fact, several countries, including the United Kingdom, Hong Kong, South Korea, and New Zealand, have already taken action on mandatory climate disclosure (Jupiter 2021), and other governments, including the United States, are exploring new climate disclosure requirements (Lee 2021b). The G20 has also indicated its support for efforts to harmonize climate risk reporting standards through the International Financial Reporting Standards Foundation. Although an increasing number of companies and financial institutions are stepping up to set net-zero goals, mandatory disclosure will be important so the financial market has consistent and comparable information from all participants. Of the world's 2,000 largest public companies by sales, only one-fifth now have net-zero commitments, and these commitments vary greatly in quality (Black et al. 2021). Mandatory disclosure could have all companies report climate-related risks in a consistent way.

FINANCE INDICATORS 5 AND 6: Properly priced emissions (Share of global emissions covered by a carbon price of at least $135 per tonne of CO_2e and total public financing for fossil fuels)

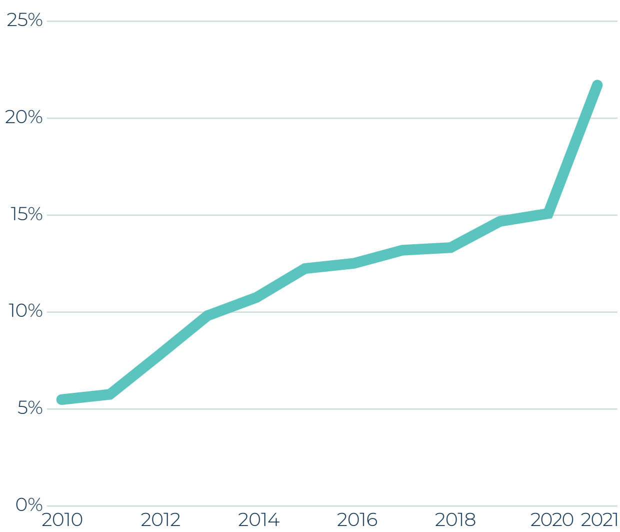
Targets: The majority of global emissions are covered by a carbon price of at least $135/$tCO_2e$ in 2030, and the majority of global emissions covered by a carbon price of at least $245/$tCO_2e$ in 2050.

Targets: Public financing for fossil fuels, including subsidies, is phased out by 2030, with G7 countries and international financial institutions achieving this by 2025.

Climate change has been called "the greatest and widest-ranging market failure ever seen," with a wide range of economists arguing that market prices do not properly account for the costs of the damages that rising GHG emissions inflict upon communities around the world (Stern 2006). Putting a sufficiently high price on carbon can send a market signal that can help shift investment and consumption decisions in a way that contributes to reducing emissions to a level compatible with a 1.5°C pathway (IPCC 2018). At the same time, significant sums of public finance for fossil fuels lower their cost, acting as a negative carbon price. Ending fossil fuel subsidies is therefore another means to ensure that GHG are properly priced (World Bank 2021b). Many fossil fuel projects rely on public support to remain profitable; in the United States, it is estimated that production subsidies bring nearly half of new, yet-to-be-developed oil investments into profitability (Erickson et al. 2017). Removing such public financing can help reduce fossil fuel use and accelerate emissions reductions, and can also help stimulate the shift of private finance flows away from fossil fuels through policy signaling and shifting financial incentives (Whitley et al. 2018).

The IPCC identified the undiscounted carbon price consistent with achieving 1.5°C as being $135–$6,050/tCO_2e in 2030 and $245–$14,300/tCO_2e in 2050, in 2010 dollars (IPCC 2018). In 2021, carbon pricing through a carbon tax or an emissions trading system (ETS) covered 21.5 percent of global GHG emissions, a significant increase from the 2020 coverage of 15.1 percent, largely due to China's launch of a national ETS (Figure 87) (World Bank 2021b). However, the majority of prices are insufficient to fully account for the costs associated with rising GHG emissions. Only 3.76 percent of global emissions are currently covered at or above the $40–$80/tCO_2e range that is currently consistent with a 2°C pathway, and

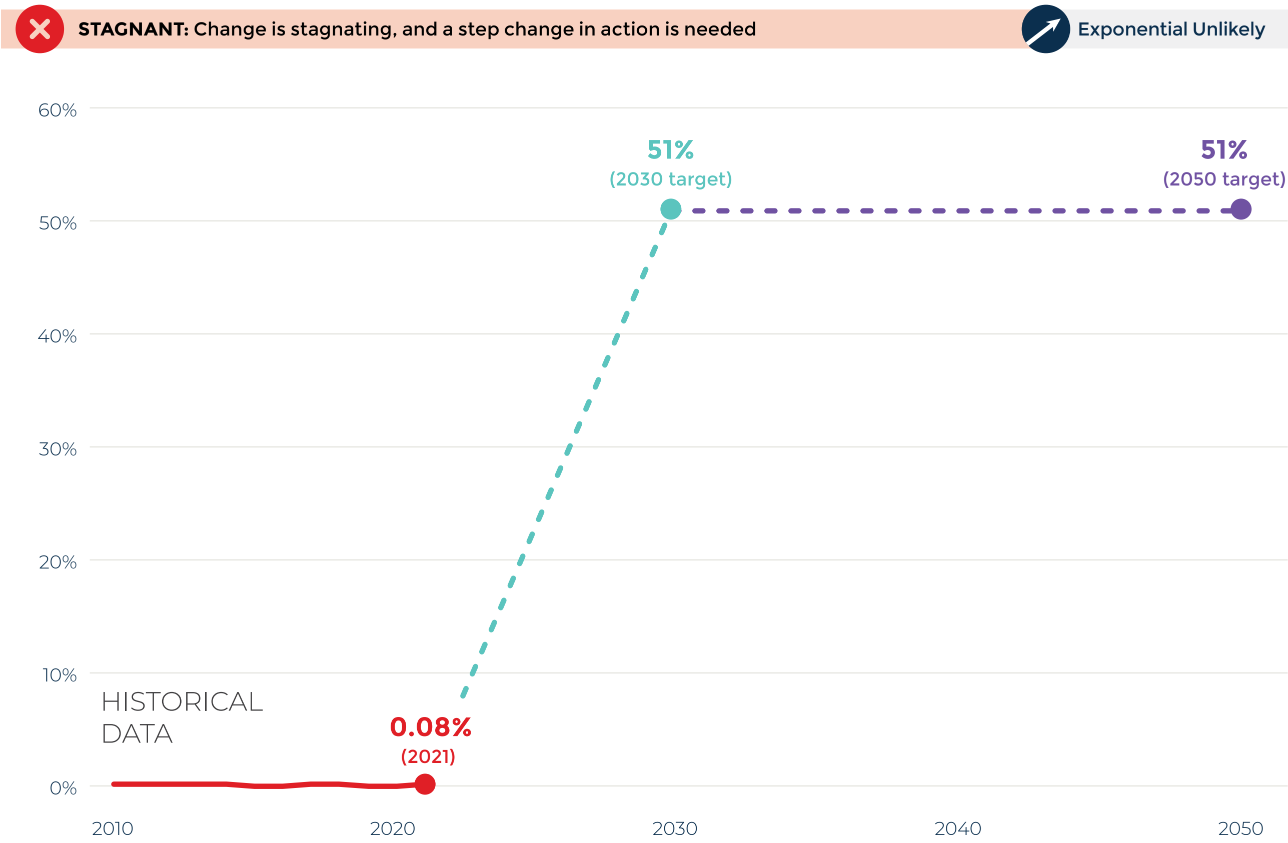
FIGURE 87. Share of global emissions covered by any carbon price



Source: Adapted from World Bank (2021a).

just 0.08 percent (Sweden's emissions) are at the \$135/tCO_2e minimum level required by 2030 to be consistent with a 1.5°C pathway (World Bank 2021b). If carbon pricing is to make a meaningful contribution to climate action, both its scope and level would need to be significantly increased (see Figure 88). It is also important to note that carbon pricing alone is not sufficient to address climate change and that complementary policies will be required (Kennedy 2019).

FIGURE 88. Historical progress toward 2030 and 2050 targets for the share of global greenhouse gas emissions covered by a carbon price of at least \$135 per tonne of CO_2e

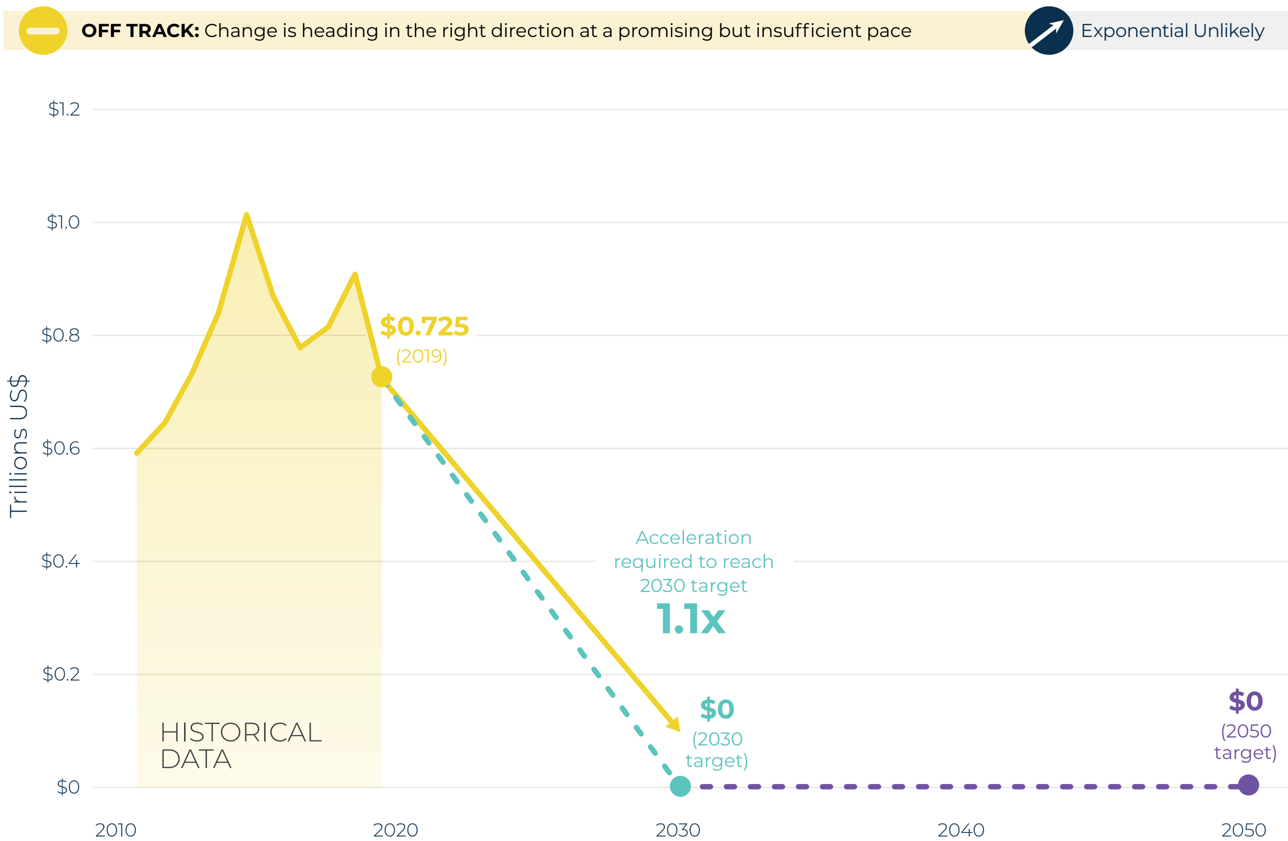


Note: CO_2e = carbon dioxide equivalent. The undiscounted carbon price the IPCC specified as the minimum level consistent with a 1.5°C pathway was \$135/tCO_2e in 2010 US\$ (IPCC 2018).
Source: Historical data adapted from World Bank (2021a); 2030 target based on IPCC (2018).

We therefore set the 2030 target at 51 percent (a simple majority) of global emissions covered at a price of at least \$135/tCO_2e and the 2050 target at 51 percent of global emissions covered at a price of at least \$245/tCO_2e. Even if these targets were met, other climate policies will be needed to address the remaining 49 percent of emissions not covered by an adequate carbon price.

The IEA's net-zero roadmap found that, beyond projects already committed to in 2021, no new investment in fossil fuel supply is required (IEA 2021c). This gives a clear signal to political leaders that public financing for new fossil fuel supply is not compatible with the Paris Agreement, and, in combination with recent IPCC findings (IPCC 2018), indicates the need to progressively phase out all fossil fuel financing along the value chain in order to meet Paris commitments (Figure 89). Both the G20 and G7 have long-standing commitments to phase out fossil fuel subsidies, with the former stating in 2009 that it would do so "over the medium term," and the latter in 2016 setting a deadline for doing so by 2025 (G20 2009; G7 2016). Yet significant public financing for fossil fuels continues, with estimates putting the total figure at \$801 billion in 2019 (Sánchez et al. 2021).[97] The OECD and IEA joint estimate of production and consumption subsidies in 81 economies through direct government payments, tax breaks, and price support was \$468 billion in 2019 (OECD 2021a), of which \$64 billion was estimated to be production subsidies and \$404 billion consumption subsidies (Sánchez et al. 2021). In addition to these amounts, public financing for fossil fuel projects from multilateral development banks (MDBs) and G20 countries' export credit agencies (ECAs) and development finance institutions (DFIs) averaged \$77 billion annually between 2016 and 2018 (Tucker and DeAngelis 2020), and capital expenditure by state-owned entities on fossil fuels was at least \$257 billion per year

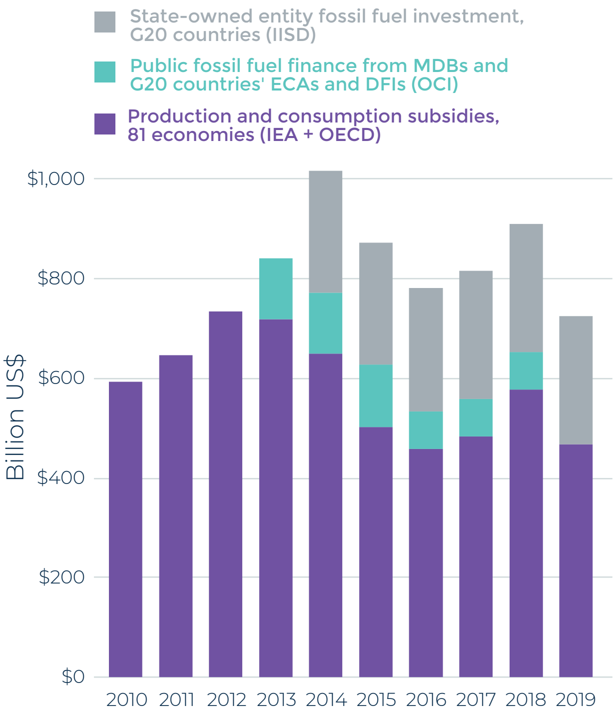
FIGURE 89. Historical progress toward 2030 and 2050 targets for total public financing for fossil fuels



Note: Historical data is a compilation of three components: 1. Production and consumption subsidies; 2. Public fossil fuel finance from multilateral development banks and G20 countries' export credit agencies and development finance institutions; 3. Fossil fuel investments by G20 countries' state-owned entities. Public fossil fuel finance estimates for multilateral development banks, export credit agencies, and development finance institutions are annualized averages for the three-year periods 2013–15 and 2016–18; estimates unavailable before 2013, or for 2019. State-owned entity fossil fuel investment estimates are annualized averages for the three-year periods 2014–16 and 2017–19; estimates unavailable before 2014.

