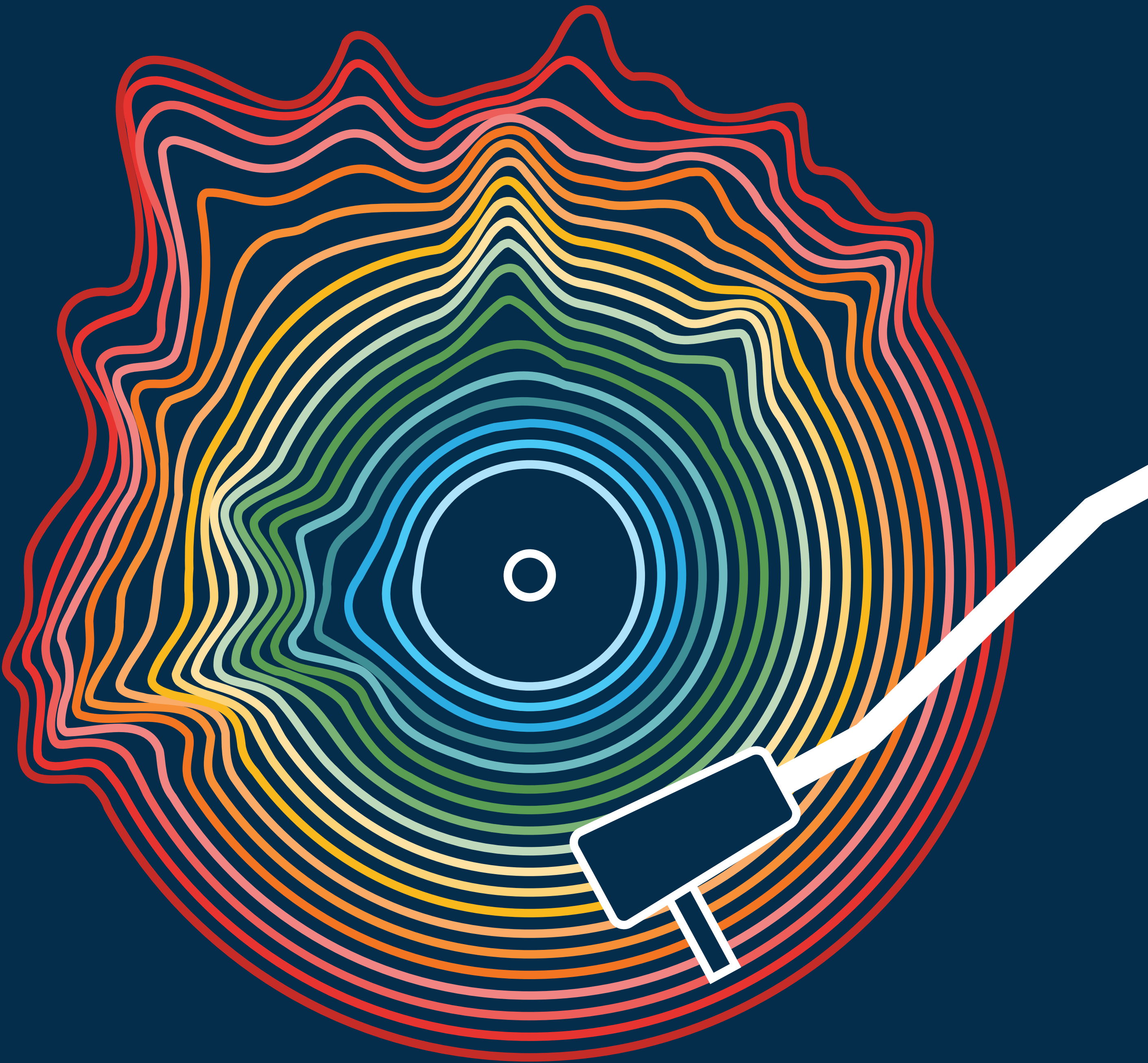
UN environment programme

Broken Record

Temperatures hit new highs, yet world fails to cut emissions (again)



Emissions Gap Report 2023

ISBN: 978-92-807-4098-1
Job number: DEW/2589/NA
DOI: https://doi.org/10.59117/20.500.11822/43922

Suggested citation

United Nations Environment Programme (2023). *Emissions Gap Report 2023: Broken Record – Temperatures hit new highs, yet world fails to cut emissions (again).* Nairobi. https://doi.org/10.59117/20.500.11822/43922.

Production: Nairobi
URL: https://www.unep.org/emissions-gap-report-2023

Co-produced with:

UN environment programme
copenhagen climate centre
CONCITO DENMARK'S GREEN THINK TANK

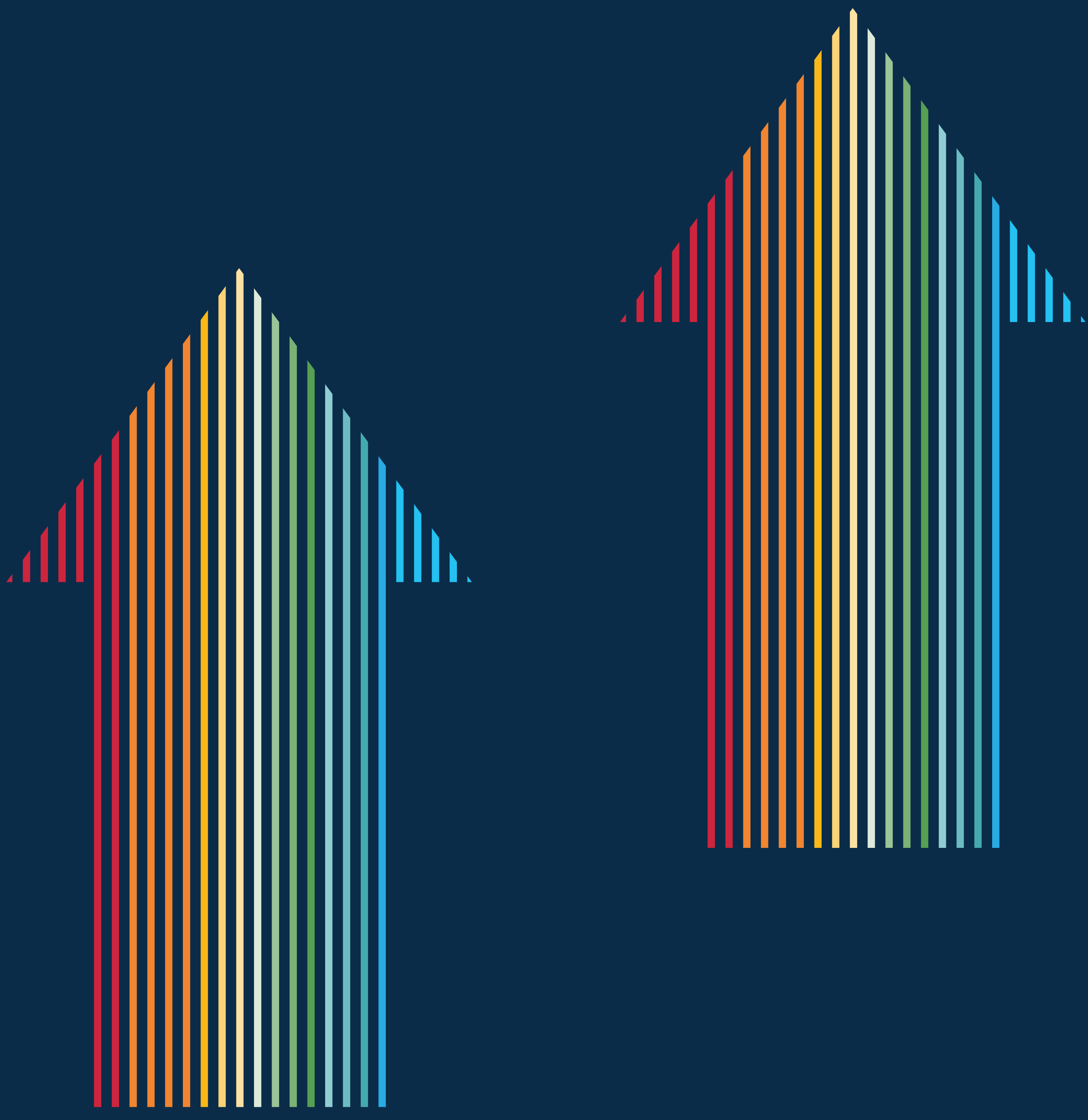
Supported by:

climateworks FOUNDATION
Supported by: Federal Ministry for Economic Affairs and Climate Action on the basis of a decision by the German Bundestag
IKI INTERNATIONAL CLIMATE INITIATIVE
MINISTRY OF FOREIGN AFFAIRS OF DENMARK
Government of the Netherlands

Broken Record

Temperatures hit new highs, yet world fails to cut emissions (again)

Emissions Gap Report 2023



Acknowledgements

The United Nations Environment Programme (UNEP) would like to thank the members of the steering committee, the lead and contributing authors, the reviewers and the Secretariat for their contribution to the preparation of this assessment report. Authors and reviewers have contributed to the report in their individual capacities. Their affiliations are only mentioned for identification purposes.

Steering committee

Muna Alamoodi (Ministry of Climate Change and Environment, United Arab Emirates), Juliane Berger (German Environment Agency), Ruta Bubniene (Secretariat of the United Nations Framework Convention on Climate Change [UNFCCC]); John Christensen (UNEP Copenhagen Climate Centre [UNEP-CCC]), María Paz Cigaran (Libélula); Navroz K. Dubash (Centre for Policy Research), Simon Evans (Carbon Brief) (steering committee observer), Jian Liu (UNEP), Gerd Leipold (Climate Transparency) (steering committee observer), Simon Maxwell (independent), Shonali Pachauri (International Institute for Applied Systems Analysis [IIASA]); Dan Plechaty (ClimateWorks Foundation), Katia Simeonova (independent), Youba Sokona (Intergovernmental Panel on Climate Change [IPCC]), Oksana Tarasova (World Meteorological Organization) and Iman Ustadi (Office of the UAE Special Envoy for Climate Change, United Arab Emirates)

Authors

Chapter 1

Authors: Anne Olhoff (CONCITO – Denmark's green think tank, Denmark) and John Christensen (UNEP-CCC, Denmark)

Chapter 2

Lead authors: William F. Lamb (Mercator Research Institute on Global Commons and Climate Change, Germany; University of Leeds, United Kingdom of Great Britain and Northern Ireland) and Minal Pathak (Ahmedabad University, India)

Contributing authors: Lucas Chancel (World Inequality Lab, Paris School of Economics, France), Monica Crippa (European Commission, Joint Research Centre [JRC], Italy), Giacomo Grassi (European Commission, JRC, Italy), Diego Guizzardi (European Commission, JRC, Italy), Jing Meng (University College London, United Kingdom), Glen P. Peters (CICERO Center for International Climate Research, Norway) and Julia Pongratz (Ludwig-Maximilians University Munich, Germany)

Chapter 3

Lead authors: Takeshi Kuramochi (NewClimate Institute, Germany), Michel den Elzen (PBL Netherlands Environmental Assessment Agency, the Netherlands) and Taryn Fransen (World Resources Institute, United States of America)

Contributing authors: Jesse Burton (University of Cape Town and E3G, South Africa), Ioannis Dafnomilis (PBL Netherlands Environmental Assessment Agency, the Netherlands), Ipek Gençsü (ODI, United Kingdom), Archie Gilmour (ODI, United Kingdom), Mariana Gutiérrez Grados (Climate Transparency, Germany), Frederic Hans (NewClimate Institute, Germany), Sarah Heck (Climate Analytics, Germany), Niklas Höhne (NewClimate Institute, Germany), Camilla Hyslop (Oxford University, United Kingdom), Anna Kanduth (Canadian Climate Institute, Canada), Ben King (Rhodium Group, United States of America), Hannah Kolus (Rhodium Group, United States of America), Ho-Mi Lee (Korea Energy Economics Institute, Republic of Korea), Jared Lewis (Climate Resource, Australia), Swithin Lui (NewClimate Institute, Germany), Natasha Lutz (Oxford University, United Kingdom), Andrew Marquard (University of Cape Town, South Africa), Silke Mooldijk (NewClimate Institute, Germany), Leonardo Nascimento (NewClimate Institute, Germany), Analuz Presbítero (Iniciativa Climática de México [ICM], Mexico), Jazmín Rocco Predassi (Farn, Argentina), Joeri Rogelj (Imperial College London, United Kingdom; International Institute for Applied Systems Analysis [IIASA], Austria), Clea Schumer (World Resources Institute, United States of America), Alister Self (Climate Resource, Australia), Kentaro Tamura (Institute for Global Environmental Strategies [IGES], Japan) and Jorge Villarreal (ICM, Mexico)

Data contributors: Johannes Gütschow (Potsdam Institute for Climate Impact Research, Germany), Christopher Henderson (World Resources Institute, United States of America), Elena Hooijschuur (PBL Netherlands Environmental Assessment Agency, the Netherlands), Kimon Keramidas (European Commission, JRC, Spain), Mia Moisio (NewClimate Institute, Germany), Mika Pflüger (Climate Resource, Germany) and Claire Stockwell (Climate Analytics, Germany)