Sources: Historical data from OECD (2021a); Doukas et al. (2017); Tucker and DeAngelis (2020); and Geddes et al. (2020); 2030 and 2050 targets based on G20 (2009) and G7 (2016) commitments.

FIGURE 90. Sources of public financing for fossil fuels



Note: IISD = International Institute for Sustainable Development; MDB = multilateral development bank; ECA = export credit agency; DFI = development finance institution; OCI = Oil Change International; IEA = International Energy Agency; OECD = Organisation for Economic Co-operation and Development. Public fossil fuel finance estimates for MDBs and G20 ECAs and DFIs are annualized averages for the three-year periods 2013–15 and 2016–18; estimates unavailable before 2013, or for 2019. State-owned entity fossil fuel investment estimates are annualized averages for the three-year periods 2014–16 and 2017–19; estimates unavailable before 2014.

Sources: Historical data from OECD (2021a); Doukas et al. (2017); Tucker and DeAngelis (2020); and Geddes et al. (2020).

on average between 2017 and 2019 (Geddes et al. 2020). Figure 90 shows the compilation of these estimates.

Consumption subsidies have been declining in recent years, due to both progress in subsidy reform and falling oil prices. The substantial drop in oil prices during the pandemic caused consumer subsidies in 42 developing country economies tracked by the IEA to fall 43 percent between 2019 and 2020 to $182 billion (IEA 2020h). Production subsidies, however, have been rising in recent years, with a 5 percent increase from 2018 to $178 billion in 2019 among the 50 OECD, G20, and European Union Eastern Partnership economies, primarily driven by an increase in direct government spending by OECD countries on fossil fuel infrastructure and corporate debt relief (OECD 2021a). COVID-19 stimulus and recovery spending looks likely to continue this trend, with multiple analyses showing greater amounts of public funding going to fossil fuels and other high-carbon sectors than to low-carbon development (UNEP and UNEP DTU Partnership 2020). Between January 2020 and August 2021, the 31 largest economies and 8 MDBs have committed $335 billion in new financing to fossil fuel-intensive sectors, compared to $273 billion in clean energy sectors (IISD 2021a).

Enablers of climate action

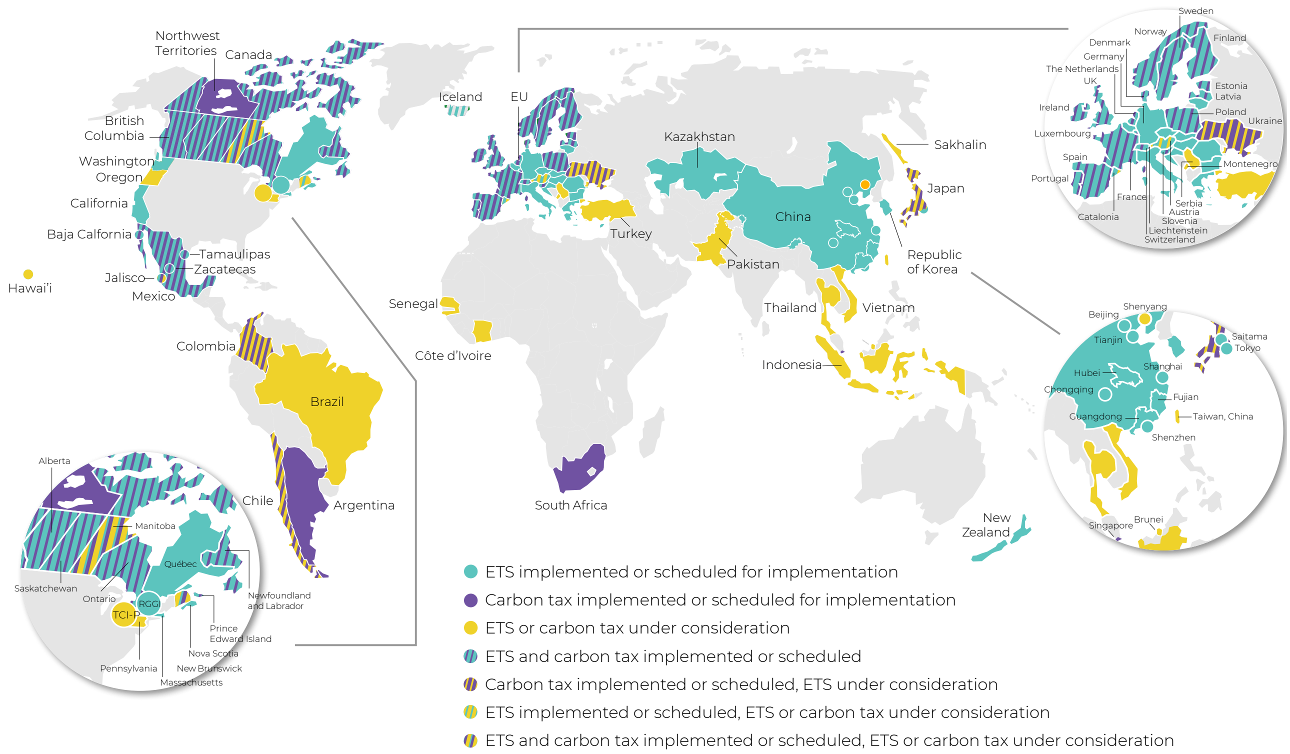
Barriers to properly pricing emissions are primarily political, including lack of support for new taxes or an end to subsidies that are seen as increasing the burden on the poor, industry opposition to ending fossil fuel subsidies, and the perceived free-rider problem where countries are reluctant to impose a carbon price on their domestic industries for fear they will move to other territories that do not have carbon pricing (carbon leakage). To the extent this phenomenon exists, or could exist, it can be addressed through greater leadership from governments to act together to implement pricing and phase out fossil fuel subsidies, thus addressing leakage concerns, and by shifting norms around the need to pay for GHG emissions.

Strengthening national commitments to establish carbon pricing and phase out fossil fuel subsidies, and international cooperation to address carbon leakage

To scale up carbon pricing globally, governments would need to establish policies to set a price on emissions, ensure they rise over time, and address potential leakage to other economies (where companies move to regimes without carbon pricing) by linking with other jurisdictions that have carbon pricing and/or by establishing border adjustment mechanisms that would apply the domestic price to imported goods as well (World Bank 2021b; UNCTAD 2021). To date, 45 countries and 35 subnational jurisdictions have implemented carbon-pricing initiatives, shown in Figure 91 (World Bank 2021a).

Governments also need to show leadership in phasing out fossil fuel subsidies. Fossil fuel consumption subsidies have already been declining, while production subsidies have continued to rise. A low oil price environment can make it politically easier to phase out consumption subsidies (IEA 2020h); however, when oil prices increase, public demand for restoration of subsidies can rise, so studies have emphasized the need to also focus on phasing out production subsidies and scaling up support for clean energy alternatives (SEI et al. 2020; Sánchez et al. 2021). These measures can reduce reliance on fossil fuels and thereby consumer sensitivity to oil prices, making the further phaseout of consumption subsidies politically easier. A growing number of governments and public finance institutions have shown leadership by committing to end most fossil fuel financing, including the European Investment Bank and the United Kingdom (EIB 2019; BEIS 2021).[98]

FIGURE 91. Map of carbon taxes and emissions trading systems



Note: ETS = emissions trading system; RGGI = Regional Greenhouse Gas Initiative; TCI-P = Transportation and Climate Initiative Program. The large circles represent cooperation initiatives on carbon pricing between subnational jurisdictions. The small circles represent carbon pricing initiatives in cities. Carbon pricing initiatives are considered "scheduled for implementation" once they have been formally adopted through legislation and have an official, planned start date. Carbon pricing initiatives are considered "under consideration if the government has announced its intention to work towards the implementation of a carbon pricing initiative and this has been formally confirmed by official government sources. The carbon pricing initiatives have been classified in ETSs and carbon taxes according to how they operate technically. ETS not only refers to cap-and-trade systems, but also baseline-and-credit systems as seen in British Columbia."

Source: Adapted from World Bank (2021b). Responsibility for the views and opinions expressed in this adaptation rests solely with the authors of the adaptation and are not endorsed by The World Bank.

Shifting social norms to support carbon pricing

A significant challenge with carbon pricing and subsidy reform is public popularity. In the UNDP's climate survey of 1.2 million people globally, making companies pay for their pollution had just 39 percent support, although this rose to 55 percent in high-income countries (UNDP 2021). Given that the business-as-usual scenario is for emissions to have no direct price, carbon pricing feels like the addition of a new burden, whereas it is designed to internalize the costs that are diffused to society at large. Engagement and education can help to shift social norms around whether emissions should be priced (Marshall et al. 2018). The use of revenues is particularly important, with higher levels of public support for carbon pricing when revenues are earmarked for investments in climate action or consumer rebates (Baranzini and Carattini 2017; Carattini et al. 2018; Klenert et al. 2018).

Economic incentives to help address the equity impacts of emissions pricing and fossil fuel subsidy phaseout on the poorest

A concern with carbon pricing is 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 as they have the least ability to pay. Policies to address equity impacts of carbon pricing, for example, by having mechanisms that provide poorer households with rebates or financial support to compensate for higher prices, can also help overcome public opposition to pricing (Klenert et al. 2018).

There are also concerns that ending fossil fuel consumption subsidies will hurt the poorest by making energy costs higher, and that fossil fuel production subsidies are necessary to protect jobs in the sector. Studies across many countries have shown that the richest households capture most of the benefits of consumption subsidies (Coady et al. 2015). This suggests that fossil fuel consumption subsidies are not an effective tool for addressing energy poverty, and that reforming energy subsidies to be technology-neutral or providing direct income support can better ensure energy access for the poorest (Zinecker et al. 2018). Removal of fossil fuel consumption subsidies should be matched by increased cash support or other measures in order to ensure equitable outcomes (see also Chapter 11, "Equity and just transition"). For production subsidies, modeling suggests that shifting away from fossil fuels toward renewable energy can stimulate greater job creation in addition to the climate benefits. 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). It will be important to provide support for the just transition of workers from fossil fuel industries and to ensure that jobs created in the clean economy are quality, well-paying jobs (see Chapter 11).

EQUITY AND JUST TRANSITION

Climate change will only worsen poverty and inequality (University of Notre Dame 2021; IPCC 2018; Herold et al. 2017; Leichenko and Silva 2014; UNDRR 2019), while keeping global warming below 2°C could create a gross number of 24 million jobs globally by 2030 while generating widespread social and health benefits (Gouldson et al. 2018; ILO 2018a; Mountford et al. 2019; NCE 2018). However, the systems transformations that will be required across countries and sectors to mitigate climate change could result in the gross loss of 6 million jobs by 2030, overwhelmingly in the energy sector, and could disrupt the economies of areas that are currently linked to the fossil fuel industry or carbon-intensive activities like manufacturing steel or cement (ILO 2018a). Moreover, low-carbon measures and technologies can generate benefits and burdens that are unequally distributed within and among countries (IPCC 2018; Markkanen and Anger-Kraavi 2019).

THIS SECTION EXPLORES BOTH A JUST transition for fossil fuel workers and communities and the wider equity implications of low-carbon systems transformations (Box 8 describes how "equity" is defined in this chapter).

A just transition for workers and communities

Achieving a just transition requires tackling the challenges faced by workers and communities whose livelihoods and economies are tied to high-carbon industries. This means undertaking inclusive planning and decision-making processes to create proactive plans that can smooth the transition to sustainable livelihoods and industries, equitably distribute the costs and benefits of transformations, and ensure justice for communities that have been especially harmed by carbon-intensive development and infrastructure (ILO 2015, 2018b; ITUC 2021a). Important components of a just transition include ensuring that

- social dialogue and stakeholder engagement take place among workers, employers, governments, communities, and civil society;
- affected workers and communities receive the social protections and support that they need to work and thrive in a zero-carbon future;

BOX 8. Definitions of equity

"The world needs an inclusive, equitable response to the many crises it now faces. Solutions must be just and fair, generating benefits shared among all rather than adverse impacts shouldered by a few. Equity must be procedural, distributional, structural, and transgenerational:

- Procedural equity ensures that everyone, everywhere has the voice, power, and ability to shape decision-making processes; equitable programs and policies include those that are developed and implemented utilizing inclusive, accessible, and representative processes.
- Distributional equity involves the fair distribution of costs and benefits across society.
- Structural equity recognizes historical, cultural, institutional, and political structures and relationships, which exist to maintain the status quo by prioritizing the privileged and the powerful, while disadvantaging the marginalized.
- Transgenerational equity considers the generational impacts of today's decisions, with a focus on reducing burdens on future generations."

Source: Levin et al. (2020).

- the benefits of systems transformations are equitably shared, including ensuring that jobs in climate-friendly sectors are high-quality and accessible;
- revenue streams that governments currently receive from fossil fuel production will be replaced in equitable ways, including avoiding regressive taxation or spending cuts that undermine equity and development goals; and
- companies create decent jobs and contribute to economic growth while taking positive action on climate change (ILO 2015; WRI 2021i).

Just transitions around the world

The concept of just transitions emerged from the labor movement in developed countries, and to date most literature and initiatives have focused on developed countries such as the United States, Canada, Germany, and Australia (ITUC 2021a; Pai et al. 2020a). However, momentum is building in developing and emerging countries, notably India, South Africa, Chile, and Indonesia (Athawale et al. 2019; Burton et al. 2019; Elliott and Setyowati 2020; Swilling et al. 2016; Tongia et al. 2020; Zhang and Wang 2018). This is starting to bring much-needed attention to the challenges and opportunities that are specific to those contexts, which may include the lack of a social safety net, a higher prevalence of informal work, and rising rates of urbanization or industrialization.

Just transition initiatives around the world offer examples and lessons for how workers and communities can benefit from the transformations that are needed to limit global warming to 1.5°C (WRI 2021i). Some positive examples include Spain's Just Transition Strategy, which outlines a structured, participatory process to protect fossil fuel workers from unemployment and plan for the future of coal regions (del Río 2017; ITUC 2019); the Noor solar power station in Morocco, which was developed with measures in place to generate economic benefits for the nearby rural, lower-income communities (Terrapon-Pfaff et al. 2019; WRI 2021m); and the Ruhr region in Germany, which successfully pivoted from coal mining to sectors like education and technology, thanks to decades of proactive planning that included extensive social dialogue with unions, widespread infrastructure investments for transport, and workforce support, including early retirement and training (Dahlbeck and Gärtner 2019; Galgóczi 2014; Oei et al. 2020; WRI 2021i).