Chapter 4

Lead authors: Joeri Rogelj (Imperial College London, United Kingdom; IIASA, Austria), Michel den Elzen (PBL Netherlands Environmental Assessment Agency, the Netherlands) and Joana Portugal-Pereira (Graduate School of Engineering [COPPE], Universidade Federal do Rio de Janeiro, Brazil)

Contributing authors: Taryn Fransen (World Resources Institute, United States of America), Jarmo Kikstra (Imperial College London, United Kingdom), Robin Lamboll (Imperial College London, United Kingdom), Malte Meinshausen (University of Melbourne, Australia) and Isabela Schmidt Tagomori (PBL Netherlands Environmental Assessment Agency, the Netherlands)

Data contributors: Ioannis Dafnomilis (PBL Netherlands Environmental Assessment Agency, the Netherlands) and Kimon Keramidas (European Commission, JRC, Spain)

Chapter 5

Lead authors: Jesse Burton (University of Cape Town and E3G, South Africa) and Greg Muttitt (International Institute for Sustainable Development [IISD], United Kingdom)

Contributing authors: Fatima Denton (United Nations University Institute for Natural Resources in Africa, Ghana), Sivan Kartha (Stockholm Environment Institute, United States of America), Narasimha Rao (Yale School of the Environment, Yale University, United States of America), Joeri Rogelj (Imperial College London, United Kingdom; IIASA, Austria), Saritha Sudharmma Vishwanathan (Indian Institute of Management Ahmedabad, India; National Institute for Environmental Studies, Japan), Dan Tong (Tsinghua University, China), Marta Torres Gunfaus (IDDRI, France) and William Wills (Centro Brasil no Clima, Brazil; Eos Consulting, Brazil)

Chapter 6

Lead authors: Narasimha Rao (Yale School of the Environment, Yale University, United States of America) and Yacob Mulugetta (University College London, United Kingdom)

Contributing authors: Jesse Burton (University Cape Town and E3G, South Africa), Joisa Dutra Saraiva (Getulio Vargas Foundation [FGV], Brazil), Ashwin Gambhir (Prayas Energy Group, India), Jessica Omukuti (University of Oxford, United Kingdom), Nadia S. Ouedraogo (United Nations Economic Commission for Africa [UNECA], Ethiopia), Setu Pelz (IIASA, Austria), Fei Teng (Tsinghua University, China) and Meron Tesfamichael (University College London, United Kingdom)

Chapter 7

Lead authors: Oliver Geden (German Institute of International and Security Affairs, Germany), Matthew Gidden (IIASA, Austria), Mai Bui (Imperial College London, United Kingdom) and Mercedes Bustamante (Universidade de Brasília, Brazil)

Contributing authors: Holly Buck (State University of New York at Buffalo, United States of America), Sabine Fuss (Mercator Research Institute on Global Commons and Climate Change, Germany), Gaurav Ganti (Climate Analytics, Germany), Jan Minx (Mercator Research Institute on Global Commons and Climate Change, Germany), Gregory Nemet (University of Wisconsin-Madison, United States of America), Julia Pongratz (University of Munich and Max Planck Institute for Meteorology, Germany), Joana Portugal-Pereira (COPPE, Universidade Federal do Rio de Janeiro, Brazil), Stephanie Roe (World Wide Fund for Nature [WWF], United States of America) and Stephen M. Smith (University of Oxford, United Kingdom)

Reviewers

Muna Alamoodi (Ministry of Climate Change and Environment, United Arab Emirates), Jesica Lelynn Andrews (UNEP Finance Initiative), Oluleke Babayomi (Shandong University), Juliane Berger (German Environment Agency), Marie Blanche Ting (UNEP-CCC), Pierre Boileau (UNEP), Olivier Bois von Kursk (IISD), Raymond Brandes (UNEP), Ruta Bubniene (Secretariat of the UNFCCC), David Carlin (UNEP Finance Initiative), Rob Dellink (Organisation for Economic Co-operation and Development [OECD]), Subash Dhar (UNEP-CCC), Paul Dowling (European Commission), Swati Dsouza (International Energy Agency [IEA]), Simon Evans (Carbon Brief), Ivetta Gerasimchuk (IISD), Niklas Hagelberg (UNEP), Yasuko Kameyama (University of Tokyo), Maarten Kappelle (UNEP), Alaa Al Khourdajie (Imperial College London), Thaddeus Idi Kiplimo (UNEP), Andrea Klaric (European Commission), Gabriel Labbate (UNEP), Kate Larsen (Rhodium Group), Gerd Leipold (Climate Transparency), Jian Liu (UNEP), Bert Metz (independent), Bavelyne Mibei (UNEP), Shonali Pachauri (IIASA), María Paz Cigaran (Libélula), Balakrishna Pisupati (UNEP), Dan Plechaty (ClimateWorks Foundation), Rula Qalyoubi (UNEP), Mark Radka (independent), Zoltán Rakonczay (European Commission), Andy Reisinger (Independent), Jade Roberts Maron (UNEP), Yann Robiou du Pont (Climate Energy College, Utrecht University), Gregor Semieniuk (University of Massachusetts Amherst), Yuli Shan (University of Birmingham), Katia Simeonova (independent), Jim Skea (Imperial College London/IPCC), Youba Sokona (IPCC), Masahiro Sugiyama (University of Tokyo), Oksana Tarasova (WMO), Iman Ustadi (Office of the UAE Special Envoy for Climate Change, United Arab Emirates), José Maria Valenzuela (University of Oxford), Chris Vivian (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection [GESAMP]), Adrien Vogt-Schilb (Inter-American Development Bank [IDB]), Daniel Wetzel (IEA), Zhao Xiusheng (Tsinghua University), Maya Zenko Ulezic (European Commission) and Jinhua Zhang (UNEP)

Chief scientific editors

Anne Olhoff (CONCITO – Denmark's green think tank), John Christensen (UNEP-CCC), Simon Maxwell (independent) and Navroz Dubash (Centre for Policy Research)

Secretariat, production and coordination

Anne Olhoff (CONCITO - Denmark's green think tank), Julia Rocha Romero (UNEP-CCC), Kaisa Uusimaa (UNEP) and Maarten Kappelle (UNEP)

Media and launch support

UNEP Communication Division and UNEP-CCC communication team

Design and layout

Weeks.de Werbeagentur GmbH (figures), Strategic Agenda (layout) and Beverley McDonald, UNEP (cover design)

Translation of the executive summary and language editing

Strategic Agenda

Thanks also to:

Siska Adriani Ringbo (UNEP-CCC), Angeline Djampou (UNEP), Dany Ghafari (UNEP), Selma Hedges (UNEP), Andrea Hinwood (UNEP), Christian Ibsen (CONCITO – Denmark's green think tank), Jason Jabbour (UNEP), Jarl Krausing (CONCITO – Denmark's green think tank), Thomas Laursen (UNEP-CCC), Anita Mujumdar (UNEP), Pia Riis Kofoed-Hansen (UNEP-CCC), Ignacio Sánchez Díaz (UNEP), Pinya Sarasas (UNEP), Ying Wang (UNEP) and Edoardo Zandri (UNEP)

The 2023 edition of the Emissions Gap Report is supported by the Environment Fund, UNEP's core financial fund. UNEP would like to thank the ClimateWorks Foundation, the Danish Ministry of Foreign Affairs, the Dutch Ministry of Economic Affairs and Climate Policy, and the German Government and its International Climate Initiative (IKI), for their support for the production of the Emissions Gap Report 2023.

Glossary

This glossary is compiled drawing on glossaries and other resources available on the websites of the following organizations, networks and projects: the Intergovernmental Panel on Climate Change, United Nations Environment Programme, United Nations Framework Convention on Climate Change (UNFCCC), and World Resources Institute.

Annex I Parties: Consists of the group of countries listed in Annex I to the UNFCCC. Under Articles 4.2 (a) and 4.2 (b) of the UNFCCC, Annex I Parties were committed to adopting national policies and measures with the non-legally binding aim to return their greenhouse gas (GHG) emissions to 1990 levels by 2000. The group is largely similar to the Annex B Parties to the Kyoto Protocol that also adopted emissions reduction targets for 2008–2012. By default, the other countries are referred to as Non-Annex I Parties (see below).

Annex II Parties: The group of countries listed in Annex II to the UNFCCC. Under Article 4 of the UNFCCC, these countries have a special obligation to provide financial resources to meet the agreed full incremental costs of implementing measures mentioned under Article 12, paragraph 1. They are also obliged to provide financial resources, including for the transfer of technology, to meet the agreed incremental costs of implementing measures covered by Article 12, paragraph 1 and agreed between developing country Parties and international entities referred to in Article 11 of the UNFCCC. This group of countries shall also assist countries that are particularly vulnerable to the adverse effects of climate change.

Anthropogenic emissions: Emissions derived from human activities.

Baseline/reference: The state against which change is measured. In the context of climate change transformation pathways, the term “baseline scenarios” refers to scenarios based on the assumption that no mitigation policies or measures will be implemented beyond those already in force and/or legislated or planned to be adopted. Baseline scenarios are not intended to be predictions of the future, but rather counterfactual constructions that can serve to highlight the level of emissions that would occur without further policy efforts. Typically, baseline scenarios are compared to mitigation scenarios that are constructed to meet different goals for GHG emissions, atmospheric concentrations or temperature change. The term “baseline scenario” is used interchangeably with “reference scenario” and “no-policy scenario”.

Carbon dioxide emission budget (or carbon budget): For a given temperature rise limit, for example a 1.5°C or 2°C long-term limit, the corresponding carbon budget reflects the total amount of carbon emissions that can be emitted for temperatures to stay below that limit. Stated differently, a carbon budget is an area under a carbon dioxide (CO_2) emission trajectory that satisfies assumptions about limits on cumulative emissions estimated to avoid a certain level of global mean surface temperature rise.

Carbon dioxide equivalent (CO_2e): A way to place emissions of various radiative forcing agents on a common footing by accounting for their effect on the climate. It describes, for a given mixture and amount of GHGs, the amount of CO_2 that would have the same global warming ability, when measured over a specified time period. For the purpose of this report, unless otherwise specified, GHG emissions are the sum of the basket of GHGs listed in Annex A to the Kyoto Protocol, expressed as CO_2e, assuming a 100-year global warming potential.

Carbon dioxide removal (CDR): Refers to anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.

Carbon markets: A term for a carbon trading system through which countries and/or companies may buy or sell units of GHG emissions to offset their GHG emissions by acquiring carbon credits from entities that either minimize or eliminate their own emissions. The term comes from the fact that CO_2 is the predominant GHG, and other gases are measured in units called CO_2 equivalents.

Carbon neutrality: Is achieved when an actor’s net contribution to global CO_2 emissions is zero. Any CO_2 emissions attributable to an actor’s activities are fully compensated by CO_2 reductions or removals exclusively claimed by the actor, irrespective of the time period or the relative magnitude of emissions and removals involved.

Carbon price: The price for a voided or released CO_2 or CO_2e emissions. This may refer to the rate of a carbon tax or the price of emission permits. In many models used to assess the economic costs of mitigation, carbon prices are used as a proxy to represent the level of effort in mitigation policies.

Conditional nationally determined contribution: A nationally determined contribution (NDC – see below) proposed by some countries that is contingent on a range of possible conditions, such as the ability of national legislatures to enact the necessary laws, ambitious action from other countries, realization of finance and technical support, or other factors.

Conference of the Parties to the United Nations Framework Convention on Climate Change (COP): The supreme body of the UNFCCC. It currently meets once a year to review the UNFCCC's progress.

Emissions pathway: The trajectory of annual GHG emissions over time.

Emissions trading: A market-based instrument used to limit emissions. The environmental objective or sum of total allowed emissions is expressed as an emissions cap. The cap is divided in tradable emission permits that are allocated – either by auctioning or handing out for free – to entities within the jurisdiction of the trading scheme. Entities need to surrender emission permits equal to the amount of their emissions (e.g. tons of CO_2). An entity may sell excess permits. Trading schemes occur at the intracompany, domestic and international levels, and may apply to CO_2, other GHGs or other substances. Emissions trading is also one of the mechanisms specified under the Kyoto Protocol.

Gross national income: Gross national income, abbreviated as GNI, is the sum of the incomes of residents of an economy in a given period. It is equal to GDP minus primary income payable by resident units to non-resident units, plus primary income receivable from the rest of the world (from non-resident units to resident units).

Global stocktake: The global stocktake was established under Article 14 of the Paris Agreement. It is a process for Member States and stakeholders to assess whether they are collectively making progress towards meeting the goals of the Paris Climate Change Agreement. The global stocktake assesses everything related to where the world stands on climate action and support, identifying the gaps, and working together to agree on solutions pathways, to 2030 and beyond. The first global stocktake takes place at COP 28 in 2023.

Global warming potential: An index representing the combined effect of the differing times GHGs remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation.

Greenhouse gases (GHGs): The atmospheric gases responsible for causing global warming and climatic change. The major GHGs are CO_2, methane (CH_4) and nitrous oxide (N_2O). Less prevalent, but very powerful, GHGs include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF6).

Integrated assessment models: Models that seek to combine knowledge from multiple disciplines in the form of equations and/or algorithms, in order to explore complex environmental problems. As such, they describe the full chain of climate change, from the production of GHGs to atmospheric responses. This necessarily includes relevant links and feedback between socioeconomic and biophysical processes.

Intended nationally determined contribution (NDC): Intended NDCs are submissions from countries describing the national actions that they intend to take to reach the Paris Agreement's long-term temperature goal of limiting warming to well below 2°C. Once a country has ratified the Paris Agreement, its intended NDC is automatically converted to its NDC, unless it chooses to further update it.

Kyoto Protocol: An international agreement signed in 1997 and which came into force in 2005, standing on its own, and requiring separate ratification by Governments, but linked to the UNFCCC. The Kyoto Protocol, among other things, sets binding targets for the reduction of GHG emissions by industrialized countries.

Land use, land-use change and forestry (LULUCF): A GHG inventory sector that covers emissions and removals of GHGs resulting from direct human-induced land use, land-use change and forestry activities.

Least-cost pathway: Least-cost pathway scenarios identify the least expensive combination of mitigation options to fulfil a specific climate target. A least-cost scenario is based on the premise that, if an overarching climate objective is set, society wants to achieve this at the lowest possible cost over time. It also assumes that global actions start at the base year of model simulations (usually close to the current year) and are implemented following a cost-optimal (cost-efficient) sharing of the mitigation burden between current and future generations, depending on the social discount rate.

Likely chance: A likelihood greater than 66 per cent chance. Used in this assessment to convey the probabilities of meeting temperature limits.

Mitigation: In the context of climate change, mitigation relates to a human intervention to reduce the sources or enhance the sinks of GHGs. Examples include using fossil fuels more efficiently for industrial processes or electricity generation, switching to solar energy or wind power, improving the insulation of buildings, and expanding forests and other "sinks" to remove greater amounts of CO_2 from the atmosphere.

Nationally determined contribution (NDC): Submissions by countries that have ratified the Paris Agreement which present their national efforts to reach the Paris Agreement's long-term temperature goal of limiting warming to well below 2°C. New or updated NDCs are to be submitted in 2020 and every five years thereafter. NDCs thus represent a country's current ambition or target for reducing emissions nationally.

Non-Annex I Parties: These consist mostly of developing countries. Certain groups of developing countries are recognized by the UNFCCC as being especially vulnerable to the adverse impacts of climate change, including countries with low-lying coastal areas and those prone to desertification and drought. Others, such as countries that rely heavily on income from fossil fuel production and commerce, feel more vulnerable to the potential economic impacts of climate change response measures. The UNFCCC emphasizes activities that promise to answer the special needs and concerns of these vulnerable countries, such as investment, insurance and technology transfer.

Offset: In climate policy, a unit of CO_2e emissions that is reduced, avoided or sequestered to compensate for emissions occurring elsewhere.

Scenario: A description of how the future may unfold, based on "if-then" propositions. Scenarios typically include an initial socioeconomic situation and a description of the key driving forces and future changes in emissions, temperatures or other climate change-related variables.

Source: Any process, activity or mechanism that releases a GHG, an aerosol or a precursor of a GHG or aerosol into the atmosphere.

Contents

Foreword

Humanity is breaking all the wrong records when it comes to climate change. Greenhouse gas emissions reached a new high in 2022. In September 2023, global average temperatures were 1.8°C above pre-industrial levels. When this year is over, according to the European Union's Copernicus Climate Change Service, it is almost certain to be the warmest year on record.

The 2023 edition of the Emissions Gap Report tells us that the world must change track, or we will be saying the same thing next year – and the year after, and the year after, like a broken record. The report finds that fully implementing and continuing mitigation efforts of unconditional nationally determined contributions (NDCs) made under the Paris Agreement for 2030 would put the world on course for limiting temperature rise to 2.9°C this century. Fully implementing conditional NDCs would lower this to 2.5°C. Given the intense climate impacts we are already seeing, neither outcome is desirable.

Progress since the Paris Agreement was signed in 2015 has shown that the world is capable of change. Greenhouse gas emissions in 2030, based on policies in place, were projected to increase by 16 per cent at the time of the agreement's adoption. Today, the projected increase is 3 per cent. However, predicted 2030 greenhouse gas emissions must fall by 28 per cent for the Paris Agreement 2°C pathway and 42 per cent for the 1.5°C pathway.

Change must come faster in the form of economy-wide, low-carbon development transformations, with a focus on the energy transition. Countries with greater capacity and responsibility for emissions will need to take more ambitious action and provide financial and technical support to developing nations. Low- and middle-income countries, which already account for more than two thirds of global emissions, should meet their development needs with low-emissions growth, which would provide universal access to energy, lift millions out of poverty, and expand strategic industries.

The first global stocktake, concluding at COP 28 in Dubai this year, will inform the next round of NDCs, which will set new national emissions targets for 2035. Ambition in these NDCs must bring greenhouse gas emissions in 2035 to levels consistent with the 2°C and 1.5°C pathways. Stronger implementation in this decade will help to make this possible. The world needs to lift the needle out of the groove of insufficient ambition and action, and start setting new records on cutting emissions, green and just transitions, and climate finance – starting now.

Inger Andersen

Executive Director
United Nations Environment Programme

Executive summary

Stocktake during a year of broken records

The world is witnessing a disturbing acceleration in the number, speed and scale of broken climate records. At the time of writing, 86 days have been recorded with temperatures exceeding 1.5°C above pre-industrial levels this year. Not only was September the hottest month ever, it also exceeded the previous record by an unprecedented 0.5°C, with global average temperatures at 1.8°C above pre-industrial levels. These records were accompanied by devastating extreme events, which the Intergovernmental Panel on Climate Change (IPCC) has warned us are merely a meek beginning. While the records do not imply that the world has exceeded the 1.5°C temperature limit specified in the Paris Agreement, which refers to global warming levels based on multi-decadal averages, they signal that we are getting closer.

This fourteenth Emissions Gap Report is published ahead of the twenty-eighth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 28). It provides an annual, independent science-based assessment of the gap between the pledged greenhouse gas (GHG) emissions reductions and the reductions required to align with the long-term temperature goal of the Paris Agreement, as well as opportunities to bridge this gap. COP 28 marks the conclusion of the first global stocktake under the Paris Agreement, held every five years to assess the global response to the climate crisis and chart a better way forward. This closely mirrors the objective of the Emissions Gap Report, and the report aims to provide findings relevant to the concluding discussions under the global stocktake.

To inform COP 28 – including on the outcomes needed from the global stocktake – and set the scene for the next round of nationally determined contributions (NDCs) that countries are requested to submit in 2025, which will include emissions reduction targets for 2035, this report looks at what is required this decade and beyond 2030 to maintain the possibility of achieving the long-term temperature goal of the Paris Agreement. It underscores that maintaining this possibility hinges on relentlessly strengthening mitigation action this decade to narrow the emissions gap. This will facilitate significantly more ambitious targets for 2035 in the next round of NDCs, and pave the way for enhancing the credibility and feasibility of the net-zero pledges that by now cover around 80 per cent of global emissions. Failure to bring global GHG emissions in 2030 below the levels implied by current NDCs will make it impossible to limit warming to 1.5°C with no or limited overshoot and strongly increase the challenge of limiting warming to 2°C.

As this report shows, not only temperature records continue to be broken – global GHG emissions and atmospheric concentrations of carbon dioxide (CO_2) also set new records in 2022. Due to the failure to stringently reduce emissions in high-income and high-emitting countries (which bear the greatest responsibility for past emissions) and to limit emissions growth in low- and middle-income countries (which account for the majority of current emissions), unprecedented action is now needed by all countries. For high-income countries, this implies further accelerating domestic emissions reductions, committing to reaching net zero as soon as possible – and sooner than the global averages from the latest IPCC report implies – and at the same time providing financial and technical support to low- and middle-income countries. For low- and middle-income countries, it means that pressing development needs must be met alongside a transition away from fossil fuels. Furthermore, the delay in stringent mitigation action will likely increase future dependence on carbon dioxide removal (CDR) from the atmosphere, but availability of large-scale CDR options in the future cannot be taken for granted. This year, the report thus explores opportunities and challenges associated with energy transitions as well as development and deployment of CDR.

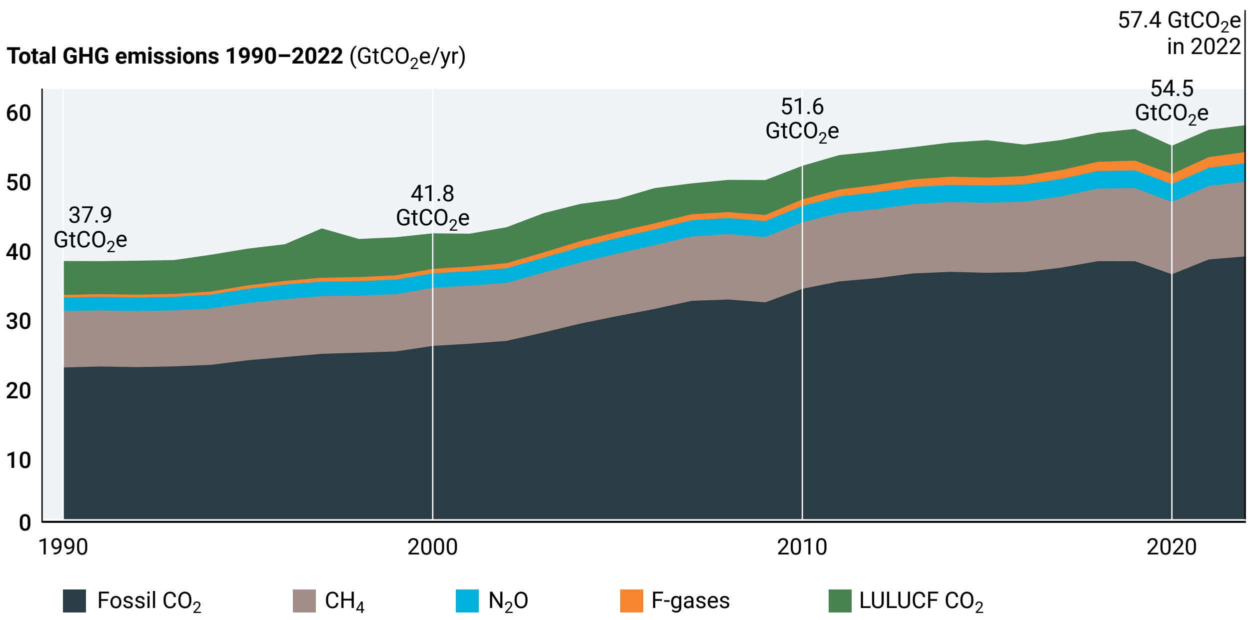
1. Global GHG emissions set new record of 57.4 $GtCO_2e$ in 2022

- Global GHG emissions increased by 1.2 per cent from 2021 to 2022 to reach a new record of 57.4 gigatons of CO_2 equivalent ($GtCO_2e$) (figure ES.1). All sectors apart from transport have fully rebounded from the drop in emissions induced by the COVID-19 pandemic and now exceed 2019 levels. CO_2 emissions from fossil fuel combustion and industrial processes were the main contributors to the overall increase, accounting for about two thirds of current GHG emissions. Emissions of methane (CH_4), nitrous oxide (N_2O) and fluorinated gases (F-gases), which have higher global warming potentials and account for about one quarter of current GHG emissions, are increasing rapidly: in

2022, F-gas emissions grew by 5.5 per cent, followed by CH_4 at 1.8 per cent and N_2O at 0.9 per cent. Based on early projections, global net land use, land-use change and forestry (LULUCF) CO_2 emissions remained steady in 2022. LULUCF CO_2 emissions and removals continue to have the largest uncertainties of all gases considered, both in terms of their absolute amounts and trends.

- GHG emissions across the G20 also increased by 1.2 per cent in 2022. However, members vary widely in their trends with increases in China, India, Indonesia and the United States of America, but decreases in Brazil, the European Union and the Russian Federation. Collectively, the G20 currently account for 76 per cent of global emissions.

Figure ES.1 Total net anthropogenic GHG emissions, 1990–2022



- Global primary energy consumption expanded in 2022 – an expansion mainly met by a growth in coal, oil and renewable electricity supply – whereas gas consumption declined by 3 per cent following the energy crisis and the war in Ukraine. Overall, net electricity demand growth in 2022 was primarily met by renewable sources (excluding hydropower), driven by a record increase in solar capacity additions. Nonetheless, investments in fossil fuel extraction and use have continued in most regions worldwide. Globally, Governments still plan to produce more than double the amount of fossil fuels in 2030 than would be consistent with the long-term temperature goal of the Paris Agreement.