Even in the context of ambitious global transformations, countries will act at different times and paces, require different levels of effort and international support, and experience different amounts and kinds of challenges and benefits (Muttitt and Kartha 2020). Therefore, a just global transition will entail equitably managing the phasing of this transition across as well as within countries, and ensuring that countries with limited capacity receive the support and resources they need to transition to a net-zero future, as well as benefit from the opportunities that these inflection points offer. This support can take the form of finance, capacity building, technical assistance, and access to technologies, and would be enhanced by undertaking inclusive processes to design those programs (Joffe et al. 2013). For example, the European Union Just Transition Mechanism supports member states' just transition efforts with financial resources and technical assistance (European Commission 2021a; WRI 2021h), and the International Labour Organization (ILO) partnered with Uruguay, Ghana, and the Philippines to support their implementation of the ILO's Just Transition Guidelines, with support from the Swedish International Development Cooperation Agency (ILO 2016, 2017).

Tracking progress toward a just transition

Beyond these examples, efforts are also being made to monitor global and national-level progress on a just transition. It is difficult to track such a multidimensional process in just a few indicators, and the task is further complicated by the early stage of many efforts and a lack of global-level data on some indicators, such as employment across fossil fuel value chains (Heyen and Beznea 2021). Two of the most robust just transition–related indices take different approaches to tracking progress. The Overseas Development Institute's "Leave No One Behind" Index monitors the extent to which national systems, institutions, and practices in 159 countries are ready to meet commitments in the 2030 Agenda for Sustainable Development. There is significant overlap in the systems, institutions, and practices need to deliver the SDGs and just transitions, including social protections like unemployment insurance and affordable health care, strong labor rights, and inclusive planning processes. In 2020, the index found that 75 countries (47 percent) are "ready" to meet their commitment, 65 (41 percent) are "partially ready," and 8 (5 percent) are "not ready" (11 countries had insufficient data) (Chattopadhyay and Salomon 2021). Compared to 2019, 10 countries improved and 12 worsened, with readiness strongly correlated with country prosperity (Chattopadhyay and Salomon 2021). Meanwhile, the European Commission's Transitions Performance Index gathered data across four dimensions—economic, social, environmental, and governance—for the European Union and 45 other countries. It found that in 2019, 3 countries (4 percent) were "transition leaders," 17 (24 percent) had a "strong transition," 21 (29 percent) had a "good transition," 23 (32 percent) had a "moderate transition," and 8 countries (11 percent) had a "weak transition" (European Commission 2020c). The world average fell in the "moderate transition" category and had improved by 5.4 percent since 2010 (European Commission 2020c). Other potential indicators could include job losses and gains in affected areas, the expansion of social protections (such as from the World Bank's ASPIRE), and indicators on job quality and labor rights and protections (such as from ILOSTAT) (World Bank Group 2021; ILO 2021).

The establishment of a just transition commission, office, task force, working group, or other entity, at any level of government, can also indicate the seriousness of the government's commitment to planning for a just transition, and can help coordinate and mainstream just transition processes in all relevant activities. A relatively small but growing number of such entities exist, including in the European Union; Canada; Scotland; and the U.S. states of Colorado and New York, though they have a range of funding levels and efficacy and some have overlapping jurisdictions (CDLE 2021; Environment and Climate Change Canada 2018; NYSERDA 2020; Scottish Government 2021; European Commission 2021a). In other places, including Nigeria, Chile, South Africa, and California (USA), efforts are underway by existing government entities or coalitions of non-governmental organizations and labor groups to develop comprehensive just transition strategies (ITUC 2021b; WRI 2021f, 2021g). As of August 2021, 14 countries and the European Union mentioned a just transition in their nationally determined contributions under the Paris Agreement (ClimateWatch 2021).

Equity implications of low-carbon transitions

Transformations across power, buildings, industry, transport, land use, coastal zone management, agriculture, and finance systems required to limit global warming to 1.5°C offer an inflection point of massive change across industries and countries. This scale of change, especially given the lock-in that may result from near-term large investments to support COVID-19 recovery, is an opportunity to reshape economic and social systems to be more equitable, inclusive, and just, and for countries to diversify their economies into climate-compatible sectors (Burrow 2020). Avoiding the catastrophic social, economic, and environmental impacts of runaway climate change is itself a major benefit—however, a growing body of literature demonstrates how climate action would improve today's status quo, with more stable and inclusive economic growth, cleaner air, and more efficient vehicles, buildings, and materials, among other benefits (NCE 2018; Mountford et al. 2019). A review of over 700 studies showed that low-carbon measures can substantially improve public health and social inclusivity (Gouldson et al. 2018).

However, these benefits won't happen automatically. Although these transitions to net zero will generally increase equity and improve outcomes for vulnerable communities, they can also create winners and losers. The benefits may not always be equitably shared, and some transformations that reduce emissions could have a disproportionate negative impact on poor or disadvantaged populations, or those whose livelihoods are tied up with a fossil fuel-intensive future (IPCC 2018, 20; Markkanen and Anger-Kraavi 2019). It will be essential to balance the benefits and burdens of climate actions across society, anticipating and avoiding disproportionate negative impacts wherever possible.

In the face of the profound economic and social changes involved in these systems transformations, citizens—especially those who are already vulnerable—need confidence that they will be protected from negative impacts and will truly benefit from new economic and social structures. Building public support for these transitions will be difficult if economic insecurity and profound inequality persist (Coalition for Urban Transitions 2019). This means that prioritizing equity and justice across the required transformations is not only a moral imperative but also essential to building and sustaining public support for climate action, and to making those actions more effective (Levin et al. 2012; World Bank 2021c). This offers governments and policymakers an opportunity to synergize environmental, economic, and social agendas and to build more durable solutions by incorporating the knowledge of affected communities.

Two significant equity issues in low-carbon transformations will likely be land access for large-scale solar and wind energy installations and critical minerals for sustainable technologies. Scaling up production of renewable energy will require building infrastructure like solar parks and wind farms, which require large areas of land with specific environmental conditions. Examples have begun to emerge of governments and corporations displacing Indigenous or rural communities to make way for large-scale renewable installations, including on the Isthmus of Tehuantepec in Oaxaca, Mexico (Cruz et al. 2019; Ramirez 2019; WRI 2021l), or of such installations exacerbating water scarcity, such as in the case of the Pavagada solar park in Karnataka, India (Rao 2019; Pratap et al. 2020; WRI 2021n). In addition, potential price increases for goods and services, such as energy or food, could disproportionately burden low-income consumers. Moreover, it might be possible to achieve deep emissions reductions without expanding access to social protections like health care and education. Meanwhile, producing low-carbon technologies like solar panels and batteries will require large quantities of minerals like lithium and cobalt (IEA 2021g; Kalantzakos 2020). Mining these critical minerals often results in local ecological damage and pollution that can affect local communities' health and livelihoods, could involve unsafe or exploitative working conditions, or could precipitate conflicts over control of these minerals (IEA 2021g).

Systems transformations to limit global warming to 1.5°C offer an opportunity to create a more equal world, but to realize these benefits, policies must be designed with equity and a just transition in mind.

CONCLUSION

The most recent IPCC report (2021) finds that limiting global temperature rise to 1.5°C is still possible, but the window to steer the world toward a net-zero future is closing rapidly. To halve GHG emissions by 2030 and achieve deep decarbonization by 2050, leaders across society must accelerate systemwide transformations across nearly all major sectors. Should we fail, warming could increase by 3.3°C to 5.7°C above preindustrial levels—temperatures that would expose communities and ecosystems around the world to devastating impacts, far beyond anything yet seen.

THE FIVE YEARS FOLLOWING THE ADOPTION of the Paris Agreement have seen increasingly ambitious climate commitments and action from governments, civil society, and the private sector. But as this report shows, these global efforts are far from commensurate with the crisis at hand. Of the 40 indicators assessed, none shows historical rates of change sufficient to meet the 2030 targets (Figure 92). Change is heading in the right direction, with progress unfolding at a promising, albeit insufficient pace for 8 indicators and in the right direction, but well below the required pace for another 17 of them. For 3 indicators, progress has stagnated and a step change in action is required, while rates of change for another 3 are headed in the wrong direction entirely. Data are insufficient to assess progress across the remaining 9 indicators with confidence, and we offer recommendations to improve tracking efforts for these indicators.

Although none of the indicators assessed is on track, we have still seen notable progress in some sectors, such as the rapid, nonlinear growth of wind and solar power and electric vehicle sales. Nearly half of this report's indicators are experiencing some form of nonlinear growth or could in the future, especially those that directly track low- or zero-emissions technology adoption. Catalyzing this rapid growth in time to avoid the worst climate impacts, however, is not guaranteed and will depend on the decisions made in this decade. All will require the right government support and economic conditions to take off.

To that end, this report identifies underlying enablers of progress—supportive policies, technological innovations, strong institutions, leadership, and shifts in social norms—for each of the 40 targets and highlights priority actions that can help overcome key barriers to change. It also outlines measures that, if implemented, can help make these systemwide transitions more just and equitable.

The year ahead offers a tremendous opportunity to accelerate the transformations needed to avoid the worst climate impacts. Countries will begin implementing their enhanced NDCs and low-emissions long-term development strategies at the same time that trillions of dollars are being mobilized for COVID-19 recovery efforts. Simultaneously, an increasing number of nonstate actors, including companies, cities, regions, and financial institutions, will start to fulfill their pledges to reduce GHG emissions, for example, through the High-Level Climate Champions' Race to Zero campaign for 2030 Sector Breakthroughs. These actions can be neither incremental nor delayed—we must seize this moment to secure a net-zero future for all.

FIGURE 92. Summary of progress towards 2030 targets

TRAJECTORY OF CHANGE — ACCELERATION FACTOR

Exponential Likely | 1.8x Exponential Unlikely | 1.5x 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

Acceleration factor	Indicator
N/A	Share of renewables in electricity generation
1.1x	Share of electricity in the industry sector's final energy demand
N/A	Share of electric vehicles in light-duty vehicle sales
N/A	Share of battery and fuel cell electric vehicles in bus sales[a]
1.9x	Crop yields
1.6x	Ruminant meat productivity
1.5x	Ruminant meat consumption in the Americas, Europe, and Oceania[b]
1.1x	Total public financing for fossil fuels[c]

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

Acceleration factor	Indicator
5.2x	Share of unabated coal in electricity generation
3.2x	Carbon intensity of electricity generation
2.7x	Energy intensity of building operations[d]
Ins. data	Low-carbon steel facilities in operation[e]
N/A	Green hydrogen production
N/A	Share of electric vehicles in the light-duty vehicle fleet[f]
N/A	Share of battery and fuel cell electric vehicles in medium- and heavy-duty vehicles sales
12x	Share of low-emissions fuels in the transport sector
N/A	Share of sustainable aviation fuel in global aviation fuel supply
N/A	Share of zero-emissions fuel in international shipping fuel supply
N/A	Rate of technological carbon removal rate
3.2x	Reforestation
4.2x	Rate of carbon removal from reforestation

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

Acceleration factor	Indicator
2.7x	Coastal wetlands restoration
13x	Total climate finance
5x	Public climate finance
23x	Private climate finance

STAGNANT: Change is stagnating, and a step change in action is needed

Acceleration factor	Indicator
N/A	Carbon intensity of global cement production
N/A	Carbon intensity of global steel production
N/A	Share of global emissions covered by a carbon price of at least $135/tCO$_2$e

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

Acceleration factor	Indicator
N/A	Share of trips made by private light-duty vehicles
N/A	Deforestation rate
N/A	Agricultural production GHG emissions

INSUFFICIENT DATA: Data are insufficient to assess the gap in action required for 2030[g]

Acceleration factor	Indicator
Ins. data	Retrofitting rate of buildings
Ins. data	Carbon intensity of building operations
Ins. data	Carbon intensity of land-based transport
Ins. data	Peatlands conversion rate
Ins. data	Peatlands restoration
Ins. data	Coastal wetlands conversion rate
Ins. data	Share of food production lost
Ins. data	Food waste
Ins. data	Corporate climate risk disclosure

FIGURE 92. Summary of progress towards 2030 targets (continued)

a Battery electric and fuel-cell electric buses have grown nonlinearly in China but have not yet taken off elsewhere. They already make up 39 percent of global bus sales due to the strong sales in China.

b This indicator is only applicable in regions where ruminant meat consumption is above the 60 kilocalories per person per day target for 2050.

c While consumption subsidies have been declining in recent years, which has led to the overall decrease, production subsidies have continued to increase (OECD 2021a). Furthermore, part of the fall in consumption subsidies is due to declining oil prices, which fell substantially as a result of the pandemic (IEA 2020h). If oil prices rise again, absent further reforms consumption subsidies are likely to increase.

d The acceleration factor refers to the full range of the benchmarks across commercial and residential buildings, because historical data are not available for the two building types separately.

e The indicator is marked as "well off track" because while no low-carbon steel facilities are currently in operation, 18 are expected to be operational by 2030. Of these 18 projects, data on production capacity are only available for 4, all of which meet the production criteria of at least 1 million tonnes annually. However, data are insufficient to calculate an acceleration factor.

f The nonlinear historical growth in electric vehicle stock is coming from a very low base, and is only due to rapid growth in the share of electric vehicles in light-duty vehicle sales, with little progress on the removal of internal combustion engine vehicles from the road.

g Although some have one historical data point and/or qualitative research that shows they are not on track, these indicators do not have enough information to assess how much recent progress must accelerate to achieve their 2030 targets. Accordingly, we classify them as having "insufficient data."

Source: Authors' analysis based on data sources listed in each chapter; see Appendix C for the methodology used to design targets and the literature from which they are derived.

APPENDICES

APPENDIX A

Defining transformation, transition, and systems change

Definitions of transformation, transition, and systems change commonly cited in the global environmental change research and policymaking communities.