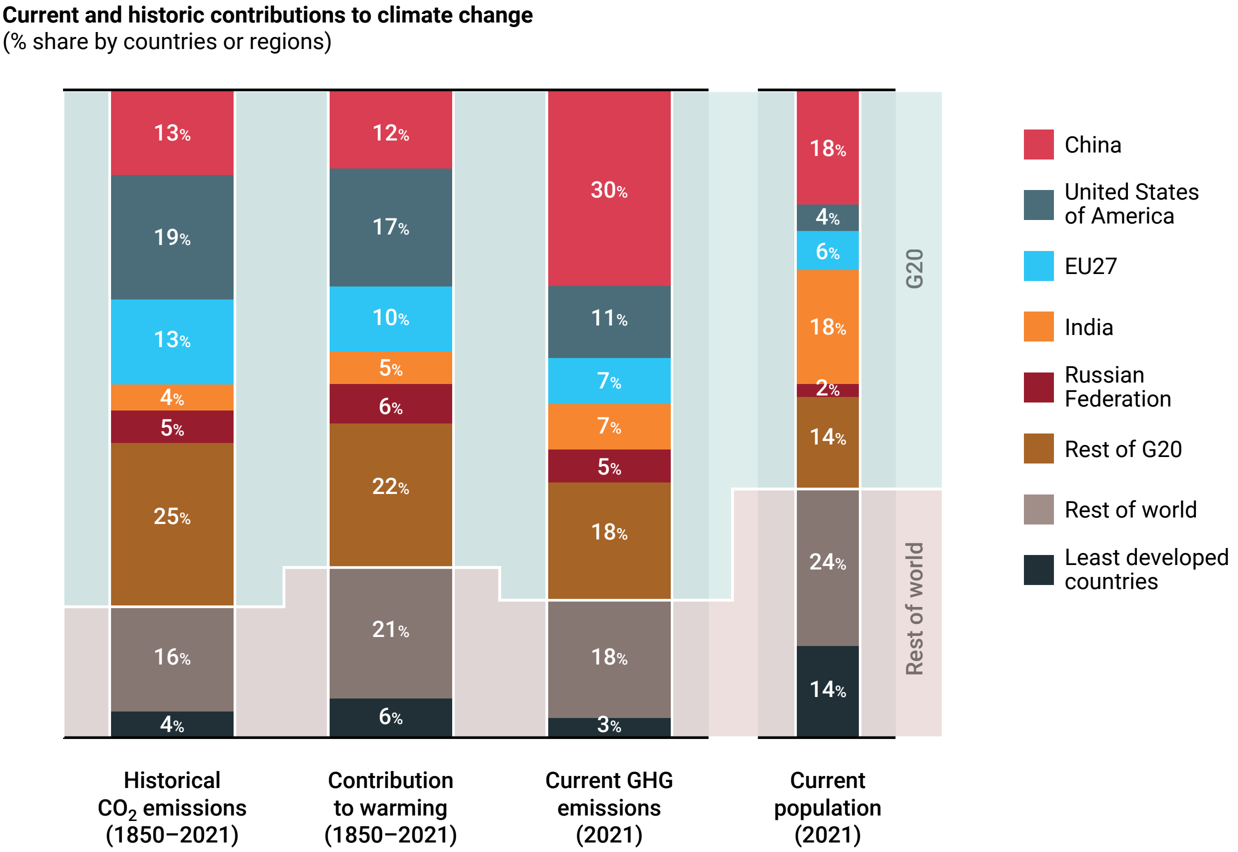
2. Current and historical emissions are highly unequally distributed within and among countries, reflecting global patterns of inequality

- Per capita territorial GHG emissions vary significantly across countries. They are more than double the world average of 6.5 tons of CO_2 equivalent (tCO_2e) in the Russian Federation and the United States of America, while those in India remain under half of it. Per capita emissions are fairly similar in Brazil, the European Union and Indonesia, and at levels slightly below the G20 average. The G20 as a group averaged 7.9 tCO_2e, whereas least developed countries averaged 2.2 tCO_2e and small island developing States averaged 4.2 tCO_2e.

- Inequality in consumption-based emissions is also found among and within countries. Globally, the 10 per cent of the population with the highest income accounted for nearly half (48 per cent) of emissions with two thirds of this group living in developed countries. The bottom 50 per cent of the world population contributed only 12 per cent of total emissions.

- Historic emissions and contribution to global warming similarly vary significantly across countries and groups of countries (figure ES.2). Nearly 80 per cent of historical cumulative fossil and LULUCF CO_2 emissions came from G20 countries, with the largest contributions from China, the United States of America and the European Union, while least developed countries contributed 4 per cent. The United States of America account for 4 per cent of current world population, but contributed 17 per cent of global warming from 1850 to 2021, including the impact of methane and nitrous oxide emissions. India, by contrast, accounts for 18 per cent of the world population, but to date only contributed 5 per cent of warming.

Figure ES.2 Current and historic contributions to climate change



3. There has been negligible movement on NDCs since COP 27, but some progress in NDCs and policies since the Paris Agreement was adopted

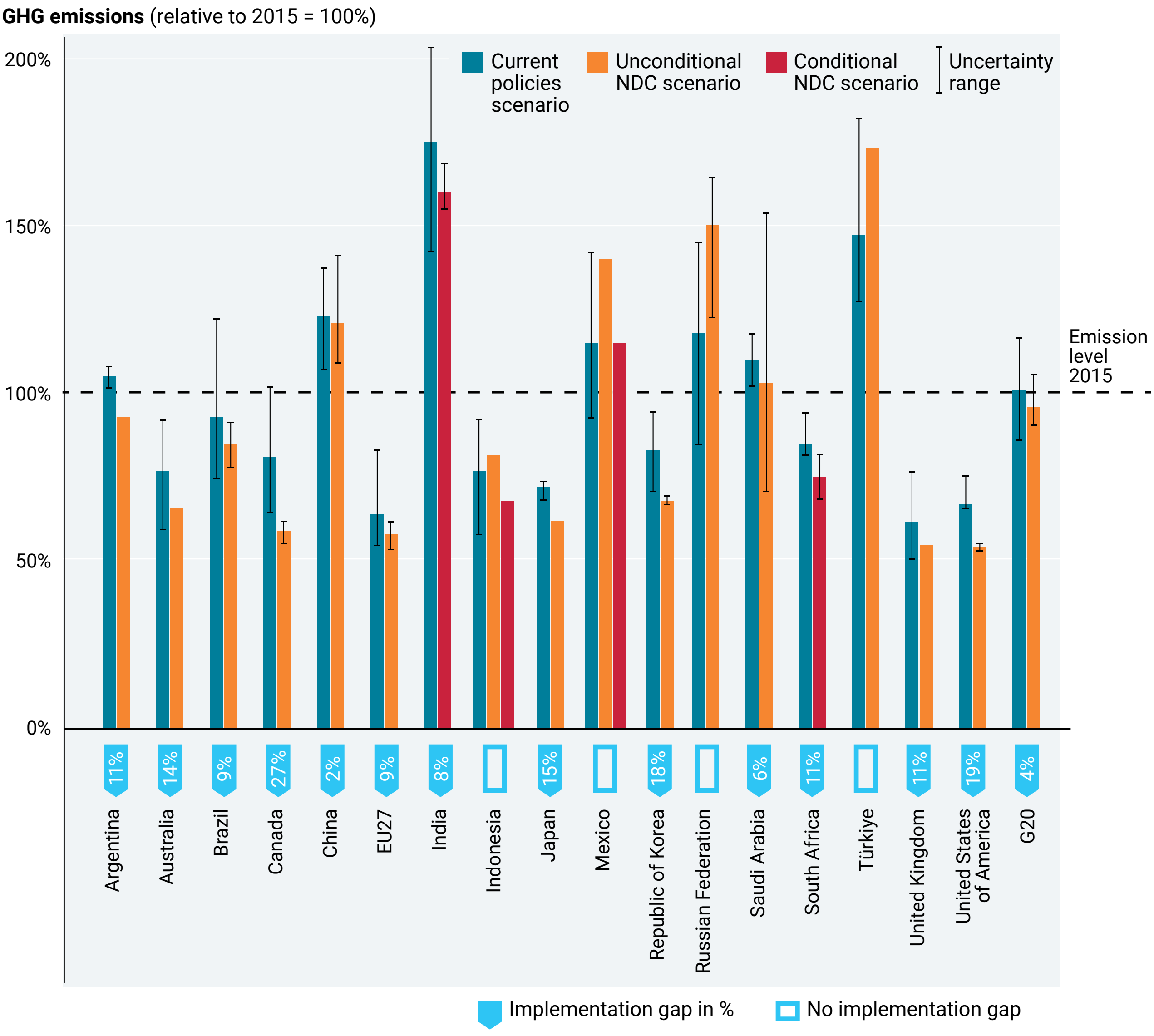
- Nine countries have submitted new or updated NDCs since COP 27, bringing the total number of NDCs that have been updated since the initial NDCs were submitted in advance of or following the Paris Agreement to 149 (counting the European Union and its 27 Member States as a single Party) as at 25 September 2023. More NDCs now contain GHG reduction targets, and more of these targets are economy-wide, covering a country's entire economy as opposed to certain sectors only.

- If all new and updated unconditional NDCs are fully implemented, they are estimated to reduce global GHG emissions by about 5.0 $GtCO_2e$ (range: 1.8–8.2 $GtCO_2e$) annually by 2030, compared with the initial NDCs. The combined effect of the nine NDCs submitted since COP 27 amounts to around 0.1 $GtCO_2e$ of this total. Thus, while NDC progress since COP 27 has been negligible, progress since the adoption of the Paris Agreement at COP 21 is more pronounced, although still insufficient to narrow the emissions gap.

- Progress since the Paris Agreement is clearer on the policy side. Globally, GHG emissions in 2030 based on policies in place were projected to increase by 16 per cent at the time of the adoption of the Paris Agreement. Now the projected increase is 3 per cent.

- Policy progress has contributed to reducing the implementation gap, defined as the difference between projected emissions under current policies and projected emissions under full implementation of the NDCs. The global implementation gap for 2030 is estimated to be around 1.5 $GtCO_2e$ for the unconditional NDCs (down from 3 $GtCO_2e$ in last year's assessment) and 5 $GtCO_2e$ for the conditional NDCs (down from 6 $GtCO_2e$ last year). The implementation gap for the G20 members has also been reduced. As a group, the G20 members are projected to fall short of their new and updated NDCs by 1.2 $GtCO_2e$ annually by 2030, which is 0.6 $GtCO_2e$ lower than last year's assessment (figure ES.3). The impact of newly implemented policies is a main driver of both lower global and G20 emission projections for 2030. Other factors include changes in emission trends and socioeconomic circumstances.

Figure ES.3 Implementation gaps between current policies and NDC pledges for the G20 members collectively and individually by 2030, relative to 2015 emissions



4. The number of net-zero pledges continues to increase, but confidence in their implementation remains low

- As at 25 September 2023, 97 Parties covering approximately 81 per cent of global GHG emissions had adopted net-zero pledges either in law (27 Parties), in a policy document such as an NDC or a long-term strategy (54 Parties), or in an announcement by a high-level government official (16 Parties). This is up from 88 Parties last year. A total of 37 per cent of global GHG emissions are covered by net-zero targets for 2050 or earlier, while 44 per cent of global emissions are covered by net-zero pledges for years later than 2050.
- Responsible for 76 per cent of global emissions, G20 members will dominate when global emissions

reach net zero. Encouragingly, all G20 members except Mexico have set net-zero targets, and over the past year, some members have taken important steps towards strengthening and implementing their targets. Overall, however, limited progress has been made on key indicators of confidence in net-zero implementation among G20 members, including legal status, the existence and quality of implementation plans, and alignment of near-term emissions trajectories with net-zero targets. Most concerningly, none of the G20 members are currently reducing emissions at a pace consistent with meeting their net-zero targets.

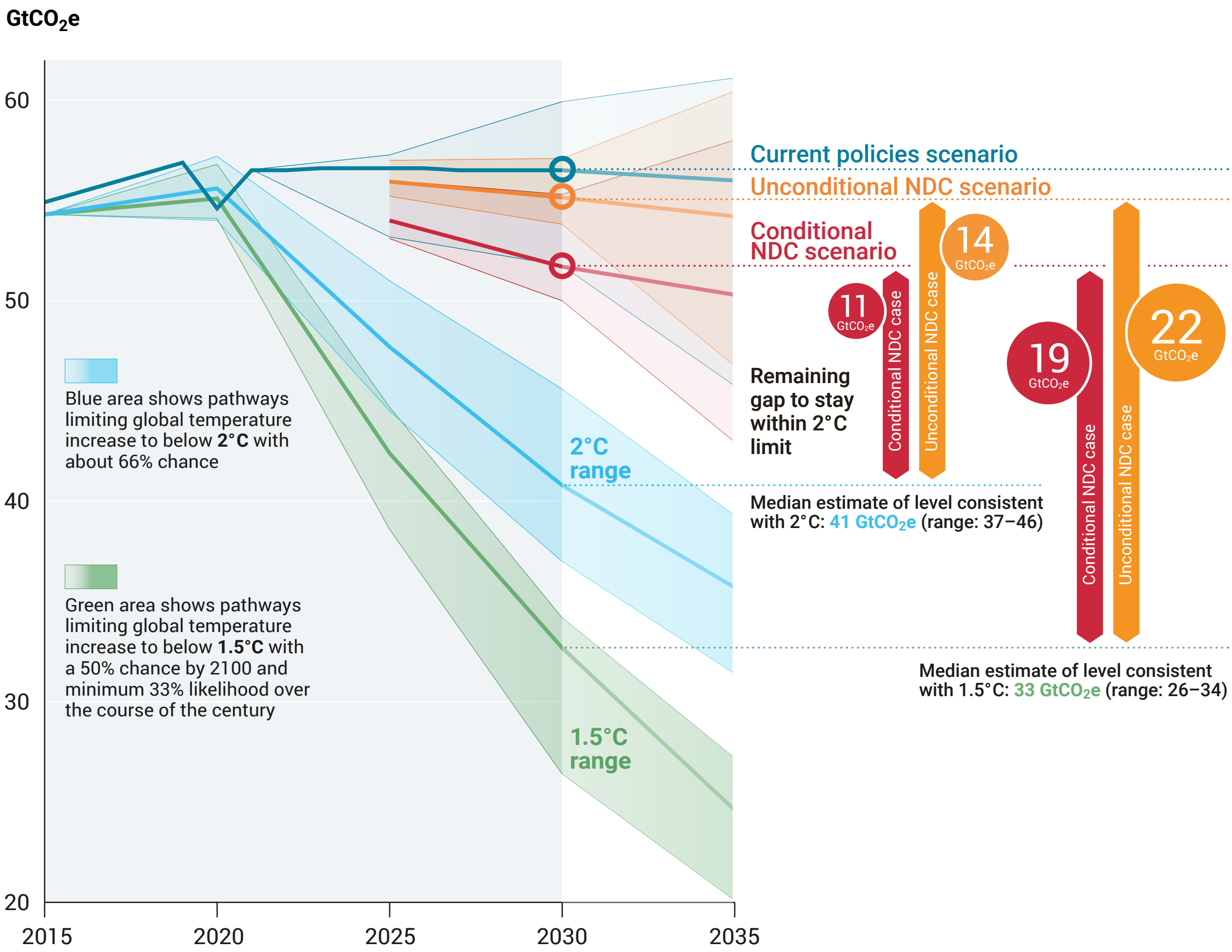
5. The emissions gap in 2030 remains high: current unconditional NDCs imply a 14 $GtCO_2e$ gap for a 2°C goal and a 22 $GtCO_2e$ gap for the 1.5°C goal. The additional implementation of the conditional NDCs reduces these estimates by 3 $GtCO_2e$

- The emissions gap is defined as the difference between the estimated global GHG emissions resulting from full implementation of the latest NDCs and those under least-cost pathways aligned with the long-term temperature goal of the Paris Agreement.
- These least-cost pathways assume stringent emissions reductions starting in 2020, which current trends contradict. Since emissions today are higher than in 2020, this implies that the world has already further depleted the limited remaining carbon budget and committed to slightly higher global warming than indicated by the least-cost pathways, unless there is further acceleration of emissions reductions after emissions levels consistent with the least-cost pathways are met. The emissions gap estimates are thus likely to be lower-bound, as they do not account for the excess emissions since 2020 compared with the least-cost pathways, and should be read with this caveat in mind.
- The emissions gap for 2030 remains largely unchanged compared with last year's assessment. Full implementation of unconditional NDCs is estimated to result in a gap with below 2°C pathways of about 14 $GtCO_2e$ (range: 13–16) with at least 66 per cent chance. If the conditional NDCs are also fully implemented, the below 2°C emissions gap is reduced to 11 $GtCO_2e$ (range: 9–15) (table ES.1 and figure ES.4).

Table ES.1 Global total GHG emissions in 2030, 2035 and 2050, and estimated gaps under different scenarios

Scenario	GHG emissions ($GtCO_2e$)	Estimated gap to least-cost pathways consistent with limiting global warming to specific levels ($GtCO_2e$)		
	Median and range	Below 2°C	Below 1.8°C	Below 1.5°C
2030				
Current policies	56 (52–60)	16 (11–19)	22 (17–25)	24 (19–27)
Unconditional NDCs	55 (54–57)	14 (13–16)	20 (19–22)	22 (21–24)
Conditional NDCs	52 (50–55)	11 (9–15)	17 (15–20)	19 (17–23)
2035				
Current policies continued	56 (45–64)	20 (9–28)	29 (18–37)	31 (20–39)
Unconditional NDCs continued	54 (47–60)	18 (11–25)	27 (20–34)	29 (22–36)
Conditional NDCs continued	51 (43–58)	15 (8–22)	24 (17–31)	26 (19–33)
2050				
Current policies continued	55 (24–72)	35 (4–52)	43 (12–60)	46 (16–63)
Unconditional NDCs and net-zero pledges using strict criteria	44 (26–58)	24 (6–38)	32 (14–46)	36 (18–49)
Conditional NDCs and all net-zero pledges	21 (6–33)	1 (-14–13)	9 (-6–21)	12 (-2–25)

Figure ES.4 Global GHG emissions under different scenarios and the emissions gap in 2030 and 2035 (median estimate and tenth to ninetieth percentile range)



- The emissions gap in 2030 between unconditional NDCs and 1.5°C pathways is about 22 $GtCO_2e$ (range: 21–24) with at least 50 per cent chance. If the conditional NDCs are also fully implemented, the 1.5°C emissions gap is reduced to 19 $GtCO_2e$ (range: 17–23).

- Unconditional and conditional NDCs for 2030 are estimated to reduce global emissions by 2 per cent and 9 per cent respectively, compared with current policy projections and assuming they are fully implemented. To get to levels consistent with least-cost pathways limiting global warming to below 2°C and 1.5°C, global GHG emissions must be reduced by 28 per cent and 42 per cent respectively. This is 2 percentage points lower than last year's assessment, illustrating the progress in narrowing the implementation gap between current policies and NDCs.

- Nonetheless, immediate, accelerated and relentless mitigation action is needed to bring about the deep annual emission cuts that are required from now to 2030 to narrow the emissions gap, with unparalleled annual cuts required to bridge the gap, even without accounting for excess emissions since 2020.

6. Action in this decade will determine the ambition required in the next round of NDCs for 2035, and the feasibility of achieving the long-term temperature goal of the Paris Agreement

- The first global stocktake under the Paris Agreement is envisaged to inform the next round of NDCs that countries are requested to submit in 2025, which will include targets for 2035. Overall, global ambition in the next round of NDCs must be sufficient to bring global GHG emissions in 2035 to the levels consistent with below 2°C and 1.5°C pathways of 36 $GtCO_2e$ (range: 31–39) and 25 $GtCO_2e$ (range: 20–27) respectively (table ES.2), while also compensating for excess emissions until levels consistent with these pathways are achieved.

- In contrast, a continuation of current policies and NDC scenarios would result in widened and likely unbridgeable gaps in 2035 (table ES.1). A continuation of current policies is projected to result in global GHG emissions of 56 $GtCO_2e$ in 2035 (table ES.1), which is 36 per cent and 55 per cent higher than the levels consistent with below 2°C and 1.5°C pathways respectively (table ES.2), without compensating for excess emissions.

- Again, these findings underline that immediate and unprecedented mitigation action in this decade is essential. Over-complying with current NDC targets for 2030 will enable countries to put forward more ambitious mitigation targets for 2035 in their next NDCs, and it will make the realization of such ambitious targets for 2035 more feasible.

- Looking beyond 2035 at mid-century scenarios (table ES.1) reinforces these findings and points to the necessity of enhancing the credibility and feasibility of net-zero pledges. Total global GHG emissions in 2050 are only brought closer to 1.5°C and 2°C pathways if the conditional NDCs are fully implemented in combination with the achievement of all net-zero pledges.

Table ES.2 Global GHG emissions in 2030, 2035 and 2050, and global warming characteristics of least-cost pathways starting in 2020 consistent with limiting global warming to specific temperature limits

Least-cost pathways consistent with limiting global warming to specific levels	Number of scenarios	Global total GHG emissions ($GtCO_2e$)			Estimated temperature outcomes			
		In 2030	In 2035	In 2050	50% chance	66% chance	90% chance	Closest IPCC Working Group III *Sixth Assessment Report* scenario class
Below 2°C (66% chance throughout the century)	195	41 (37–46)	36 (31–39)	20 (16–24)	Peak: 1.7–1.8°C In 2100: 1.4–1.7°C	**Peak: 1.8–1.9°C In 2100: 1.6–1.9°C**	Peak: 2.2–2.4°C In 2100: 2–2.4°C	C3a
Below 1.8°C (66% chance throughout the century)	139	35 (28–41)	27 (21–31)	12 (8–16)	Peak: 1.5–1.7°C In 2100: 1.3–1.6°C	**Peak: 1.6–1.8°C In 2100: 1.4–1.7°C**	Peak: 1.9°C–2.2°C In 2100: 1.8–2.2°C	N/A
Below 1.5°C (50% chance in 2100 and minimum 33% chance throughout the century)	50	33 (26–34)	25 (20–27)	8 (5–13)	Peak: 1.5–1.6°C In 2100: 1.1–1-3°C	**Peak: 1.6–1.7°C In 2100: 1.2–1.5°C**	Peak: 1.9–2.1°C In 2100: 1.6–1.9°C	C1a

7. If current policies are continued, global warming is estimated to be limited to 3°C. Delivering on all unconditional and conditional pledges by 2030 lowers this estimate to 2.5°C, with the additional fulfilment of all net-zero pledges bringing it to 2°C

- A continuation of the level of climate change mitigation efforts implied by current policies is estimated to limit global warming to 3°C (range: 1.9–3.8°C) throughout the century with a 66 per cent chance. Warming is expected to increase further after 2100 as CO_2 emissions are not yet projected to reach net-zero levels.

- A continuation of the unconditional NDC scenario lowers this estimate to 2.9°C (range: 2–3.7°C), whereas the additional achievement and continuation of conditional NDCs lowers this by around 0.4°C to 2.5°C (range: 1.9–3.6°C).

- In the most optimistic scenario where all conditional NDCs and net-zero pledges, including those made as part of long-term low-emissions development strategies, are assumed to be fully achieved, global warming is projected to be limited to 2°C (range: 1.8–2.5°C) with 66 per cent chance over the course of the century. However, as noted previously, net-zero pledges remain highly uncertain.

- Even in the most optimistic scenario considered in this report, the chance of limiting global warming to 1.5°C is only 14 per cent, and the various scenarios leave open a large possibility that global warming exceeds 2°C or even 3°C. This further illustrates the need to bring global emissions in 2030 lower than levels associated with full implementation of the current

NDCs, to expand the coverage of net-zero pledges to all GHG emissions and to achieve these pledges.

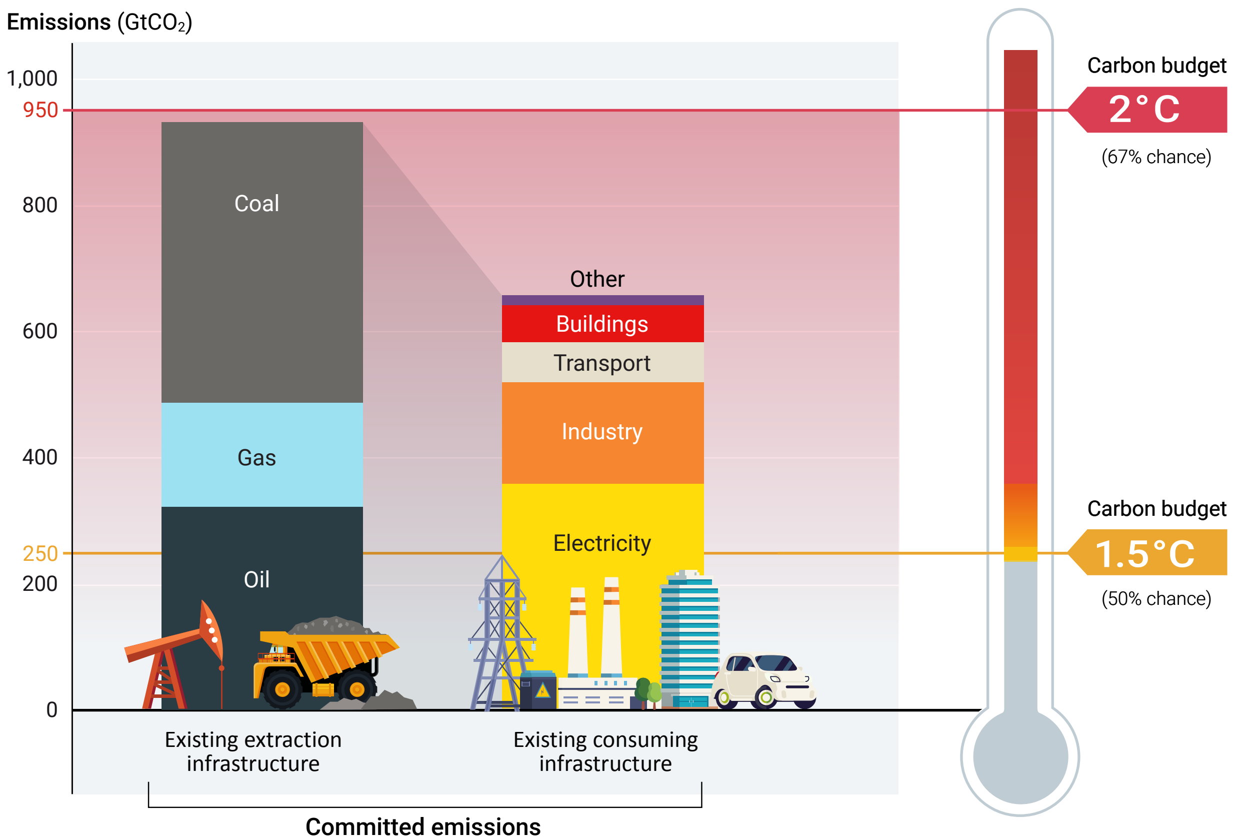
- Central temperature projections are slightly higher than in the 2022 edition of the Emissions Gap Report, as a larger number of models have been included in the estimation of future emissions. However, the projections are consistent with those from other major assessments, such as the International Energy Agency's 2023 Announced Pledges Scenario, the Climate Action Tracker and the United Nations Framework Convention on Climate Change 2023 NDC Synthesis Report, noting that these report temperature projections with a 50 per cent rather than a 66 per cent chance.