Concepts	Definitions	Quoted source
Transformability	"The capacity to create a fundamentally new system when ecological, economic, or social (including political) conditions make the existing system untenable."	Walker et al. (2004)
	"Transformability means defining and creating novel system configurations by introducing new components and ways of governing [social-ecological systems], thereby changing the state variables, and often the scales of key cycles, that define the system. Transformations fundamentally change the structures and processes that alternate feedback loops in [social-ecological systems]."	Olsson et al. (2006)
	"The capacity to transform the stability landscape itself in order to become a different kind of system, to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable. . . . Deliberate transformation involves breaking down the resilience of the old and building the resilience of the new."	Folke et al. (2010)
Transformation	"In the context of ecosystem stewardship, transformations involve forward-looking decisions to convert a system trapped in an undesirable state to a fundamentally different, potentially more beneficial system, whose properties reflect different social-ecological controls."	Chapin et al. (2010)
	"A fundamental reorganization of the [social-ecological system], so that the system functions in a qualitatively different way than it did before."	Biggs et al. (2010)
	"A change in the fundamental attributes of natural and human systems."	IPCC (2018)
Transition	"Transitions (changes from one stable regime to another) are conceptualized . . . as occurring when landscape pressures destabilize prevailing regimes, providing breakthrough opportunities for promising niches. This implies a nonlinear process of change in which, after passing critical thresholds, elements of a previously dominant regime recombine with successful niches into a new dynamically stable configuration."	Westley et al. (2011)
	"A transition is a radical, structural change of a societal (sub)system that is the result of a coevolution of economic, cultural, technological, ecological and institutional developments at different scale levels."	Rotmans and Loorbach (2009)
	"The process of changing from one state or condition to another in a given period of time. Transition can be in individuals, firms, cities, regions and nations, and can be based on incremental or transformative change."	IPCC (2018)
Sociotechnical transition	"Transitions entail major changes in the "socio-technical systems" that provide societal functions such as mobility, heat, housing, and sustenance. These systems consist of an interdependent and co-evolving mix of technologies, supply chains, infrastructures, markets, regulations, user practices, and cultural meaning."	Geels et al. (2017b)
	"We define such transitions as shifts from one socio-technical system to another. . . . We consider transitions as having the following characteristics: Transitions are co-evolution processes that require multiple changes in socio-technical systems . . . are multi-actor processes, which entail interactions between social groups . . . are radical shifts from one system to another . . . are long-term processes . . . [and] are macroscopic."	Grin et al. (2010)
Large systems change	"By large systems change (LSC), we mean change with two characteristics. One we refer to as breadth: change that engages a very large number of individuals, organizations and geographies across a wide range of systems. . . . The second characteristic we refer to as depth: LSC is not simply adding more of what exists or making rearrangements within existing power structures and relationships, but rather changes the complex relationships among these elements at multiple levels simultaneously."	Waddell et al. (2015)

APPENDIX B
Target design by institution

Target	Organization that led development of target
POWER	
Reduce the carbon intensity of electricity generation to 50–125 gCO_2/kWh by 2030 and to below zero in 2050.	CAT Consortium
Increase the share of renewables in electricity generation to 55–90% by 2030 and to 98–100% by 2050.	CAT Consortium
Lower the share of unabated coal in electricity generation to 0–2.5% by 2030 and to 0% by 2050.	CAT Consortium
BUILDINGS	
Reduce the carbon intensity of operations in select regions by 45–65% in residential buildings and by 65–75% in commercial buildings by 2030, relative to 2015; reach near zero carbon intensity globally by 2050.	CAT Consortium
Decrease the energy intensity of residential building operations in key countries and regions by 20–30% by 2030 and by 20–60% by 2050, relative to 2015; reduce the energy intensity of commercial building operations in key countries and regions by 10–30% by 2030 and by 15–50% by 2050, relative to 2015.	CAT Consortium
Increase buildings' retrofitting rate to 2.5–3.5% annually by 2030 and to 3.5% annually by 2040; ensure that all buildings are well insulated and fitted with zero-carbon technologies by 2050.	CAT Consortium
INDUSTRY	
Increase the share of electricity in the industry sector's final energy demand to 35% by 2030, 40–45% by 2040, and 50–55% by 2050.	CAT Consortium
Reduce global cement production's carbon intensity by 40% by 2030 and by 85–91% by 2050, relative to 2015.	CAT Consortium
Reduce global steel production's carbon intensity by 25–30% by 2030 and by 93–100% by 2050, relative to 2015.	CAT Consortium
Build and operate 20 low-carbon commercial steel facilities, with each producing at least 1 Mt annually by 2030; ensure that all steel facilities are net-zero GHG emissions by 2050.	High-Level Climate Champions
Boost green hydrogen production capacity to 0.23–3.5 Mt (25 GW cumulative electrolyzer capacity) by 2026 and to 500–800 Mt (2,630–20,000 GW cumulative electrolyzer capacity) by 2050.	High-Level Climate Champions
TRANSPORT	
Reduce the percentage of trips made by private LDVs to between 4% to 14% below BAU levels by 2030.	WRI
Reduce the carbon intensity of land-based passenger transport to 35–60 gCO_2/pkm by 2030 and reach near zero by 2050.	CAT Consortium
Increase the share of EVs to 75–95% of total annual LDV sales by 2030 and to 100% by 2035.	CAT Consortium
Expand the share of EVs to account for 20–40% of total LDV fleet by 2030 and 85–100% by 2050.	CAT Consortium
Boost the share of BEVs and FCEVs to reach 75% of annual global bus sales by 2025 and to reach 100% of annual bus sales in leading markets by 2030.	High-Level Climate Champions
Increase the share of BEVs and FCEVs to 8% of global annual MHDV sales by 2025 and to 100% in leading markets by 2040.	High-Level Climate Champions
Raise the share of low-emissions fuels in the transport sector to 15% by 2030 and to 70–95% by 2050.	CAT Consortium
Increase SAF's share of global aviation fuel supply to 10% by 2030 and to 100% by 2050.	High-Level Climate Champions
Raise ZEF's share of international shipping fuel to 5% by 2030 and to 100% by 2050.	High-Level Climate Champions
TECHNOLOGICAL CARBON REMOVAL	
Scale up technological carbon removal to 75 $MtCO_2$ annually by 2030 and to 4.5 $GtCO_2$ annually by 2050.	WRI
LAND USE AND COASTAL ZONE MANAGEMENT	
Reduce the rate of deforestation by 70% by 2030 and by 95% by 2050, relative to 2018.	WRI
Reforest 259 Mha of land by 2030 and 678 Mha in total by 2050, relative to 2018.	WRI
Remove 3.0 $GtCO_2$ annually through reforestation by 2030 and 7.8 $GtCO_2$ annually by 2050.	WRI
Reduce the degradation and destruction of peatlands by 70% by 2030 and by 95% by 2050, relative to 2018.	WRI
Restore 22 Mha of peatlands by 2030 and 46 Mha in total by 2050, relative to 2018.	WRI
Reduce the conversion of coastal wetlands by 70% by 2030 and by 95% by 2050, relative to 2018.	WRI
Restore 7 Mha of coastal wetlands by 2030 and 29 Mha in total by 2050, relative to 2018.	WRI

Target	Organization that led development of target
AGRICULTURE	
Reduce agricultural production emissions by 22% by 2030 and by 39% by 2050, relative to 2017.	WRI
Increase crop yields by 18% by 2030 and by 45% by 2050, relative to 2017.	WRI
Increase ruminant meat productivity per hectare by 27% by 2030 and by 58% by 2050, relative to 2017.	WRI
Reduce share of food loss by 50% by 2030 and maintain this reduction through 2050, relative to 2016.	WRI
Reduce per capita food waste by 50% by 2030 and maintain this reduction through 2050, relative to 2019.	WRI
Reduce ruminant meat consumption in high-consuming regions to 79 kcal/capita/day by 2030 and to 60 kcal/capita/day by 2050.	WRI
FINANCE	
Increase total climate finance flows to $5 trillion per year by 2030 and sustain this level of funding through 2050.	WRI
Raise public climate finance flows to at least $1.25 trillion per year by 2030 and sustain through 2050.	WRI
Boost private climate finance flows to at least $3.75 trillion per year by 2030 and sustain through 2050.	WRI
Jurisdictions representing three-quarters of global emissions mandate TCFD-aligned climate risk reporting and all of the world's 2,000 largest public companies report on climate risk in line with TCFD recommendations by 2030.	WRI
Ensure that a carbon price of at least $135/t$CO_2$e covers the majority of the world's GHG emissions by 2030 and then increases to at least $245/t$CO_2$e by 2050.	WRI
Phase out public financing for fossil fuels, including subsidies, by 2030, with G7 countries and international financial institutions achieving this by 2025.	WRI

Note: CAT = Climate Action Tracker; WRI = World Resources Institute; gCO_2/kWh = grams of carbon dioxide per kilowatt-hour; GHG = greenhouse gas; Mt = million tonnes; MtCO_2 = million tonnes of carbon dioxide ; GW = gigawatts (billion watts); BEV = battery electric vehicle; FCEV = fuel cell electric vehicle; MHDV = medium- and heavy-duty vehicle; EV = electric vehicle; LDV = light-duty vehicle; SAF = sustainable aviation fuel; ZEF = zero-emissions fuel; BAU = business as usual; gCO_2/pkm = grams of carbon dioxide per passenger kilometer; GtCO_2 = gigatonnes (billion tonnes) of carbon dioxide; Mha = million hectares; kcal/capita/day = kilocalories per capita per day; TCFD = Task Force on Climate-Related Financial Disclosures; tCO_2e = tonnes of carbon dioxide equivalent. The CAT Consortium is a collaboration of two organizations, Climate Analytics and NewClimate Institute.

Methodology for designing targets

THE DEVELOPMENT OF THE TARGETS WAS informed by multiple sources of information and, as a result, may be presented as a single target or a range. When targets are presented as a range of values, the lower end of the range represents estimates based on current technologies and strategies. The more ambitious end of the range may represent trade-offs in decarbonization with other sectors and/or uncertainty in terms of feasibility (CAT 2020b). The targets were derived using various sustainability criteria. Dependence on fossil-based carbon capture and storage (CCS) will further increase the mitigation burden (only ~90 percent of emissions are captured in an idealized system) and pressure land-use sectors to extract more emissions from the atmosphere. Nuclear power generation suffers from political acceptability, safety issues, concerns in relation to the nuclear fuel cycle (including disposal of high-level nuclear waste, which is nowhere resolved), high economic cost, slow build times, and inflexibility. Given the difficulties mentioned, the Climate Action Tracker (CAT) benchmarks therefore do not assess fossil-based CCS and sustained use of nuclear as viable emission-free power generation options to target in scenarios compatible with the Paris Agreement. For more information on the design of targets, see CAT (2020a).

Power, Industry, Building, and Transportation Targets

The CAT team developed the majority of power, industry, buildings, and transportation targets (see Table 1) and used both top-down and bottom-up methods to establish their targets (CAT 2020b):

- Integrated assessment models (IAMs): The CAT team first considered the IAMs that were able to limit warming to 1.5°C ("no overshoot" and "low overshoot" scenarios in which a brief and limited overshoot of average warming occurred). The team then refined its selection to include only those scenarios that assumed sustainable use of carbon removal and use of biomass (max use of biomass in 2050 of about 8,000 terawatt-hours electric). These pathways are defined on a least-cost pathway and do not consider equitable distribution of costs and required action.
- Downscaled IAMs: In addition to the global scenarios from the IAMs, the CAT team used a simplified IAM[99] to downscale regional IAM pathways to the country level. These modeled pathways on the country level account for the initial energy mix of the countries and the regional transition. The downscaling is done for 1.5°C-compatible pathways that are harmonized to country-specific historical data.
- Bottom-up sectoral modeling and studies at the national level: The CAT team also used a combination of its own bottom-up modeling (e.g., steel, electric vehicles, cement, buildings) and other independent literature. Each sectoral target that was derived from such bottom-up analyses was still compared with 1.5°C-compatible IAMs to ensure that, if there was any discrepancy, the bottom-up approaches were more ambitious in achieving decarbonization more rapidly.

See Transport Indicator 1 for a description of how WRI designed the modal shift target.

The High-Level Climate Champions used a range of different methods to develop the following targets:

- For hydrogen, the range represents the hydrogen needed to supply 15–20 percent of final global energy demand by 2050. This estimate accounts for uncertainty around end users and varying projections of energy productivity (ETC 2021b). This range aligns with analysis from Bloomberg New Energy Finance, the Hydrogen Council, and the International Renewable Energy Agency (BloombergNEF 2020b; Hydrogen Council 2017; IRENA 2021c).
- For medium- and heavy-duty vehicles and buses, the High-Level Climate Champions developed targets based on an S-curve (a smoothed sigmoid curve that starts with a low level of action, followed by acceleration and approach to a new state) forced to 100 percent by 2040 given the starting point. The S-curve represents normative goals suggested by various groups (advocacy, research, foundations) in the United States and Europe, which included the High-Level Climate Champions team. The Climate

Leadership Initiative convened them between January and July 2020.

- The shipping target is based on a 2019 analysis by University Maritime Advisory Services and UK Maritime Plan. It found that zero-emissions fuel adoption in international shipping needs to reach 27 percent by 2036. The 2030 estimate of 5 percent and 93 percent by 2046 were developed by using indicative S-curve modeling using a logistic curve.
- The sustainable aviation fuel (SAF) target was based on an ICCT (2021) analysis that shows SAF is capable of meeting 5.5 percent of projected EU jet fuel demand in 2030 (approximately 3.4 million tonnes of advanced SAF production annually) and 6 percent in 2035. Indicative S-curves are based on starting point and ambition for 100 percent SAF penetration according to a logistic S-curve formula. The indicative S-curves were developed by a small working team from the High-Level Climate Champions and industry, which looked at several sources. It created three scenarios to backcast from 2050 to establish an ambitious but reasonable 2030 target.

For the steel plant targets, the High-Level Climate Champions established a normative target modeled by the Energy Transition Commission's Net-Zero Steel Initiative and the target accounts for number of announced or planned facilities by 2030 but at higher plant productivity. This accounts for 5 percent of current primary production, and 10 percent under the 2050 primary production estimate.

Technological Carbon Removal Target

The technological carbon removal target, also developed by WRI, was based on the recent literature (NAS 2019; IPCC 2018; Fuss et al. 2018), which establishes ranges for 1.5°C-compatible carbon removal pathways that also meet sustainability criteria.

Land Use and Coastal Zone Management Targets

This report's 2030 forests targets, as well as those for peatlands and coastal wetlands, are derived from an assessment by Roe et al. (2019) of the land sector's contribution to limiting global temperature rise to 1.5°C above preindustrial levels. In their paper, Roe et al. (2019) reconcile top-down and bottom-up estimates of mitigation potentials to establish an overarching mitigation target for the land sector. They then divide this required effort into priority measures—or wedges—that consider cost-effectiveness, as well as food security, biodiversity, and fiber production safeguards. Reforestation and restoration targets, specifically, exclude land-use changes across the world's boreal biome, as adding trees to these landscapes could alter the reflectivity of the planet's surface in ways that could increase global warming (Griscom et al. 2017; Roe et al. 2019).

Our 2050 reforestation and restoration targets also account for these safeguards but reflect the maximum potential areas that can be reforested or restored sustainably (Griscom et al. 2017). These midcentury targets, then, go beyond what Roe et al. (2019) suggest is needed to limit global temperature rise to 1.5°C, in part because they assume very conservative use of BECCS and relatively low levels of soil carbon sequestration on working agricultural lands (Ranganathan et al. 2020; Searchinger and Ranganathan 2020). They are also relatively well aligned with Searchinger et al. (2019), who find that, through a series of supply- and demand-side shifts, approximately 800 million hectares (Mha) of agricultural lands could be liberated by 2050.

This report's 2030 and 2050 targets for reducing deforestation, peatland degradation, and coastal wetlands conversion also differ slightly from those found in Roe et al. (2019). We use area, rather than avoided emissions, as our metric for consistency with our previous report, which was published when emissions data were less readily available, consistency with other indicators, and due to its actionability. For forests, the area of deforestation is highly correlated with emissions from deforestation (see Figure 55). For peatlands and coastal wetlands, data limitations make it difficult to assess correlation between area loss and emissions. Instead, we use the "maximum rate of avoidable impact (Mha/yr)" from Griscom et al. (2017)—the source on which Roe et al. (2019) rely to estimate the mitigation potential for avoided emissions from the loss of these ecosystems.

Agriculture Targets

Agriculture targets were set using a model from Searchinger et al. (2019). Determining criteria for these targets were food security for 9.8 billion people by 2050, nearly 600 million hectares of reforestation, and no more than 4 gigatonnes of carbon dioxide equivalent per year of agricultural production emissions by midcentury. Additional details are provided in Lebling et al. (2020). The targets for food loss and waste are based on Sustainable Development Goal Target 12.3 on food loss and waste reduction.