8. The failure to stringently reduce emissions in high-income countries and to prevent further emissions growth in low- and middle-income countries implies that all countries must urgently accelerate economy-wide, low-carbon transformations to achieve the long-term temperature goal of the Paris Agreement

- Delivering transformational change requires unprecedented global cooperation reflecting the Paris Agreement principle of common but differentiated responsibilities and respective capabilities in light of national circumstances. This principle implies that countries with greater capacity and greater historic responsibility for emissions – particularly high-income and high-emitting countries among the G20 – will need to take more ambitious and rapid action, setting the course and demonstrating the viability of fossil-free development. However, this will not be sufficient as low- and middle-income countries already account for more than two thirds of global GHG emissions. Accordingly, the Climate Solidarity Pact proposed by the United Nations Secretary-General calls on all big emitters to make extra efforts to cut emissions and wealthier countries to provide financial and technical resources to support low- and middle-income countries in their transformation, reflecting differentiated timelines.

- Energy is the dominant source of GHG emissions, currently accounting for 86 per cent of global CO_2 emissions. The coal, oil and gas extracted over the lifetime of producing and under-construction mines and fields as at 2018 would emit more than 3.5 times the carbon budget available to limit warming to 1.5°C with 50 per cent probability, and almost the size of the budget available for 2°C with 67 per cent probability. Global transformation of energy systems is thus essential, including in low- and middle-income countries, where pressing development objectives must be met alongside a transition away from fossil fuels.

Figure ES.5 Committed CO_2 emissions from existing fossil fuel infrastructure, compared with carbon budgets reflecting the long-term temperature goal of the Paris Agreement



9. Low- and middle-income countries face substantial economic and institutional challenges in low-carbon energy transitions, but can also exploit opportunities

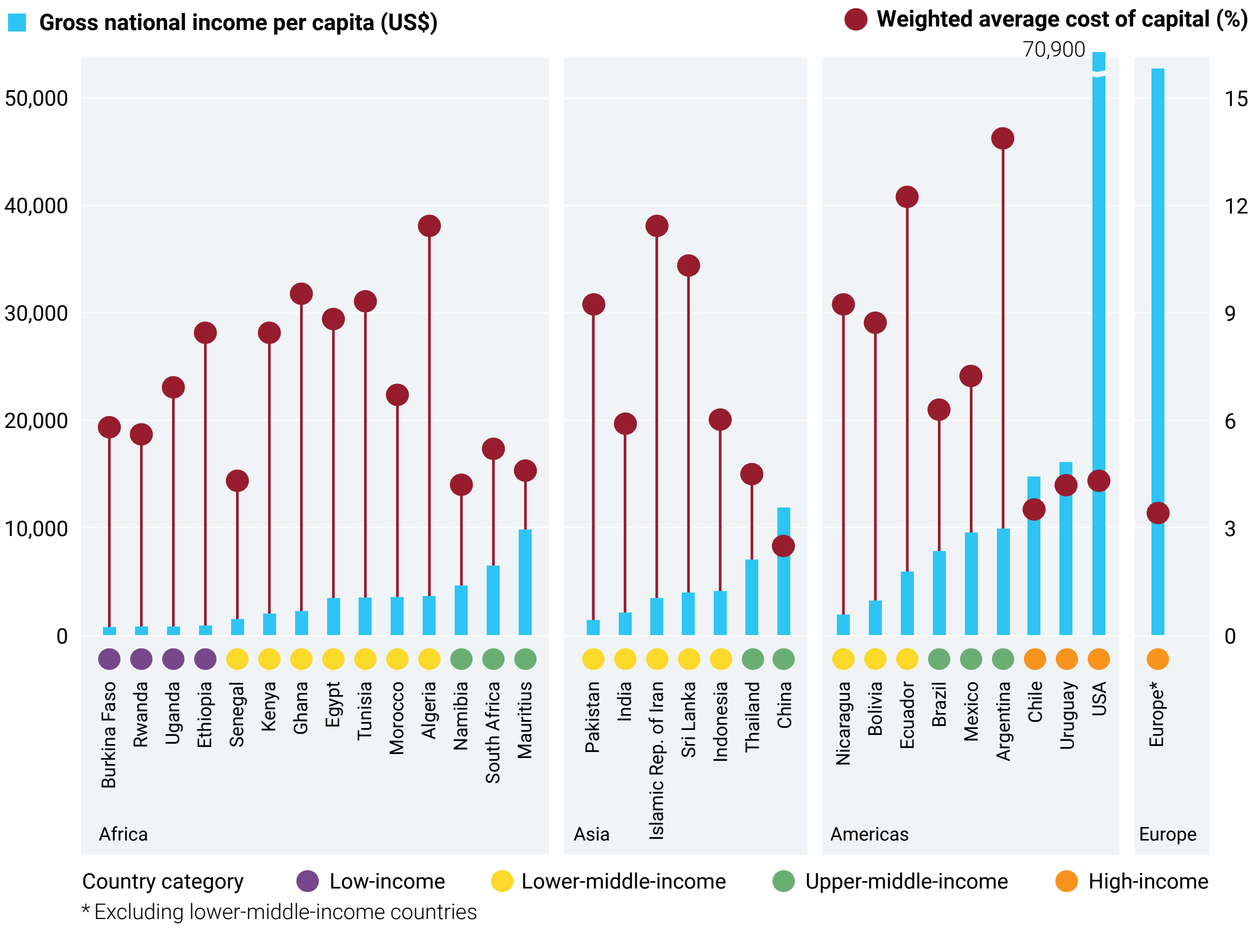
- Energy transitions in low- and middle-income countries are shaped by the overarching objective of pursuing development. Low- and middle-income countries face several common challenges in having to bring millions out of poverty, expand strategic industries, urbanize and deal with the political challenges of a transition away from fossil fuel use. Meeting basic energy needs of people living in poverty would have a limited impact on global GHG emissions. Yet today, 2.4 billion people lack access to clean cooking and 775 million to electricity, with women and children disproportionately affected. Meeting energy needs for broader human development will lead to significant energy demand growth, but there is scope to meet this growth more efficiently and equitably, and with low-carbon energy as renewables get cheaper.

- National circumstances vary with natural resource endowments and economic conditions, and will shape energy transition pathways. Capacity and institutions are often weak in low- and middle-income countries, and they may face different and additional political economic challenges from high-income countries, especially in view of the required speed of transition.

- Low- and lower-middle-income countries are in the greatest need of affordable finance as they are already saddled with debt, receive disproportionately low clean energy investments, are more vulnerable to volatile fossil fuel markets either as exporters or importers, and may face future stranded fossil fuel assets. Upper-middle-income countries are typically further along in building clean energy economies, but still face risks of stranded assets and related employment implications and macroeconomic shocks.

- Access to affordable finance is therefore a prerequisite for increasing mitigation ambition in low- and middle-income countries. Yet, costs of capital are up to seven times higher in these countries compared with the United States of America and Europe (figure ES.6). International financial assistance will therefore have to be significantly scaled up from existing levels, and new public and private sources of capital better distributed towards low-income countries, restructured through financing mechanisms that lower costs of capital. These include debt financing, increasing long-term concessional finance, guarantees and catalytic finance.

Figure ES.6 Weighted average cost of capital for solar photovoltaic projects against per capita gross national income for select countries in 2021



- Low- and middle-income countries can take ownership of their low-carbon development agenda by laying out national low-carbon development strategies suited to their national context, including by adopting measures in key energy-intensive demand sectors, such as housing, transport and food, which have known synergies between climate mitigation and human development. This will require strengthening domestic energy and climate institutions to undertake strategic planning and enhanced coordination across sectors. Furthermore, strong stakeholder engagement is needed to ensure just outcomes and economic diversification.

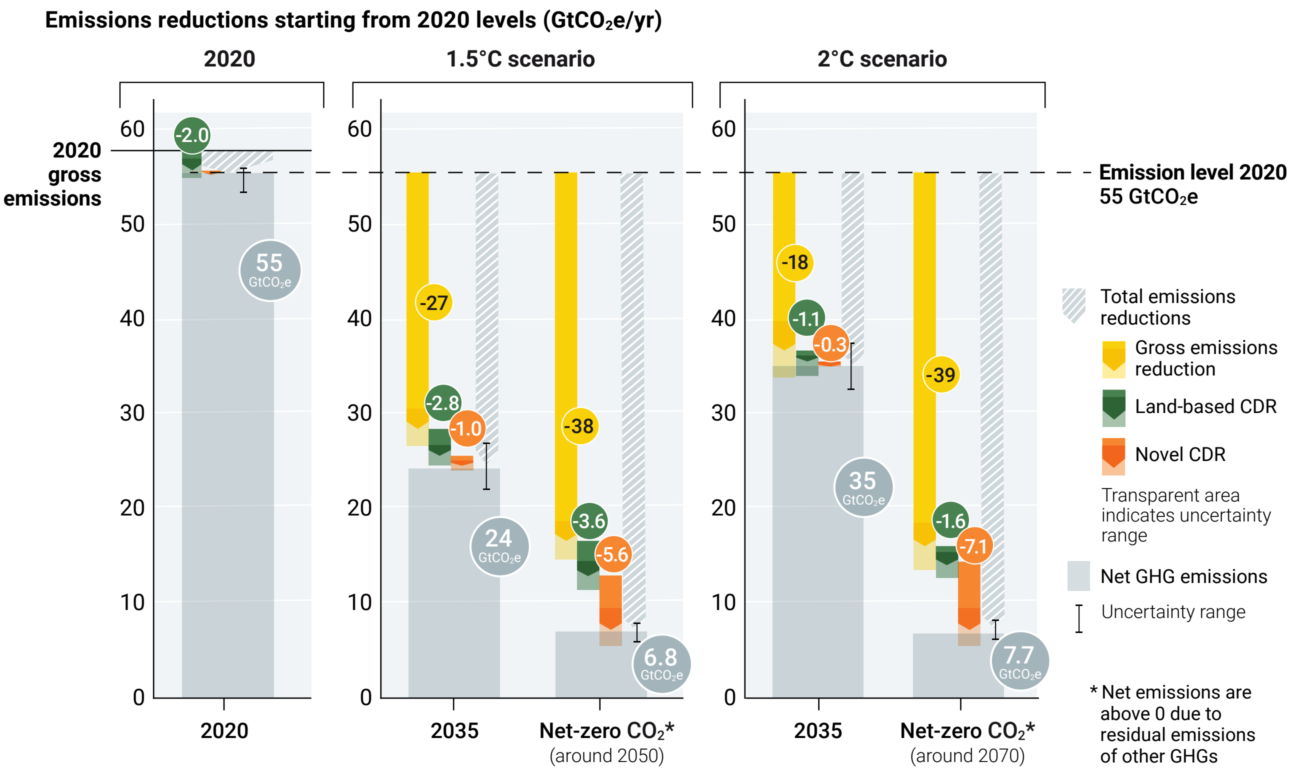
- The preparation of the next round of NDCs offers an opportunity for low- and middle-income countries to develop nationally driven road maps with broad domestic visions for ambitious development and climate policies and targets, for which implementation progress can be measured, finance and technology needs are clearly specified, and detailed investment-ready implementation plans are prepared. With less than two years left until the next round of NDCs are due, COP 28 would be a timely occasion to call for international support to prepare such robust and ambitious NDCs that integrate development and climate objectives.

10. Further delay of stringent global GHG emissions reductions will increase future reliance on CDR to meet the long-term temperature goal of the Paris Agreement

- Immediate and stringent emissions reductions are required to bridge the emissions gap and maintain the feasibility of achieving the long-term temperature goal of the Paris Agreement. All least-cost pathways starting in 2020 consistent with meeting this goal require immediate and deep emission cuts as well as a growing quantum of CDR over time (figure ES.7). With the delay in stringent mitigation action, the need for CDR in the longer term will likely increase even further.

- CDR is necessary to achieve the long-term goal of the Paris Agreement as reaching net-zero CO_2 emissions is required to stabilize global warming, whereas net-zero GHG emissions will result in a peak and decline in global warming. Since it is impossible to fully eliminate all CO_2 or other GHG emissions through stringent emissions reductions, residual emissions must be balanced by removals from the atmosphere, i.e. through CDR, to reach net-zero emissions.

Figure ES.7 The role of emissions reductions and CDR in least-cost pathways consistent with the long-term temperature goal of the Paris Agreement



- CDR is already deployed today – mainly in the form of conventional land-based methods, such as afforestation, reforestation and management of existing forests, with a large share located in developing countries. Present-day direct removals through conventional land-based methods are estimated to be 2.0 (±0.9) $GtCO_2$ annually, almost entirely through conventional land-based methods. Direct removals through novel CDR methods, such as bioenergy with carbon capture and storage, biochar, direct air carbon capture and storage, and enhanced weathering, are currently miniscule at 0.002 $GtCO_2$ annually.

- Nonetheless, 1.5°C and 2°C least-cost pathways assume significant increases in both conventional and novel CDR over time (figure ES.7). Conventional CDR grows to up to 6 $GtCO_2$ annually by 2050 under these pathways and novel CDR up to 4 $GtCO_2$ annually by 2050. Conventional land-based CDR plays a stronger role in the near- and mid-term, while novel CDR plays a stronger role later in the century to reach net-negative emissions, noting that levels depend on the underlying economic and technological assumptions as well as the magnitude of temperature drawdown after achieving net-zero CO_2 emissions.

- Achievement of the gigaton levels of CDR implied later in this century by pathways consistent with the Paris Agreement is uncertain and associated with several risks. Increased reliance on conventional land-based CDR is risky due to issues of land competition, protection of Indigenous and traditional communities' land tenure and rights, and sustainability, biodiversity and permanence risks of forest-based CDR, including from forest fires and other disturbances. Novel CDR methods are generally at an early stage of development and are associated with different types of risks, including that the technical, economic and political requirements for large-scale deployment may not materialize in time. Furthermore, public acceptance is still uncertain, particularly for approaches involving carbon capture and storage, or the open ocean. These risks can negatively affect the prospects for scale-up, despite technical potentials.

- To spur innovation and enable scaling up of novel CDR technologies, these technologies will first need to go through a formative phase, which will require strong policy and financial support. Given the time it takes to mature technologies, the next decade will be crucial for novel CDR methods. Failure to create momentum in this formative phase will result in a widening discrepancy between the levels of novel CDR needed and available by 2050 and beyond.

- This points to four important areas for political action:

  1) Setting and signalling CDR priorities
  2) Developing robust measurement, reporting and verification systems to enhance credibility
  3) Harnessing synergies and co-benefits with other efforts
  4) Accelerating innovation.

1 Introduction

Authors:

Anne Olhoff (CONCITO – Denmark's green think tank, Denmark) and John Christensen ((UNEP Copenhagen Climate Centre [UNEP-CCC], Denmark)

1.1 Context and framing of the Emissions Gap Report 2023

The world is witnessing a disturbing acceleration in the number, speed and scale of broken climate records: 2023 is on track to become the warmest year on record. At the time of writing, 86 days have been recorded with temperatures exceeding 1.5°C above pre-industrial levels. Not only was September the hottest month ever, it exceeded the previous record by an unprecedented 0.5°C, with global average temperatures at 1.8°C above pre-industrial levels (Copernicus Climate Change Services 2023a; Copernicus Climate Change Services 2023b). This does not imply that the world has exceeded the 1.5°C temperature limit specified in the Paris Agreement, which refers to global warming levels based on multi-decadal averages. However, it does signal that we are getting closer to that point. These temperature records were accompanied by devastating extreme events, which the Intergovernmental Panel on Climate Change (IPCC) has warned us are merely a meek beginning. Every increment of warming results in rapidly escalating hazards with extensive implications for human livelihoods and ecosystems (IPCC 2023).

This is the fourteenth Emissions Gap Report by UNEP, published ahead of the twenty-eighth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 28). COP 28 is special, as it marks the conclusion of the first global stocktake under the Paris Agreement. The global stocktakes are held every five years to assess the global response to the climate crisis and chart a better way forward. This objective closely mirrors that of the Emissions Gap Report, which is to provide an annual, independent science-based assessment of the gap between pledged greenhouse gas (GHG) emissions reductions and the reductions required to align with the long-term temperature goal of the Paris Agreement, and opportunities to bridge this gap.

To inform the discussions at COP 28 – including on the outcomes needed from the global stocktake – and set the scene for the next round of nationally determined contributions (NDCs) that countries are requested to submit in 2025, which will include emissions reduction targets for 2035, this report looks at what is required this decade and beyond 2030 to maintain the possibility of achieving the long-term temperature goal of the Paris Agreement.

The IPCC concluded that global emissions levels by 2030 resulting from the implementation of the current NDCs will make it impossible to limit warming to 1.5°C with no or limited overshoot, and strongly increase the challenge of limiting warming to 2°C (Pathak *et al.* 2022). This finding is reiterated in this report. It highlights that maintaining the possibility of achieving the long-term goal of the Paris Agreement hinges on relentlessly strengthening ambition and implementation this decade, thereby facilitating significantly more ambitious targets for 2035 in the next round of NDCs and paving the way for operationalizing and implementing the net-zero pledges by countries that currently cover around 80 per cent of global emissions.

The report shows that movement on the NDCs has been negligible since COP 27, and although the ambition of the NDCs has been strengthened since the adoption of the Paris Agreement at COP 21 in 2015, it has been insufficient to narrow the 2030 emissions gap.

Progress since the adoption of the Paris Agreement is more visible on the policy implementation side. Globally, GHG emissions in 2030 based on policies in place were projected to increase by 16 per cent at the time of the adoption of the Paris Agreement. Now the projected increase is 3 per cent.

However, the challenge remains immense. In just seven years, global GHG emissions must be reduced by 28–42 per cent compared to where they are headed under policies currently in place, to get to levels consistent with pathways that limit global warming to well below 2.0°C and 1.5°C respectively.

Due to the failure to stringently reduce emissions in high-income countries – which bear the greatest responsibility for past emissions – and to limit emissions growth in low- and middle-income countries, which account for the majority of current emissions, unprecedented action is now needed by all countries. For high-income countries, this implies further accelerating domestic emissions reductions, committing to reaching net-zero as soon as possible – and sooner than the global averages from the latest IPCC report implies – and at the same time providing financial and technical support to low- and middle-income countries. For low- and middle-income countries, this means that pressing development needs must be met alongside a transition away from fossil fuels.

Furthermore, the delay in stringent mitigation action will likely increase future dependence on carbon dioxide removal (CDR) from the atmosphere. However, availability of large-scale CDR opportunities in the future cannot be taken for granted. The second part of the report explores the opportunities and challenges associated with energy transformation, and development and deployment of CDR.

The feasibility of the necessary transformation hinges on reconciling development and climate objectives in all countries. As has been amply illustrated during the COVID-19 pandemic and the energy crisis, development choices and responses to economic shocks are inseparable from – and often determine – climate outcomes. Previous editions of the Emissions Gap Report have illustrated that well planned and socially just transformations can bring economic benefits, create new jobs, advance gender equality, and empower people, communities and societies. All available evidence confirms the availability of a wide range of mature, efficient and economically attractive options to reduce GHG emissions. They just need to be deployed, immediately and at unprecedented rates (Pathak *et al.* 2022; International Energy Agency 2023; Lee *et al.* 2023).

Doing so could simultaneously help reverse the concerning general international setback on the achievement of the global Sustainable Development Goals for 2030. A preliminary assessment shows that of the around 140 targets for which data is available, only 12 per cent are on track, whereas more than half are moderately or severely off track, and around 30 per cent have either seen no movement or have regressed below the 2015 baseline (United Nations 2023).

1.2 Approach and structure of the report

The Emissions Gap Report is an assessment report. It provides an evaluation of scientifically and technically credible knowledge on emissions trends, progress, gaps and opportunities, based on a synthesis of the latest scientific literature, models, and data analysis and interpretation, including that published by the IPCC.

As in previous years, this Emissions Gap Report has been prepared by an international team of leading experts. This year, 79 leading scientists from 47 expert institutions across 22 countries have been engaged in producing the report. The assessment process has been overseen by an international steering committee and has been transparent and participatory. Geographical diversity and gender balance has been considered to the extent possible. All chapters have undergone external review, and the assessment methodology and preliminary findings were made available to the Governments of the countries specifically mentioned in the report, to provide them with the opportunity to comment on the findings.

The report is organized into seven chapters, including this introduction. Chapter 2 assesses the trends in global GHG emissions. Chapter 3 provides a global update of NDCs and long-term net-zero emissions pledges, and assesses the progress of G20 members towards achieving their NDCs and net-zero emissions pledges. Chapter 4 updates the assessment of the emissions gap by 2030 based on the latest NDCs, and looks at potential gaps beyond 2030. It also considers the implications of the emissions gap on the feasibility of achieving the long-term temperature goal of the Paris Agreement. Chapter 5 frames the second part of the report, laying out global issues related to energy transformation and CDR. Chapter 6 assesses challenges and opportunities for accelerating energy transitions in low- and middle-income countries, while meeting critical development needs and priorities. Finally, chapter 7 considers the role, status and scope for CDR in achieving the long-term temperature goal of the Paris Agreement.

2 Global emissions trends

Lead authors:

William F. Lamb (Mercator Research Institute on Global Commons and Climate Change, Germany; University of Leeds, United Kingdom of Great Britain and Northern Ireland) and Minal Pathak (Ahmedabad University, India)

Contributing authors:

Lucas Chancel (World Inequality Lab, Paris School of Economics, France), Monica Crippa (European Commission, Joint Research Centre [JRC], Italy), Giacomo Grassi (European Commission, JRC, Italy), Diego Guizzardi (European Commission, JRC, Italy), Jing Meng (University College London, United Kingdom), Glen P. Peters (CICERO Center for International Climate Research, Norway) and Julia Pongratz (Ludwig-Maximilians University Munich, Germany)

2.1 Introduction

This chapter assesses greenhouse gas (GHG) emissions trends up to and including 2022. Starting from global emissions trends by GHG and sector (section 2.2), it describes the emissions of the G20 and top emitters (section 2.3) before covering household and consumption-based emissions (sections 2.4 and 2.5). In doing so, it sets the stage for subsequent chapters on G20 policies and the emissions gap.[1] Importantly, this chapter provides multiple perspectives on national emissions, including absolute, per capita and historical cumulative emissions. Each of these perspectives offer insight into inequalities in contributions to climate change, while highlighting that turning around global emissions growth now requires ambitious and urgent efforts from all countries to reduce fossil fuel use and deforestation.

As in previous years, the Emissions Gap Report focuses on total net GHG emissions across all major groups of anthropogenic sources and sinks reported under the United Nations Framework Convention on Climate Change (UNFCCC). This includes carbon dioxide (CO_2) emissions from fossil fuel and industry (fossil CO_2), CO_2 emissions and removals from land use, land-use change and forestry (LULUCF CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions. It includes fluorinated gas (F-gas) emissions reported under the UNFCCC, but excludes F-gas emissions regulated under the Montreal Protocol on ozone depleting substances, which accounted for approximately 1.6 gigatons of CO_2 equivalent ($GtCO_2e$) in 2021 (Forster *et al.* 2023). Non-CO_2 LULUCF emissions are also excluded due to data limitations.

Following the change in methodology outlined in the Emissions Gap Report 2022 (United Nations Environment Programme [UNEP] 2022), the global bookkeeping approach is used to report global estimates of net LULUCF CO_2 emissions and the national inventory approach to report national estimates of net LULUCF CO_2 emissions. This ensures that global estimates are consistent with the mitigation scenarios presented in chapter 4, as well as the carbon cycle and climate science literature; while national estimates are consistent with those reported by countries to the UNFCCC. As this chapter reports, total net LULUCF CO_2 emissions differ substantially between these two approaches, due to known differences in system boundaries and other assumptions.

Where GHG emissions are aggregated to CO_2 equivalents in this report, 100-year global warming potentials from the latest Intergovernmental Panel on Climate Change (IPCC) Working Group (WG) I *Sixth Assessment Report* (AR6) (Forster *et al.* 2021) are used. Alternative metrics can be used – for instance, global warming potentials with a 20-year time horizon would highlight the relative importance of CH_4 on near-term warming – but are not explored here. Uncertainties in emissions estimates are reported following the IPCC WGIII AR6 of ±8 per cent for fossil CO_2, ±70 per cent for LULUCF CO_2, ±30 per cent for CH_4 and F-gases, and

1 The African Union became a permanent member of the G20 in September 2023, which was after the assessments for this report had been completed. Consequently, the African Union is not included in the G20 assessment this year.

±60 per cent for N_2O (Dhakal *et al.* 2022). This chapter follows a territorial-based accounting of emissions (i.e. emissions are allocated to the sectors and nations where they occur) unless otherwise noted. Indirect and consumption-based perspectives are considered in section 2.5, in particular in the context of household emissions.

The principal sources in this chapter include the Emissions Database for Global Atmospheric Research dataset for fossil CO_2, CH_4, N_2O and F-gas emissions (Crippa *et al.* 2023); the Global Carbon Budget for global LULUCF CO_2 estimates, taking the average of three bookkeeping models (Friedlingstein *et al.* 2022); and Grassi *et al.* (2022; 2023) for national inventory-based LULUCF CO_2 (with updates to the latest inventories for the top emitters). The latest years of data in these sources should be treated as preliminary – particularly in the case of LULUCF CO_2 and non-CO_2 GHG emissions – due to the use of provisional methodologies based on available activity data. Emissions are generally reported up to 2022. However, due to data limitations, this is not possible for inventory-based LULUCF CO_2. Complete national totals including LULUCF CO_2 are therefore only given up to 2021. Lamb (2023) contains the code and data used to produce all emissions estimates in this chapter.