Finance Targets

The finance targets were developed by WRI, using a variety of methods:

- The overall climate finance targets were based on the mean of different energy and infrastructure needs estimates for 1.5°C or 2°C pathways (IPCC 2018; IEA 2021c; OECD 2017), combined with estimates of finance needed for nature-based solutions (UNEP 2021b) and adaptation in developing countries (UNEP 2016). See Table 16.
- The division between public and private finance to meet these needs was based on World Bank analysis (IPCC 2018).
- The measurement, management, and disclosure of climate risk targets are based on adoption of reporting guidelines from the Task Force on Climate-Related Financial Disclosures (TCFD 2017).
- The carbon-pricing targets are set based on analysis by the Intergovernmental Panel on Climate Change of the minimum undiscounted carbon price necessary for a 1.5°C pathway (IPCC 2018); the share of global emissions to be covered at that price was stated as "a majority" since other policies can be complementary to carbon pricing at reducing emissions, so covering 100 percent of emissions with carbon pricing at the set levels may not be necessary (and probably isn't feasible).
- The public financing for fossil fuel targets is based on commitments by the G7 and G20 to phase out fossil fuel subsidies, with the former setting a 2025 end date in 2016, and the latter committing in 2009 to do so "over the medium term"; 2030 would be 21 years after the G20 commitment was made, stretching the limit of the definition of "medium term" (G7 2016; G20 2009).

Addition of New Targets

In comparison to last year's *State of Climate Action* report (Lebling et al. 2020), which included 21 indicators with targets for 2030 and 2050, this report includes 40 indicators. The addition of these new indicators, also generally with targets for 2030 and 2050, reflects a more comprehensive evaluation of shifts needed (e.g., use of hydrogen, protection and restoration of peatlands and coastal wetlands, modal shifts in transportation) and addresses gaps that were identified in the 2020 report (e.g., shipping, aviation, and technological carbon removal). The new indicators fit the same criteria as indicators included in the 2020 report but reflect a broadening and improvement of its scope. It should be noted that the indicators chosen in this report represent a set of critical actions but are not comprehensive of all shifts that need to happen economy-wide.

APPENDIX D.

Changes in targets and indicators between this and last year's report

Targets and indicators	Comparison with Lebling et al. (2020)
POWER	
Reduce the carbon intensity of electricity generation to 50–125 gCO_2/kWh by 2030 and to below zero in 2050.	Target and indicator are the same.
Increase the share of renewables in electricity generation to 55–90% by 2030 and to 98–100% by 2050.	Target and indicator are the same.
Lower the share of unabated coal in electricity generation to 0–2.5% by 2030 and to 0% by 2050.	Target and indicator are the same.
BUILDINGS	
Reduce the carbon intensity of operations in select regions by 45–65% in residential buildings and by 65–75% in commercial buildings by 2030, relative to 2015; reach near zero carbon intensity globally by 2050.	Target and indicator are the same.
Decrease the energy intensity of residential building operations in key countries and regions by 20–30% by 2030 and by 20–60% by 2050, relative to 2015; reduce the energy intensity of commercial building operations in key countries and regions by 10–30% by 2030 and by 15–50% by 2050, relative to 2015.	Target and indicator are the same.
Increase buildings' retrofitting rate to 2.5–3.5% annually by 2030 and to 3.5% annually by 2040; ensure that all buildings are well insulated and fitted with zero-carbon technologies by 2050.	Target and indicator are the same.
INDUSTRY	
Increase the share of electricity in the industry sector's final energy demand to 35% by 2030, 40–45% by 2040, and 50–55% by 2050.	Target and indicator are the same.
Reduce global cement production's carbon intensity by 40% by 2030 and by 85–91% by 2050, relative to 2015.	Target and indicator are the same.
Reduce global steel production's carbon intensity by 25–30% by 2030 and by 93–100% by 2050, relative to 2015.	Target and indicator are the same.
Build and operate 20 low-carbon commercial steel facilities, with each producing at least 1 Mt annually by 2030; ensure that all steel facilities are net-zero GHG emissions by 2050.	New target and new indicator identified.
Boost green hydrogen production capacity to 0.23–3.5 Mt (25 GW cumulative electrolyzer capacity) by 2026 and to 500–800 Mt (2,630–20,000 GW cumulative electrolyzer capacity) by 2050.	New target and new indicator identified.
TRANSPORT	
Reduce the percentage of trips made by private LDVs to between 4% to 14% below BAU levels by 2030.	New target and new indicator identified.
Reduce the carbon intensity of land-based passenger transport to 35–60 gCO_2/pkm by 2030 and reach near zero by 2050.	Target and indicator are the same.
Increase the share of EVs to 75–95% of total annual LDV sales by 2030 and to 100% by 2035.	The EV share of the global LDV sales benchmark was changed this year to reflect the date at which the underlying internal Climate Action Tracker model achieves 100% sales, which is 2035. This is also in line with other global electric vehicle sales benchmarks in existing literature, including CAT (2016), Kuramochi et al. (2017), and Climate Transparency (2020).
Expand the share of EVs to account for 20–40% of total LDV fleet by 2030 and 85–100% by 2050.	Target and indicator are the same.
Boost the share of BEVs and FCEVs to reach 75% of annual global bus sales by 2025 and to reach 100% of annual bus sales in leading markets by 2030.	New target and new indicator identified.
Increase the share of BEVs and FCEVs to 8% of global annual MHDV sales by 2025 and to 100% in leading markets by 2040.	New target and new indicator identified.
Raise the share of low-emissions fuels in the transport sector to 15% by 2030 and to 70–95% by 2050.	Target and indicator are the same.

Targets and indicators	Comparison with Lebling et al. (2020)
TRANSPORT (CONTINUED)	
Increase SAF's share of global aviation fuel supply to 10% by 2030 and to 100% by 2050.	New target and new indicator identified.
Raise ZEF's share of international shipping fuel to 5% by 2030 and to 100% by 2050.	New target and new indicator identified.
TECHNOLOGICAL CARBON REMOVAL	
Scale up technological carbon removal to 75 $MtCO_2$ annually by 2030 and to 4.5 $GtCO_2$ annually by 2050.	New target and new indicator identified.
LAND USE AND COASTAL ZONE MANAGEMENT	
Reduce the rate of deforestation by 70% by 2030 and by 95% by 2050, relative to 2018.	We changed the target's baseline year from 2019 to 2018 to better align with Roe et al. (2019). However, because the deforestation rates in 2018 and 2019 were nearly the same (6.75 Mha in 2018 and 6.77 Mha in 2019), the difference between our targets in this report and Lebling et al. (2020) is relatively minor. This indicator, however, remains unchanged.
Reforest 259 Mha of land by 2030 and 678 Mha in total by 2050, relative to 2018.	While our indicator and 2050 target remain unchanged from the last iteration of the *State of Climate Action* (Lebling et al. 2020), this year's report provides an updated target for 2030, reflecting new estimates of annual carbon sequestration potential per hectare (Cook-Patton et al. 2020). To ensure alignment with the mitigation potential that Roe et al. (2019) found for reforestation (3.0 $GtCO_2$/yr by 2030), from which our carbon removal for reforestation target is derived, we used the annual carbon sequestration potential per hectare from Cook-Patton et al. (2020) to estimate the area that must be reforested by 2030 to remove 3.0 $GtCO_2$ annually. Although this new 2030 target falls below those set by the Bonn Challenge and the New York Declaration on Forests (350 Mha by 2030), it focuses solely on reforestation, while both international commitments include pledges to plant trees across a broader range of land uses, such as agroforestry systems or tree plantations.
Remove 3.0 $GtCO_2$ annually through reforestation by 2030 and 7.8 $GtCO_2$ annually by 2050.	Our carbon removal from reforestation indicator and targets were updated from Lebling et al. (2020), using more recent estimates of annual carbon sequestration potential per hectare for forest regrowth from Cook-Patton et al. (2020). This report also translates cumulative targets from Lebling et al. (2020) into annual benchmarks.
Reduce the degradation and destruction of peatlands by 70% by 2030 and by 95% by 2050, relative to 2018.	New target and new indicator identified, which were key omissions from Lebling et al. (2020). Although data are still limited for this indicator, efforts to track global losses in peatland area are improving, and this is among the best indicators available to measure progress toward this target.
Restore 22 Mha of peatlands by 2030 and 46 Mha in total by 2050, relative to 2018.	New target and new indicator identified, which were key omissions from Lebling et al. (2020). Although data are still limited for this indicator, efforts to track gross gains in peatland area globally are improving, and this is among the best indicators available to measure progress toward this target.
Reduce the conversion of coastal wetlands by 70% by 2030 and by 95% by 2050, relative to 2018.	New target and new indicator identified, which were key omissions from Lebling et al. (2020). Although data are still limited for this indicator, efforts to track global losses in coastal wetlands areas are improving, and this is among the best indicators available to measure progress toward this target.
Restore 7 Mha of coastal wetlands by 2030 and 29 Mha in total by 2050, relative to 2018.	New target and new indicator identified, which were key omissions from Lebling et al. (2020). Although data are still limited for this indicator, efforts to track gross gains in coastal wetlands areas globally are improving, and this is among the best indicators available to measure progress toward this target.
AGRICULTURE	
Reduce agricultural production emissions by 22% by 2030 and by 39% by 2050, relative to 2017.	Target and indicator are the same.
Increase crop yields by 18% by 2030 and by 45% by 2050, relative to 2017.	Target was updated from last year (now 13% increase by 2030; 38% increase by 2050, relative to 2017) to be consistent with Searchinger et al. (2021). The indicator remains unchanged.
Increase ruminant meat productivity per hectare by 27% by 2030 and by 58% by 2050, relative to 2017.	Target and indicator are the same.

Targets and indicators	Comparison with Lebling et al. (2020)
AGRICULTURE (continued)	
Reduce share of food loss by 50% by 2030 and maintain this reduction through 2050, relative to 2016.	We have now separated targets out for food loss and food waste. Our targets for food loss and waste have been updated to better align with SDG Target 12.3. Our indicator for food loss has changed to align with FAO's Food Loss Index, but our indicator for food waste remains the same.
Reduce per capita food waste by 50% by 2030 and maintain this reduction through 2050, relative to 2019.	
Reduce ruminant meat consumption in high-consuming regions to 79 kcal/capita/day by 2030 and to 60 kcal/capita/day by 2050.	Target is the same, but the expression of it was changed by narrowing the geographic focus. Instead of showing global per capita consumption (which included all regions, thus both high and low consumers of meat) per Lebling et al. (2020), in this report we solely focus on the necessary decline in per capita consumption in high-consuming countries, given that this is the focus of the challenge at hand. The indicator remains unchanged.
FINANCE	
Increase total climate finance flows to $5 trillion per year by 2030 and sustain this level of funding through 2050.	New target and new indicator indentified.
Raise public climate finance flows to at least $1.25 trillion per year by 2030 and sustain through 2050.	New target and new indicator indentified.
Boost private climate finance flows to at least $3.75 trillion per year by 2030 and sustain through 2050.	New target and new indicator indentified.
Jurisdictions representing three-quarters of global emissions mandate TCFD-aligned climate risk reporting and all of the world's 2,000 largest public companies report on climate risk in line with TCFD recommendations by 2030.	New target and new indicator indentified.
Ensure that a carbon price of at least $135/t$CO_2$e covers the majority of the world's GHG emissions by 2030 and then increases to at least $245/t$CO_2$e by 2050.	New target and new indicator indentified.
Phase out public financing for fossil fuels, including subsidies, by 2030, with G7 countries and international financial institutions achieving this by 2025.	New target and new indicator indentified.

Note: gCO_2/kWh = grams of carbon dioxide per kilowatt-hour; GHG = greenhouse gas; Mt = million tonnes; MtCO_2 = million tonnes of carbon dioxide; GW = gigawatts (billion watts); BEV = battery electric vehicle; FCEV = fuel cell electric vehicle; MHDV = medium- and heavy-duty vehicle; EV = electric vehicle; LDV = light-duty vehicle; SAF = sustainable aviation fuel; ZEF = zero-emissions fuel; BAU = business as usual; GCO_2/pkm = gigatonnes (billion tonnes) of carbon dioxide per passenger kilometer; GtCO_2 = gigatonnes of carbon dioxide; Mha = million hectares; SDG = Sustainable Development Goal; FAO = Food and Agriculture Organization of the United Nations; kcal/capita/day = kilocalories per capita per day; TCFD = Task Force on Climate-Related Financial Disclosures; tCO_2e = tonnes of carbon dioxide.

APPENDIX E.

Application of S-curves

S-curve formula

FOR THE INDICATORS THAT ARE DIRECTLY tracking technology adoption and have at least one historical data point, we present S-curves in the report to show one possible pathway for what's needed to meet the 2030 and 2050 targets. These S-curves are simply illustrative. They show one potential pathway among many that could be used to reach the targets and are not predicting what future growth will be.

We used simple logistic S-curves to illustrate. We constructed these in Excel using the formula for simple logistic S-curves:

Deployment at time (t) = $K/(1+((K-Y_0)/ Y_0)*EXP(-\alpha*t))$

- K is the saturation value: in our circumstances, this is the 2050 target.
- Y_0 is the most recent historical value.
- α is the intrinsic growth rate. It sets the trajectory of growth at the beginning then gradually reduces as it approaches the saturation value. The intrinsic growth rate is calculated from the S-curve's emergence growth rate using the Excel formula: LOG([1+emergence growth rate],EXP(1)). The emergence growth rate is the rate of growth in the first year after the most recent historical value, which gradually tapers off as the curve approaches the saturation value.
- t is the year, starting at 1 for the first year after the most recent year with data.

Logistic S-curves are symmetrical with the speed of acceleration in the first half being mirrored with the speed of saturation in the second half. This is not necessarily borne out in the data—again, it is simply illustrative.

Indicators that could possibly follow some type of exponential growth

For the nine indicators in this report we categorized as "exponential possible," we provide further explanation here. These indicators are not directly tracking technology adoption, so they wouldn't be expected to closely follow S-curve dynamics. But these indicators are dependent on technology adoption to some degree, so likely would not follow purely linear growth either. For example, some indicators track emissions or carbon intensity in various sectors, which could be influenced by technology adoption but also by many other factors, like resource efficiency. Some indicators track technology adoption but are dependent on multiple technologies that aren't closely related. For all of these indicators, nonlinear growth could apply in some way but would likely be more complex than simple S-curve dynamics. These include the following:

Power

- Carbon intensity of electricity generation (dependent on renewable energy adoption but also other factors like natural gas adoption and energy efficiency)
- Share of unabated coal in electricity generation (dependent on renewable energy adoption, but also other factors like natural gas adoption)

Buildings

- Carbon intensity of building operations (dependent on zero-carbon building technology adoption, but this includes multiple types of unrelated technologies, and is also dependent on energy efficiency)

Industry

- Share of electricity in the industry sector's final energy demand (dependent on adoption of multiple unrelated technologies)
- Carbon intensity of global cement production (dependent on zero-carbon cement adoption, but this includes multiple types of unrelated technologies, and is also dependent on activities and practices like clinker substitution and energy efficiency)
- Carbon intensity of global steel production (dependent on low-carbon steel technology adoption, but this also includes multiple types of unrelated technologies, and is also dependent on energy efficiency)
- Number of low-carbon steel facilities in operation (dependent on low-carbon steel technology adoption but not directly tracking low-carbon steel adoption)

Transport

- Share of low-emissions fuels in the transport sector (dependent on multiple unrelated technologies like electric vehicles [EVs], biofuels, and hydrogen)
- Carbon intensity of land-based transport (dependent on both low-carbon technologies like EVs and energy efficiency of existing vehicles)

APPENDIX F.

Changes in acceleration factors between this and last year's report

2030 and 2050 targets	2020 acceleration factor	2021 acceleration factor	Explanation of differences
POWER			
Increase the share of renewables in electricity generation to 55–90% by 2030 and to 98–100% by 2050.	5.6x	n/a; progress evaluated based on expert judgment and the literature	Previously assessed on the basis of linear growth, this time renewables are assessed based on the potential for accelerated, nonlinear growth, and so they do not have an acceleration factor.
Lower the share of unabated coal in electricity generation to 0–2.5% by 2030 and to 0% by 2050.	5.1x	5.2x	Updated data in the IEA World Energy Balance and CO_2 emissions database. The latest year of data now available is 2018, while in the last report it was 2017.
Reduce the carbon intensity of electricity generation to 50–125 gCO_2/kWh by 2030 and to below zero in 2050.	3.6x	3.2x	Updated data in the IEA World Energy Balance and CO_2 emissions database. The latest year of data now available is 2018, while in the last report it was 2017.
BUILDINGS			
Reduce the carbon intensity of operations in select regions by 45–65% in residential buildings and by 65–75% in commercial buildings by 2030, relative to 2015; reach near zero carbon intensity globally by 2050.	Insufficient data	Insufficient data	No difference between this and last year.
Decrease the energy intensity of residential building operations in key countries and regions by 20–30% by 2030 and by 20–60% by 2050, relative to 2015; reduce the energy intensity of commercial building operations in key countries and regions by 10–30% by 2030 and by 15–50% by 2050, relative to 2015.	Insufficient data	2.7x	New data were available for the 2021 report.
Increase buildings' retrofitting rate to 2.5–3.5% annually by 2030 and to 3.5% annually by 2040; ensure that all buildings are well insulated and fitted with zero-carbon technologies by 2050.	Insufficient data	Insufficient data	No difference between this and last year.
INDUSTRY			
Increase the share of electricity in the industry sector's final energy demand to 35% by 2030, 40–45% by 2040, and 50–55% by 2050.	1.4x	1.1x	Data set updated with more recent data.
Reduce global cement production's carbon intensity by 40% by 2030 and by 85–91% by 2050, relative to 2015.	Insufficient data	n/a; step change needed	n/a
Reduce global steel production's carbon intensity by 25–30% by 2030 and by 93–100% by 2050, relative to 2015.	Insufficient data	n/a; step change needed	n/a
Build and operate 20 low-carbon commercial steel facilities, with each producing at least 1 Mt annually by 2030; ensure that all steel facilities are net-zero GHG emissions by 2050.	n/a	Insufficient data	n/a; this report establishes a new target and indicator.
Boost green hydrogen production capacity to 0.23–3.5 Mt (25 GW cumulative electrolyzer capacity) by 2026 and to 500–800 Mt (2,630–20,000 GW cumulative electrolyzer capacity) by 2050.	n/a	n/a; progress evaluated based on expert judgment and the literature	n/a; this report establishes a new target and indicator.
TRANSPORT			
Reduce the percentage of trips made by private LDVs to between 4% to 14% below BAU levels by 2030.	n/a	n/a; U-turn needed	n/a; this report establishes a new target and indicator.
Reduce the carbon intensity of land-based passenger transport to 35–60 gCO_2/pkm by 2030 and reach near zero by 2050.	Insufficient data	Insufficient data	No difference between this and last year.

2030 and 2050 targets	2020 acceleration factor	2021 acceleration factor	Explanation of differences
TRANSPORT (continued)			
Increase the share of EVs to 75–95% of total annual LDV sales by 2030 and to 100% by 2035.	12x	n/a; progress evaluated based on expert judgment and the literature	Previously assessed on the basis of linear growth, this time EVs are assessed based on the potential for accelerated, nonlinear growth, and so they do not have an acceleration factor.
Expand the share of EVs to account for 20–40% of total LDV fleet by 2030 and 85–100% by 2050.	22x	n/a; progress evaluated based on expert judgment and the literature	Previously assessed on the basis of linear growth, this time EVs are assessed based on the potential for accelerated, nonlinear growth, and so they do not have an acceleration factor.
Boost the share of BEVs and FCEVs to reach 75% of annual global bus sales by 2025 and to reach 100% of annual bus sales in leading markets by 2030.	n/a	n/a; progress evaluated based on expert judgment and the literature	n/a; this report establishes a new target and indicator.
Increase the share of BEVs and FCEVs to 8% of global annual MHDV sales by 2025 and to 100% in leading markets by 2040.	n/a	n/a; progress evaluated based on expert judgment and the literature	n/a; this report establishes a new target and indicator.
Raise the share of low-emissions fuels in the transport sector to 15% by 2030 and to 70–95% by 2050.	8x	12x	Data set updated with more recent data. Because historical data values are so small, any changes result in large changes in the acceleration factor.
Increase SAF's share of global aviation fuel supply to 10% by 2030 and to 100% by 2050.	n/a	n/a; progress evaluated based on expert judgment and the literature	n/a; this report establishes a new target and indicator.
Raise ZEF's share of international shipping fuel to 5% by 2030 and to 100% by 2050.	n/a	n/a; progress evaluated based on expert judgment and the literature	n/a; this report establishes a new target and indicator.
TECHNOLOGICAL CARBON REMOVAL			
Scale up technological carbon removal to 75 $MtCO_2$ annually by 2030 and to 4.5 $GtCO_2$ annually by 2050.	n/a	n/a; progress evaluated based on expert judgment and the literature	n/a; this report establishes a new target and indicator.
LAND USE AND COASTAL ZONE MANAGEMENT			
Reduce the rate of deforestation by 70% by 2030 and by 95% by 2050, relative to 2018.	n/a; U-turn needed	n/a; U-turn needed	No difference between this and last year.
Reforest 259 Mha of land by 2030 and 678 Mha in total by 2050, relative to 2018.	5.2x	3.2x	While our indicator and 2050 target remain unchanged from last year's report, this year's report provides an updated target for 2030, reflecting new estimates of annual carbon sequestration potential per hectare. See more in Appendix B.
Remove 3.0 $GtCO_2$ annually through reforestation by 2030 and 7.8 $GtCO_2$ annually by 2050.	11x	4.2x	As above, the 2030 target has been updated, and, given that carbon removal from reforestation is related to reforestation amount, the acceleration factor here has also changed.
Reduce the degradation and destruction of peatlands by 70% by 2030 and by 95% by 2050, relative to 2018.	n/a	Insufficient data	n/a; this report establishes a new target and indicator.
Restore 22 Mha of peatlands by 2030 and 46 Mha in total by 2050, relative to 2018.	n/a	Insufficient data	n/a; this report establishes a new target and indicator.

2030 and 2050 targets	2020 acceleration factor	2021 acceleration factor	Explanation of differences
LAND USE AND COASTAL ZONE MANAGEMENT (CONTINUED)			
Reduce the conversion of coastal wetlands by 70% by 2030 and by 95% by 2050, relative to 2018.	n/a	Insufficient data	n/a; this report establishes a new target and indicator.
Restore 7 Mha of coastal wetlands by 2030 and 29 Mha in total by 2050, relative to 2018.	n/a	2.7x	n/a; this report establishes a new target and indicator.
AGRICULTURE			
Reduce agricultural production emissions by 22% by 2030 and by 39% by 2050, relative to 2017.	n/a; U-turn needed	n/a; U-turn needed	No difference between this and last year.
Increase crop yields by 18% by 2030 and by 45% by 2050, relative to 2017.	n/a; on track if action is sustained	1.9x	Target was updated from last year (now 13 percent increase by 2030; 38 percent increase by 2050, relative to 2017) to be consistent with Searchinger et al. (2021). The indicator remains unchanged.
Increase ruminant meat productivity per hectare by 27% by 2030 and by 58% by 2050, relative to 2017.	2.3x	1.6x	Data set updated with more recent data.
Reduce share of food loss by 50% by 2030 and maintain this reduction through 2050, relative to 2016.	Insufficient data	Insufficient data	No difference between this and last year.
Reduce per capita food waste by 50% by 2030 and maintain this reduction through 2050, relative to 2019.	Insufficient data	Insufficient data	No difference between this and last year.
Reduce ruminant meat consumption in high-consuming regions to 79 kcal/capita/day by 2030 and to 60 kcal/capita/day by 2050.	n/a; on track if action is sustained	1.5x	Target is the same, but the expression of it was changed by narrowing the geographic focus. Instead of showing global per capita consumption (which included all regions, thus both high and low consumers of meat), per Lebling et al. (2020), in this report we solely focus on the necessary decline in per capita consumption in high-consuming countries, given this is the focus of the challenge at hand. The indicator remains unchanged.
FINANCE			
Increase total climate finance flows to $5 trillion per year by 2030 and sustain this level of funding through 2050.	n/a	13x	n/a; this report establishes a new target and indicator.
Raise public climate finance flows to at least $1.25 trillion per year by 2030 and sustain through 2050.	n/a	5x	n/a; this report establishes a new target and indicator.
Boost private climate finance flows to at least $3.75 trillion per year by 2030 and sustain through 2050.	n/a	23x	n/a; this report establishes a new target and indicator.
Jurisdictions representing three-quarters of global emissions mandate TCFD-aligned climate risk reporting and all of the world's 2,000 largest public companies report on climate risk in line with TCFD recommendations by 2030.	n/a	n/a	n/a; this report establishes a new target and indicator.
Ensure that a carbon price of at least $135/t$CO_2$e covers the majority of the world's GHG emissions by 2030 and then increases to at least $245/t$CO_2$e by 2050.	n/a	n/a; step change needed	n/a; this report establishes a new target and indicator.
Phase out public financing for fossil fuels, including subsidies, by 2030, with G7 countries and international financial institutions achieving this by 2025.	n/a	1.1x	n/a; this report establishes a new target and indicator.

Note: n/a = not applicable; IEA = International Energy Agency; gCO_2/kWh = grams of carbon dioxide per kilowatt-hour; GHG = greenhouse gas; Mt = million tonnes; GW = gigawatts (billion watts); BEV = battery electric vehicle; FCEV = fuel cell electric vehicle; MHDV = medium- and heavy-duty vehicle; EV = electric vehicle; LDV = light-duty vehicle; SAF = sustainable aviation fuel; ZEF = zero-emissions fuel; BAU = business as usual; gCO_2/pkm = grams of carbon dioxide per passenger kilometer; GtCO_2 = gigatonnes (billion tonnes) of carbon dioxide; MtCO_2 = million tonnes of carbon dioxide; Mha = million hectares; kcal/capita/day = kilocalories per capita per day; TCFD = Task Force on Climate-Related Financial Disclosures; tCO_2e = tonnes of carbon dioxide equivalent.

APPENDIX G.

Methodology for selecting enablers of climate action

TO IDENTIFY A SUBSET OF ENABLERS FOR each target and indicator, we reviewed the academic literature, as well as well-cited papers published by independent research institutions, UN agencies, and high-level sectoral coalitions (e.g., Energy Transitions Commission and the High-Level Panel for a Sustainable Ocean Economy). We conducted this literature review in English and constrained the dates of our search from 2015 to 2021. For some targets and indicators (e.g., protecting and restoring coastal wetlands), however, analysis of this recent body of literature suggested that several highly cited and seminal papers were published prior to 2015. In such instances, we included those studies in our review.

Repositories searched included Google Scholar and EBSCO. We also searched for recent publications directly from the websites of independent research institutions, UN agencies, and high-level sectoral coalitions. Keywords used for each indicator are detailed in Table G1. These were paired with phrases from the five overarching buckets of enablers: innovation, regulations and incentives, strong institutions, leadership from key change agents, and shifts in behavior and social norms.

TABLE G1. Keywords searched in literature review

Indicator	Keywords
POWER	
Share of renewables in electricity generation (%)	Renewable electricity generation; solar power; wind power
Share of unabated coal in electricity generation (%)	Coal-fired power; coal phaseout in electricity generation
Carbon intensity of electricity generation (gCO_2/kWh)	Carbon intensity of electricity generation; emissions intensity of electricity generation
BUILDINGS	
Carbon intensity of building operations ($kgCO_2/m^2$)	Renewable energy for heating; carbon intensity of buildings
Energy intensity of building operations (% change indexed to 2015, for which 2015 equals 100)	Energy efficiency of buildings; building envelope improvements; near-zero buildings
Retrofitting rate of buildings (%/yr)	Retrofitting rate; deep retrofitting of buildings
INDUSTRY	
Share of electricity in the industry sector's final energy demand (%)	Electrification of heat; industry decarbonization
Carbon intensity of global cement production ($kgCO_2$/t cement)	Cement decarbonization; cement roadmap; novel cements; cement production; cement emissions
Carbon intensity of global steel production ($kgCO_2$/t steel)	Steel decarbonization; steel roadmap; hydrogen-based steel; steel emissions; steel production
Low-carbon steel facilities in operation (# of facilities)	Steel decarbonization projects; nonstate climate action; steel emissions; Hybrit, Hisarna; CCS
Green hydrogen production (Mt)	Green hydrogen production; low-carbon hydrogen; electrolysis capacity; hydrogen strategy
TRANSPORT	
Share of trips made by private LDVs (%)	Modal split; modal share; passenger vehicles; public transit; walk; bicycle; passenger kilometers traveled
Carbon intensity of land-based transport (gCO_2/pkm)	Transport electrification; e-fuels/green hydrogen research; advanced biofuels; modal shift behavior change
Share of EVs in LDV sales (%)	Electric vehicle; zero-emissions vehicle; EV incentives; lithium-ion battery
Share of EVs in the LDV fleet (%)	Electric vehicle stock; electric vehicle fleet; ICE vehicle phaseout
Share of BEVs and FCEVs in bus sales (%)	Zero emission buses; transit electrification and decarbonization; barriers; BEV and FCEV incentives; enabling infrastructure

Indicator	Keywords
TRANSPORT (CONTINUED)	
Share of BEVs and FCEVs in MHDV sales (%)	Zero emission trucks and commercial vehicles; fleet electrification and decarbonization; barriers; BEV and FCEV incentives; enabling infrastructure
Share of low-emissions fuels in the transport sector (%)	Development of low-emissions fuels; green hydrogen market creation; e-fuels; PtX
Share of SAF in global aviation fuel supply (%)	Aviation; sustainable aviation fuel; biofuel; jet fuel
Share of ZEF in international shipping fuel supply (%)	Shipping; international shipping; zero-emissions fuels; drivers; enablers; ammonia; hydrogen; decarbonization
TECH CDR	
Rate of technological carbon removal ($MtCO_2$ removed/yr)	Carbon removal scale-up; DAC; BECCS; mineralization; carbon removal policies
LAND USE AND COASTAL ZONE MANAGEMENT	
Deforestation rate (Mha/yr)	Deforestation; reducing deforestation
Reforestation (cumulative Mha)	Reforestation; forest landscape restoration; nature-based solutions; natural carbon removal
Rate of carbon removal from reforestation ($GtCO_2$/yr)	Reforestation; forest landscape restoration; nature-based solutions; natural carbon removal
Peatlands conversion rate (Mha/yr)	Peatlands conversion; peatland drainage; palm oil
Peatlands restoration (cumulative Mha)	Peatlands restoration; palm oil
Coastal wetlands conversion rate (Mha/yr)	Blue carbon; coastal wetlands; coastal ecosystems; coastal wetlands conversion
Coastal wetlands restoration (cumulative Mha)	Blue carbon; coastal wetlands; coastal ecosystems; coastal wetlands restoration
AGRICULTURE	
Agricultural production GHG emissions ($GtCO_2e$/yr)	GHG emissions; agricultural production; climate-smart agriculture
Crop yields (t/ha/yr)	Sustainable crop yield intensification; sustainable increases in crop productivity; low-emissions crop yield gains; crop production
Ruminant meat productivity (kg/ha/yr)	Sustainable livestock intensification; sustainable increases in meat productivity; sustainable increases in dairy; livestock production
Share of food production lost (%)	Food loss and waste; reducing GHG emissions from food loss and waste; food wastage
Food waste (kg/capita/yr)	
Ruminant meat consumption in the Americas, Europe, and Oceania (kcal/capita/day)	Ruminant meat consumption; shifting diets; sustainable diets; low-emissions diets; beef consumption; plant-based diets
FINANCE	
Total climate finance (billion $)	Public climate finance; government investment climate; climate investment; scaling climate finance; increase climate finance; private climate finance; private investment climate; mobilize private climate finance; private climate finance mobilization
Public climate finance (billion $)	Public climate finance; government investment climate; climate investment; scaling climate finance; increase climate finance
Private climate finance (billion $)	Private climate finance; private investment climate; climate investment; scaling climate finance; increase climate finance; mobilize private climate finance; private climate finance mobilization
Corporate climate risk disclosure	Corporate climate risks; corporate climate risk disclosure; climate-related financial disclosures
Share of global emissions covered by a carbon price of at least $135 per tonne of CO_2e (%)	Carbon pricing; carbon tax; emissions pricing; emissions tax; emissions trading schemes; carbon-pricing policy
Total public financing for fossil fuels (billion $)	Fossil fuel subsidy; fossil fuel subsidy phaseout; end fossil fuel subsidies; fossil fuel production subsidies; fossil fuel consumption subsidies; public finance for fossil fuel

Note: gCO_2/kWh = grams of carbon dioxide per kilowatt-hour; $kgCO_2/m^2$ = kilograms of carbon dioxide per square meter; $kgCO_2$/t = kilograms of carbon dioxide per tonne; CCS = carbon capture and storage; Mt = million tonnes; ZEF = zero-emissions fuel; EV = electric vehicle; LDV = light-duty vehicle; ICE = internal combustion engine; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle; MDHV = medium- and heavy-duty vehicle; PtX = Power-to-X; SAF = sustainable aviation fuel; pkm = passenger kilometer; CDR = carbon dioxide removal; DAC = direct air capture; BECCS = bioenergy with carbon capture and storage; Mha = million hectares; $GtCO_2$/yr = gigatonnes (billion tonnes) of carbon dioxide per year; GHG = greenhouse gas; t/ha/yr = tonnes per hectare per year; tCO_2e = tonnes of carbon dioxide equivalent.

ENDNOTES

1 According to 2010 data, buildings are responsible for as much as 18 percent of global GHG emissions when including the indirect emissions from electricity and heat consumption (IPCC 2014).

2 Medium- and heavy-duty vehicles include buses, medium freight trucks, and heavy freight trucks.

3 These targets are based on scenarios in the IPCC's Special Report on 1.5°C that meet sustainability criteria set out in Fuss et al. (2018) (20 of the 53 scenarios) and use direct air capture, bioenergy with carbon capture and storage, and mineralization as technological carbon removal approaches. Targets are set at the median of these scenarios; interquartile ranges are 0–660 $MtCO_2$ for 2030 and 3.3–6.1 $GtCO_2$ for 2050.

4 Unlike in 2016, when temperatures were higher due to a strong El Niño, in 2020 the Pacific had entered a La Niña period, which has a cooling effect but did not sufficiently offset the warming from human-induced climate change.

5 Carbon dioxide emissions are reduced to net zero by 2050 and total GHG emissions reach net zero by 2063–68 on average for 1.5°C scenarios with limited or no overshoot of 1.5°C.

6 CAT refers to "targets" as "benchmarks" in its report and methodology. See CAT (2020b, 2020a).

7 This report focuses on the global progress and therefore excludes country-specific data.

8 In a few cases, we are unable to calculate the historical linear rate of change because we only had data for a total change over a multiyear time period rather than data for each year. This is the case for the reforestation, carbon sequestration from reforestation, and peatlands conversion indicators, whose data are available as totals over 12 years, 12 years, and 18 years, respectively. Data for coastal wetlands restoration are available for 16 years for mangroves and much longer for other ecosystems, but similarly, they are only available as a total, not year by year, so an acceleration factor can't be calculated.

9 However, the power sector's carbon intensity in China is still above the world average, and a large pipeline of coal power plants is planned or under construction.

10 Implies the biomass power generation with carbon capture and storage in combination.

11 These targets are set at the highest level of ambition technically achievable based on national energy transition studies. Integrated assessment models build economy-wide scenarios (i.e., not just the power sector) across aggregated regions and come to a wider range of the share of renewables. This indicates that there are 1.5°C-compatible scenarios with a renewable penetration of less than 98–100 percent. Grid stability and reliability in these scenarios is maintained in a cost-effective manner through multiple technologies, including storage. Storage on week-to-month timescales is enabled by pumped storage and on hourly-daily timescales by battery technologies and compressed air storage. Models can still find the need for spinning up gas-based reserves to help balance electrical load; in 100 percent renewable energy (RE) scenarios, such turbines are fueled with synthetic gas derived from renewable sources (e.g., methanation, electrolysis).

12 The IEA includes tidal energy and heat pumps in its definition of "other" new renewables.

13 The targets in this report derive from scenarios with low amounts of carbon capture and storage technology based on concerns related to cost, continued reliance on fossil fuels, and incomplete capture. With capture rates of 90 percent, fossil CCS would still result in carbon intensities greater than 50 g/kWh and would require costly compensation with larger amounts of biomass power generation with CCS or direct air capture. Nuclear power is also limited due to concerns over safety, cost, waste disposal, and inflexibility. Grid stability and reliability is maintained in a cost-effective manner through multiple technologies, including storage. Short-term storage on an hourly basis is mostly powered by batteries and compressed air storage. Longer-term weekly and monthly storage is enabled by pumped storage and power-to-X technologies. The models that underlie the targets also employ spinning up gas-based reserves to help balance electrical load. In 100 percent RE scenarios, such turbines are fueled with synthetic gas derived from renewable sources (e.g., methanation, electrolysis).

14 The price of solar PV has risen 18 percent since the start of 2021, because the cost of polysilicon has quadrupled (Murtaugh and Eckhouse 2021). A similar disruption was observed once earlier in the past decade (in 2013). It remains to be seen whether this year's rise will also be temporary.

15 "Unabated" refers to coal power generation that does not use carbon capture technology.

16 According to 2010 data, buildings are responsible for as much as 18 percent of global GHG emissions, when including the indirect emissions from electricity and heat consumption (IPCC 2014). This covers energy use for space heating and cooling, water heating, cooking, appliances, and lighting in the commercial and residential buildings.

17 This target is based on Climate Action Tracker, which for 2030 provides targets for the United States, the European Union, Brazil, India, China and South Africa. The 45 percent reduction for residential buildings reflects the least ambitious target of all those countries. The range of 65–75 percent reduction for commercial buildings covers all countries' targets.

18 A heat pump is a device that moves thermal energy from one place to the other. There are heat pumps for heating and cooling. For heating, the pump moves thermal energy into the building. For cooling, the thermal energy is moved out of the building.

19 Hydrogen is an expensive source of energy, not only because it is a rather new technology but also because the conversion from electricity to hydrogen is much less efficient than other solutions. This will not change with further technology development. Paris-compatible scenarios thus do not envision a large role for hydrogen in the buildings sector.

20 Final energy demand of the building, independently of how the demand is met.

21 As of August 2021.

22 This target is based on Climate Action Tracker, which for 2030 provides targets for the United States, the European Union, Brazil, India, China, and South Africa. All of those countries fall in the target range of 20–30 percent.

23 This target is based on Climate Action Tracker, which for 2030 provides targets for the United States, the European Union, Brazil, India, China, and South Africa. All of those countries fall in the target range of 20–30 percent.

24 Note that the acceleration factor is highly sensitive to the choice of historical data years. Using the data as of 2015 only would give a factor of 4.5.

25 Embodied carbon is not part of this indicator (see summary at the beginning of this chapter).

26 However, the IEA data do not breakdown emissions sources separately.

27 *Deep retrofit* is not a clearly defined term. Research from the United States indicates that energy efficiency can be improved by around 25–50 percent for most building types (Rocky Mountain Institute 2012). This does not yet include the decarbonization of the remaining energy needs.

28 Shallow retrofitting rates are those for which average energy intensity reductions are generally less than 15 percent.

29 Other energy-intensive subsectors in industry include chemicals, aluminum, paper, other nonmetallic minerals and nonferrous metals, as well as light industries that produce vehicles, machinery, food, timber, textiles, and other consumer goods, together with the energy consumed in construction and mining operations (IEA 2021c).

30 Traditional cement production involves blending clinker (the initial output of the cement production process) with additional materials (e.g., SCMs), and the clinker-to-cement ratio refers to the amount of clinker that is used per tonne of cement. SCMs are materials that can be added in place of clinker to reduce the clinker-to-cement ratio, and in doing so, can lower the overall emissions intensity of cement. Traditional SCMs include fly ash and blast furnace slag, which are byproducts from coal-fired power and steel production. However, new SCMs are being developed, of which one of the most promising is calcined clay. This material is abundantly available globally and can reduce the clinker-to-cement ratio to 40 percent in some cases.

31 Since the primary GHG emitted during cement production is CO_2, *carbon intensity and emissions intensity are used interchangeably throughout this section.*

32 Since clinker production requires high heat, this technology cannot be easily electrified, although ongoing research is investigating the potential of using electricity and/or hydrogen.

33 Novel cements refers to a group of cements produced using different techniques and with either similar or completely different raw materials. Novel cements do not contain any clinker, which reduces both process and energy-related emissions to varying extents depending on the type of novel cement.

34 *Low-carbon steel facilities are facilities using a technology that leads to full or near-zero emissions. Although some projects only lead to partial emissions reductions in the near term, such as DRI-EAF using a blend of green hydrogen and natural gas, these are still considered "low-carbon facilities" as they plan to reach near-zero emissions in the medium to long term. By "operational," we refer to full-scale projects.*

35 For low- and zero-carbon steel plants, the High-Level Climate Champions established a normative target based on project pipeline announcements and scenarios modeled by the Energy Transition Commission's Net-Zero Steel Initiative. This target focuses on increasing the number of announced or planned facilities with annual productivity levels that exceed 1 million tonnes by 2030.

36 The most commonly used route is the blast furnace–basic oxygen furnace (BF-BOF) route and is based on coked coal. The second-most commonly practiced route is the scrap to electric arc furnace (scrap-EAF) route where scrap steel is melted in an electric arc furnace, fully fed by electricity. Least used is the direct reduced iron–electric arc furnace route (DRI-EAF) route, which uses natural gas or other fuels to reduce the iron ore before it is fed to an EAF.

37 Refers to mentioned key decarbonization technologies including CCUS, green hydrogen–based DRI, and direct electrolysis (Figure 26).

38 This estimate accounts for uncertainty around end uses and variable energy productivity. The low end of this target, 500 Mt, represents a scenario with maximum economy-wide energy productivity improvements where global energy demand is 17 percent lower than 2019 levels. The high end, 800 Mt, represents a scenario where global energy demand is 15 percent higher than 2019 with no additional productivity improvement (ETC 2021b).

39 Range assumes electrolyzer utilization rate will range from 40 to 65 percent depending on location and that 1 MW electrolyzer capacity will produce 90–140 tonnes green hydrogen per year.

40 Excluding externalities related to climate change (i.e., assuming the electrification of the vehicle fleet), Parry et al. (2007) quantified all other externalities related to car usage at $0.10 per mile driven.

41 See http://transferproject.org/wp-content/uploads/2017/09/Transportation-Demand-Management.pdf for a more complete list.

42 Advanced biofuels are those that make use of feedstock from nonfood and nonfeed biomass, including waste materials (such as vegetable oils or animal fats) and energy-specific crops that can be grown on less-productive and degraded land. They thus have a lower impact on food resources and should be less likely to cause land-use change.

43 China, the European Union, Japan, and the United States.

44 Financing schemes that allow purchasers to cover the cost of the battery of a vehicle through payments over the lifetime of the asset.

45 China, the European Union, Japan, and the United States.

46 Medium- and heavy-duty vehicles include buses, medium freight trucks, and heavy freight trucks.

47 Total cost of ownership for a truck includes capital costs, fuel costs, and operating costs associated with vehicle maintenance, tire replacement, registration, insurance, and road taxes.

48 Trucks here refers to medium- and heavy-duty vehicles (MHDVs). MHDVs are generally involved in applications such as freight and cargo distribution, construction, refuse applications, and drayage. Medium-duty vehicles generally weigh between 3.2 and 13.6 tonnes (3.5 and 15 U.S. conventional tons) and heavy-duty vehicles weigh more than 13.6 tonnes (15 U.S. conventional tons). These vehicles can cover more than 161,000 kilometers (100,000 miles) annually depending on the type of application.

49 Drayage trucks transport containers and bulk freight cargo, such as agricultural and petroleum products, between ports and intermodal rail facilities or distribution centers.

50 Vehicles in long-haul heavy-duty applications generally weigh more than 12.7 tonnes (14 U.S. conventional tons) in the United States and 13.6 tonnes (15 U.S. conventional tons) in other markets like China and Europe. Such vehicles can cover a daily distance of 346–402 kilometers (215–250 miles) (or more than 161,000 kilometers [100,000 miles] annually) in road freight movement.

51 Fuel cells offer higher power densities than lithium-ion batteries, and the range of FCEVs can be increased by adding more hydrogen tanks to a vehicle and without increasing the fuel cell stack size. Additionally, FCEVs can also be refueled faster than BEVs. Such characteristics are expected to make FCEVs more suitable for long-haul heavy-duty applications.

52 A learning rate of 22 percent implies that doubling the rate of fuel cell production could decrease the cost of fuel cell stacks (in $/kW) by 22 percent.

53 The price of hydrogen at refueling stations includes hydrogen production, transport, and storage costs.

54 Commercial chargers here refer to 50 kW, 150 kW, and 350 kW chargers.

55 California's ACT rule applies to class 2b to class 8 vehicles, which are those having a gross vehicle weight rating of more than 3.8 tonnes (4.25 U.S. conventional tons).

56 Biofuels that require the use of arable land to produce feedstock are unsustainable and do not lead to significant emissions reductions. Advanced biofuels that do not use such feedstock, or that are derived from waste materials, are those that can be considered low carbon. Such biofuels can help to lower emissions while internal combustion engine vehicles remain on the roads, but they will not be needed as vehicle fleets become fully electrified.

57 These trends include demand increases from conventional biofuels. Policy should shift away from encouraging blending mandates that include conventional biofuels due to their unsustainable nature.

58 An electrolyzer uses electricity to convert water into hydrogen and oxygen gas.

59 Large-scale solar and onshore wind projects require significant tracts of suitable land, something that is lacking in both Japan and South Korea.

60 *Power-to-X* refers to the process of creating green hydrogen, then combining this hydrogen with carbon dioxide or nitrogen to form various types of synthetic fuels.

61 Notably, aviation may account for more than 4.5 percent of global CO_2 emissions by midcentury after considering decarbonization of other sectors (Carbon Brief 2016).

62 The HEFA pathway refines vegetable oils, waste oils, or fats into fuel through hydrogenation. The gasification-FT pathway gasifies feedstocks such as waste and woody residues to produce syngas, which is then fed into a Fischer-Tropsch reactor in the presence of catalysts to form jet fuel. The alcohol-to-jet pathway converts biomass into ethanol, which is then converted to aviation fuel. Finally, the power-to-liquid pathway produces syngas via electrolysis of sustainable CO_2 (using green hydrogen or renewable electricity); this syngas is then converted to hydrocarbons via a Fischer-Tropsch reaction like in the gasification process (WEF 2020).

63 As the HEFA pathway utilizes either virgin vegetable oils with sustainability concerns or waste lipids, which may be highly constrained in supply as they are already largely collected and utilized, other pathways that have more flexibility to use different lignocellulosic or waste feedstocks should continue to be developed for commercialization.

64 *Sustainable CO_2* is the term used for CO_2 emissions that are captured either before or after being released into the atmosphere and that are then "reused" to create a new product. At present, sustainable CO_2 can be derived from three primary sources: as an industrial waste gas from burning fossils such as coal or gas (point-source captured CO_2); from sustainable biomass (bioenergy carbon capture and storage or BECCS); or as direct air capture (DAC), a process that extracts CO_2 directly from the atmosphere (WEF 2020).

65 The four different viable SAF production pathways rely on different combinations of the above inputs: sustainable biomass is needed to produce the HEFA, gasification, and alcohol-to-jet SAF pathways; renewable energy is needed to produce all SAF pathways; green hydrogen is needed to produce the HEFA and power-to-liquid SAF pathways; and sustainable CO_2 is needed to produce the power-to-liquid SAF pathway.

66 BloombergNEF estimates that a carbon price of around $250/tonne of CO_2e would bring the price of fossil-based jet fuel in line with current price estimates for several SAF pathways (BloombergNEF 2021b).

67 In 2019, 96 billion gallons of aviation fuel were used to power the global aviation sector; therefore, the coalition's commitment to supply 2 billion gallons of sustainable aviation fuel in 2030 represents just under 1 percent of global supply. Accordingly, while the coalition's collaboration should be applauded, further ambition toward 2030 is necessary.

68 Only land-based carbon removal approaches are discussed here, but there is also great, though arguably even less well-understood, potential to leverage the ocean to sequester more carbon through approaches like macroalgae cultivation and alkalinity enhancement.

69 These targets are based on scenarios in the IPCC's Special Report on 1.5°C that meet sustainability criteria set out in Fuss et al. (2018) (20 of the 53 scenarios) and use direct air capture, bioenergy with carbon capture and storage and mineralization as technological carbon removal approaches. Targets are set at the median of these scenarios; interquartile ranges are 0–660 $MtCO_2$ for 2030 and 3.3–6.1 $GtCO_2$ for 2050.

70 The California Air Resources Board expects the credit value to decline to less than $100/$tCO_2$ by 2022 (Larsen et al. 2019).

71 Note that our indicator uses area of deforestation, rather than emissions from deforestation as used by Roe et al. (2019). We chose area as our metric due to consistency with previous reports, when emissions data were less readily available, consistency with other indicators, and due to its actionability. The area of deforestation is highly correlated with emissions from deforestation, as shown in Figure 55.

72 These figures are based on an update to Curtis et al. (2018) by World Resources Institute and The Sustainability Consortium, which separates annual tree cover loss data described in

Hansen et al. (2013) into five drivers: commodity-driven deforestation, shifting agriculture, forestry, wildfire, and urbanization (Curtis et al. 2018; Hansen et al. 2013). We define *deforestation* for the purposes of this report as tree cover loss due to commodity-driven deforestation and urbanization, and tree cover loss due to shifting agriculture that occurs in primary forests (as mapped by Turubanova et al. 2018).

73 Gross tree cover gain is among the best available proxy indicators for reforestation, measuring the establishment of tree canopy in an area that previously had no tree cover. This metric, however, also includes tree cover gains made within areas that are not typically considered forests, such as industrial tree plantations or, in some instances, dense agroforestry systems. An area is defined as experiencing tree cover gain when an increase in tree cover to at least 50 percent canopy cover has occurred (measured at a 30-meter resolution in satellite imagery). This indicator also measures "gross" tree cover gain—that is, the total gain irrespective of any tree cover loss that may have occurred during that same year (WRI 2021b).

74 While our 2050 target remains unchanged from the last iteration of the *State of Climate Action* (Lebling et al. 2020), this year's report provides an updated target for 2030, reflecting new estimates of annual carbon sequestration potential rates per hectare (Cook-Patton et al. 2020). To ensure alignment with the mitigation potential that Roe et al. (2019) found for reforestation (3.0 $GtCO_2$ per year by 2030), from which our carbon removal for reforestation target is derived, we used the annual carbon sequestration potential rates per hectare from Cook-Patton et al. (2020) to estimate the area that must be reforested by 2030 to remove 3.0 $GtCO_2$ annually. Although this new 2030 target falls below those set by the Bonn Challenge and the New York Declaration on Forests (350 Mha by 2030), it focuses solely on reforestation, while both international commitments include pledges to plant trees across a broader range of land uses, such as agroforestry systems or tree plantations.

75 Reforestation is defined as the conversion from nonforested lands to forests in areas where forests historically occurred. This excludes afforestation or restoration of nonforested landscapes.

76 This is the maximum additional area of land that can be reforested from actions that go beyond business-as-usual land use activities. It is additional to gross tree cover gain that occurred prior to the baseline year of 2018, which includes the time period for which historical data exist (2000–2012).

77 Carbon removal from reforestation targets were updated from Lebling et al. (2020), using new estimates of annual carbon sequestration potential rates per hectare for forest regrowth from Cook-Patton et al. (2020). This report also translates cumulative targets from Lebling et al. (2020) into annual targets.

78 Because soil carbon sequestration rates across agricultural lands are relatively low (Ranganathan et al. 2020; Searchinger and Ranganathan 2020) and the scale-up of BECCS may undercut food security, sustainable development, and climate mitigation goals (Searchinger et al. 2019; Searchinger and Heimlich 2015), this report does not establish targets for either mitigation "wedge." It instead sets a higher target for carbon removal from reforestation.

79 While historical case studies of reforestation exist, papers that analyze these studies to identify common, key enablers of success primarily focus on forest landscape restoration more broadly. This report defines *forest landscape restoration* as the process of regaining ecological functionality and strengthening human well-being across deforested or degraded forest landscapes (Hanson et al. 2015).

80 Although they tend to spare land globally, gains in agricultural productivity can also improve the local economics of farming. By reducing local production costs and increasing the profitability of each hectare in some regions, these improvements in yields can incentivize farmers to expand their croplands and pastures into nearby natural ecosystems. These local rebound effects have likely spurred the expansion of beef, soybeans, and maize production in Brazil, as well as palm oil in Indonesia and Malaysia (Chaturvedi et al. 2019).

81 This target and its associated indicator are both derived from Roe et al. (2019) and Griscom et al. (2017), the latter of which defines coastal wetlands conversion "as the anthropogenic loss of organic carbon stocks in mangroves, saltmarshes, and seagrass ecosystems." This definition does not explicitly include losses from mangrove forests and salt marshes that have drowned from increases in relative sea level rise—a climate impact that will likely intensify in the coming decades. Future iterations of this report may update this target and indicator, as data on the global extent of these ecosystems improve and related methods for distinguishing submergence-related losses from other forms of conversion become available.

82 Mangrove forests, salt marshes, and seagrass meadows are vegetated coastal ecosystems that sit at the intersection of land and the ocean. These ecosystems are classified by their foundational plant species and are among the most productive in the world. Mangrove forests occur primarily in the tropics between the low and high tide. Salt marshes also occupy this intertidal zone, and although they are generally found in middle to high latitudes, some exist alongside mangroves. Unlike mangroves and salt marshes, seagrass meadows are found primarily in coastal waters around the world, with a depth range from the intertidal zone to offshore waters of up to 80 meters (Steven et al. 2020; Lipkin et al. 2003; UNEP et al. 2020). Also, although the coastal literature does not generally consider seagrass meadows to be coastal wetlands, the global climate change community often does (e.g., Roe et al. 2019; Griscom et al. 2017; Hiraishi et al. 2014), and this report follows their lead, particularly the IPCC's *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, which includes seagrass meadows in its guidelines for estimating emissions and removals of GHG from coastal wetlands (Hiraishi et al. 2014).

83 For comparison, the magnitude of global carbon stocks in terrestrial forests ranges from 166 tonnes of carbon per hectare within tropical dry forests to 272 tonnes of carbon per hectare within temperate conifer forests. These estimates include aboveground and belowground biomass, as well as soil organic carbon within the top 30 centimeters in forests and within the top 1 meter in wetlands.

84 This global estimate of avoided emissions does not account for fluxes in methane and nitrous oxide that may occur during conversion, representing one critical gap in the scientific community's understanding of the role coastal wetlands play in climate change mitigation.

85 Estimates of coastal wetlands' global area, historical extent of conversion, and current rates of loss for are highly uncertain and constrained by significant data limitations. Griscom et al. (2017) estimate this rate of loss (0.63 Mha per year) from recently reported estimates of global extent (13.8 Mha for mangroves, 5.1 Mha for salt marshes, and 30 Mha for seagrass meadows) and annual rates of loss (0.7 percent for mangroves, 1.5 percent for salt marshes, and 1.5 percent for seagrasses) from the literature (Pendleton et al. 2012; Giri et al. 2011; Siikamäki et al. 2013). But some of these estimates, particularly for salt marshes, rely on data ranging back to the 1800s and are highly uncertain.

86 This target and associated indicator are derived from Roe et al. (2019) and Griscom et al. (2017), which focus solely on mitigation outcomes attributed to human activities. It does not include gains in mangrove forest and salt marsh area that occur from inland migration, a natural, adaptive response that

both ecosystems have to relative sea level rise (Schuerch et al. 2018; Kirwan et al. 2016).

87 Both annual carbon sequestration rates presented for coastal wetlands (0.2 $GtCO_2$ and 0.8 $GtCO_2$) are likely overestimates, given that they do not account for fluxes of nitrous oxide and methane that occur naturally within these ecosystems and partially offset their carbon burial rates (Rosentreter et al. 2018, 2021).

88 In some countries, coastal wetlands are not included within marine protected areas and are often managed by an authority that does not work on ocean affairs, such as agencies focused on managing forests or local planning authorities. Such a disconnect can complicate efforts to protect these ecosystems, and in these countries, improved coordination across these agencies is critical.

89 The global valuation of ecosystem services and functions by Costanza et al. (2014) includes gas regulation, climate regulation, disturbance regulation, water regulation, water supply, erosion control, soil formation, nutrient cycling, waste treatment, pollination, biological control, habitat, food production, raw materials, genetic resources, recreation, and cultural services.

90 CPI's data err toward conservative accounting, including by making 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;
- research and development 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 (some entities report certain financing for fossil fuel projects as climate finance on the pretext that it is lower-carbon than an alternative approach due to efficiency, such as an ultra-supercritical coal power plant compared to a supercritical or subcritical one, or the lower carbon content of the fuel such as gas as compared to coal); and
- data where they are unreliable, such as private sector energy efficiency investment (Buchner et al. 2019).

91 Total developed to developing country climate finance, including private mobilized finance, was estimated by the OECD to have reached $79.6 billion in 2019 (OECD 2021c).

92 Jurisdictional studies also exist: the U.S. Congressional Budget Office projected that a U.S. FTT of 0.1 percent could raise $109 billion annually by 2030 (CBO 2020), while the European Commission's proposal in Eurozone countries was projected to raise €31 billion a year in revenues (European Commission 2013).

93 Carbon pricing can be a useful source of revenue in the short and medium term, but it would need to be replaced by other sources as emissions are reduced over time (IMF 2019).

94 The United Kingdom (73 percent), followed by Germany, Australia, and Canada (all 68 percent), South Africa (65 percent), Italy (64 percent), Japan (59 percent), the United States (57 percent), France (56 percent), and Argentina, Brazil, and Indonesia (all 51 percent).

95 For CPI's 2019 climate finance landscape, tracked private finance is limited to investment in renewable energy, electric vehicles, and infrastructure projects from IJGlobal and from a Climate Bonds Initiative bond data set (Buchner et al. 2019).

96 When considering the use of public finance to derisk private investments, it is important to assess whether the alternative use of public finance to directly own or operate infrastructure and services would deliver a better return to the public (Gabor 2021).

97 This was compiled based on summing the production and consumption subsidy data for 2019 (OECD 2021a), the average state-owned entity fossil fuel capital expenditure between 2017 and 2019 (Geddes et al. 2020), and average of public fossil fuel finance from MDBs and G20 countries' ECAs and DFIs between 2016 and 2018, since an estimate for 2019 was not available (Tucker and DeAngelis 2020).

98 The United Kingdom's policy applies to its international support only; the government still finances fossil fuels domestically.

99 SIAMESE, or the Simplified Integrated Assessment Model with Energy System Emulator.

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ABOUT OUR PARTNERS

THE SYSTEMS CHANGE LAB

As a core component of the Global Commons Alliance and the University of Tokyo's Center for Global Commons, the Systems Change Lab is a joint initiative between World Resources Institute, the High-Level Climate Champions, Bezos Earth Fund, and the Global Environment Facility. As a dynamic, virtual situation room for systems change, the Lab monitors, learns from, and mobilizes action for the transformations required to safeguard the global commons.

THE HIGH-LEVEL CLIMATE CHAMPIONS

The UN High-Level Champions for Climate Action from Chile and United Kingdom - Gonzalo Muñoz 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. Gonzalo 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 scientific analysis that tracks government climate action and measures it against the globally agreed Paris Agreement aim of "holding warming well below 2°C, and pursuing efforts to limit warming to 1.5°C." A collaboration of two organizations, Climate Analytics and NewClimate Institute, CAT has been providing this independent analysis to policymakers since 2009. CAT quantifies and evaluates climate change mitigation commitments, and assesses, whether countries are on track to meeting those. It then aggregates country action to the global level, determining likely temperature increase by the end of the century. CAT also develops sectoral analysis to illustrate required pathways for meeting the global temperature goals.

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 has granted over $1.3 billion to more than 600 grantees in over 50 countries.

THE BEZOS EARTH FUND

The 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.

RACE TO ZERO

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