2.2 Global emissions trends

2.2.1 Global emissions increased to record levels in 2022

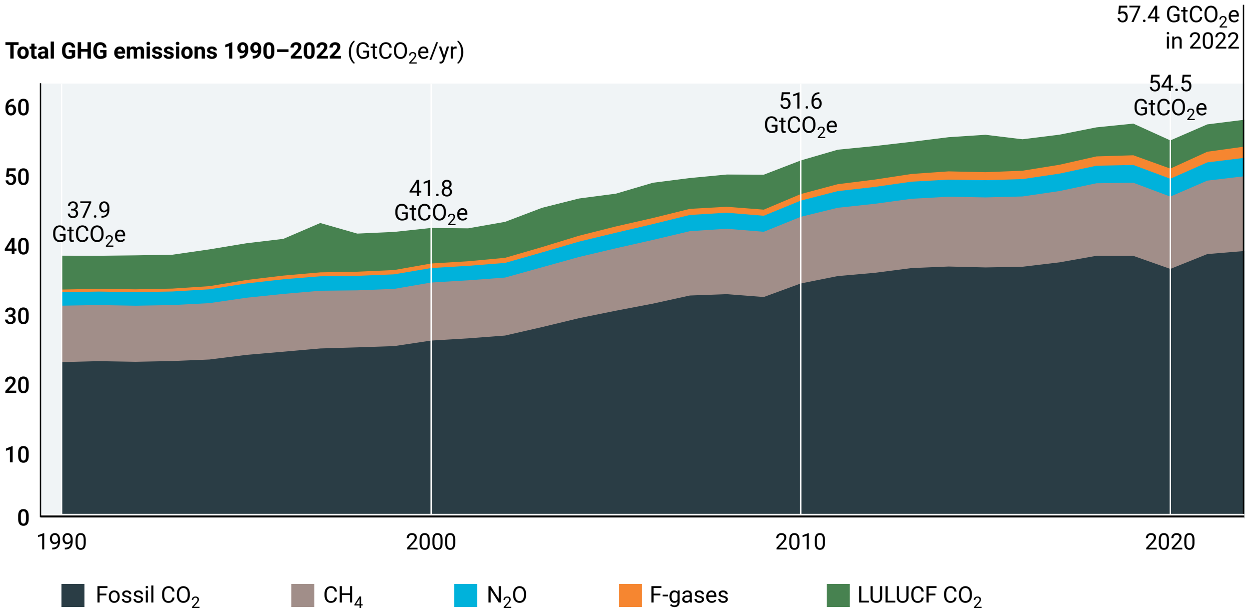
Global GHG emissions reached a record high of 57.4 $GtCO_2e$ in 2022, growing by 1.2 per cent (0.6 $GtCO_2e$) from the previous year (figure 2.1 and table 2.1). This rate is slightly above the average rate in the decade preceding the COVID-19 pandemic (2010–2019), when GHG emissions growth averaged 0.9 per cent per year, but was slower than the emissions growth of the 1990s (1.2 per cent per year) and 2000s (2.2 per cent per year). Atmospheric CO_2 concentrations grew to 417.9 ± 0.2 parts per million in 2022 (World Meteorological Organization 2023), and will continue to grow until annual emissions are reduced sufficiently to be balanced by removals. In contrast, as shown in chapter 4 of this report, global GHG emissions must decline to levels between 33 and 41 $GtCO_2e$ by 2030 (chapter 4 and table 4.2) to get on a least-cost pathway to meeting the temperature goal of the Paris Agreement.

Fossil CO_2 emissions account for approximately two thirds of current GHG emissions using 100-year global warming potentials. According to multiple datasets, fossil CO_2 emissions grew between 0.8–1.5 per cent in 2022 and were the main contributor to the overall increase in GHG emissions (Friedlingstein *et al.* 2022; Energy Institute 2023; International Energy Agency 2023; Liu *et al.* 2023). CH_4, N_2O and F-gas emissions account for about one quarter of current GHG emissions. Although their absolute contribution to the overall increase in 2022 was lower since they represent a much smaller share of the total, emissions of these gases are increasing rapidly: in 2022, F-gas emissions grew by 5.5 per cent, followed by CH_4 at 1.8 per cent and N_2O at 0.9 per cent.

Global net LULUCF CO_2 emissions – using the global bookkeeping approach – remained steady in 2022, but are based on an early projection of land-use activity with relatively high uncertainties (Friedlingstein *et al.* 2022). Updated estimates indicate that net LULUCF CO_2 emissions slowly declined in the past two decades, with average emissions of 4.5 gigatons of CO_2 ($GtCO_2$) per year during 2012–2021, compared with 4.9 $GtCO_2$ per year during 2002–2011. The primary driver behind the decline is an increase in removals on forest land (from 3.0 to 3.5 $GtCO_2$ per year), including afforestation/reforestation, while emissions from deforestation remained high (6.8 and 6.7 $GtCO_2$ per year for 2002–2011 and 2012–2021, respectively). LULUCF CO_2 emissions and removals continue to have the largest uncertainties of all gases considered here, both in terms of their absolute amounts and trends.

Global bookkeeping and national inventory-based accounts of LULUCF CO_2 emissions diverged by approximately 6.4 $GtCO_2$ in 2021 (table 2.1). This is due to known differences in system boundaries between each approach, in particular the fact that bookkeeping models consider only "direct" human-induced fluxes as anthropogenic (e.g. deforestation, afforestation and other land use-related vegetation changes), whereas national inventories typically also include most of the "indirect" human-induced fluxes (e.g. enhanced vegetation growth due to increased atmospheric CO_2) that occur on managed land (Grassi *et al.* 2021; UNEP 2022, p. 4).

Figure 2.1 Total net anthropogenic GHG emissions, 1990–2022



Sources: Crippa *et al.* (2023) for GHG emissions; Friedlingstein *et al.* (2022) for bookkeeping LULUCF CO_2; Grassi *et al.* (2023) for inventory-based LULUCF CO_2.

Note: GHG emissions include fossil CO_2, LULUCF CO_2, CH_4, N_2O and F-gas emissions. Bookkeeping-based net LULUCF CO_2 emissions are depicted. Non-CO_2 gases are converted to CO_2 equivalents using global warming potentials with a 100-year time horizon from the IPCC AR6 (Forster *et al.* 2021).

Global primary energy consumption expanded in 2022, and was mainly met by a growth in coal, oil and renewable electricity supply (Energy Institute 2023; International Energy Agency 2023). Gas consumption declined by 3 per cent in 2022 following the war in Ukraine (Energy Institute 2023). Coal consumption increased, in part driven by switching from gas to coal, as well as the steady growth of coal-fired power production in some emerging economies. Net electricity demand growth in 2022 was primarily met by renewable sources (excluding hydropower), in particular driven by a record increase in solar capacity additions (Energy Institute 2023). Overall, while investments in renewables increased globally, investments in coal, oil and gas have continued and even increased in some countries.

Table 2.1 Total global emissions by source

$GtCO_2e$	2010–2019 (average)	2020	2021	2022
GHG	54.6 ± 5.55	54.5 ± 5.36	56.8 ± 5.45	57.4 ± 5.48
Fossil CO_2	36.1 ± 2.89	35.9 ± 2.88	38.1 ± 3.05	38.5 ± 3.08
LULUCF CO_2 (global bookkeeping)	4.72 ± 3.3	4.06 ± 2.84	3.94 ± 2.76	3.87 ± 2.71
LULUCF CO_2 (national inventory)*	-2.64 ± -1.85	-2.49 ± -1.74	-2.4 ± -1.68	N/A
CH_4	10.1 ± 3.03	10.4 ± 3.13	10.6 ± 3.18	10.8 ± 3.23
N_2O	2.47 ± 1.48	2.57 ± 1.54	2.63 ± 1.58	2.65 ± 1.59
F-gases	1.17 ± 0.351	1.46 ± 0.439	1.54 ± 0.461	1.62 ± 0.486

Note: * Inventory-based LULUCF CO_2 is excluded from total GHG emissions. Non-CO_2 greenhouse gases are converted to CO_2 equivalents using global warming potentials with a 100-year time horizon from the IPCC WGI AR6 (Forster *et al.* 2021).

2.2.2 Emissions rebounded across most global sectors following the COVID-19 pandemic

Emissions can be split into five major economic sectors: energy supply, industry, agriculture and LULUCF, transport and buildings. In 2022, energy supply was the largest source of emissions at 20.9 $GtCO_2e$ (36 per cent of the total), which is mainly due to combustion emissions in the power sector (14.8 $GtCO_2e$) and emissions from fossil fuel production including fugitive methane (6.1 $GtCO_2e$). The energy supply sector is the largest contributor to the increase in emissions over the past decades, largely due to the worldwide expansion of coal- and gas-fired power generation (International Energy Agency 2023). However, it is also one of the only sectors where some countries have made progress in reducing emissions by switching to lower emission fuels and by scaling up renewable sources.

Industry is the second largest sector when accounting by direct emissions (14.4 $GtCO_2e$, 25 per cent of the total), followed by agriculture and LULUCF CO_2 (global bookkeeping approach) (10.3 $GtCO_2e$, 18 per cent), transport (8.1 $GtCO_2e$, 14 per cent) and buildings (3.8 $GtCO_2e$, 6.7 per cent). However, if power sector emissions are reallocated to final sectors based on their use of electricity and heat (i.e. indirect emissions, which highlight a demand perspective), then the contribution of the industry and buildings sectors increase significantly (to 34 per cent and 16 per cent, respectively) (Lamb *et al.* 2021b).

The latest data up to 2022 indicate that most global sectors have fully rebounded from the drop in 2020 emissions, which was induced by COVID-19, and now exceed 2019 levels with little change in the overall composition of sector emissions (Liu *et al.* 2023). An exception is aviation emissions, which remain at 74 per cent of their 2019 peak of 1.0 $GtCO_2e$, but are likely to continue to rebound in 2023 as air passenger numbers start to reach pre-pandemic levels (International Air Transport Association 2023).

2.3 Emissions trends of major emitters

2.3.1 Emissions of the G20 members increased in 2022 and accounted for three quarters of the total

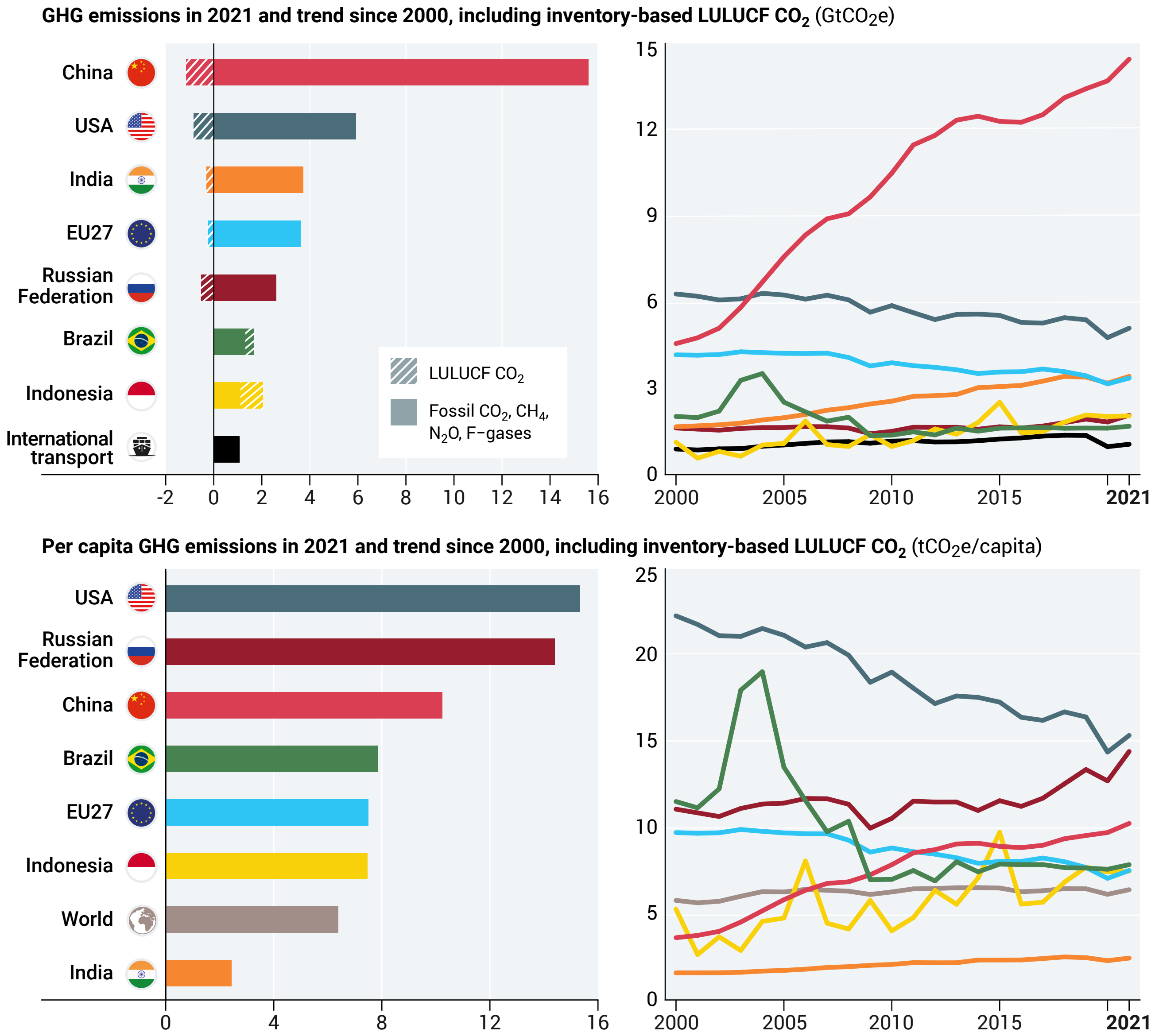
Preliminary estimates for 2022 (which exclude LULUCF CO_2 for which data is only available up to 2021) show an increase in GHG emissions compared with 2021 in Indonesia (+10 per cent), India (+5.1 per cent), the United States of America (+1.6 per cent) and China (+0.3 per cent), and a decrease in the European Union (-0.8 per cent), the Russian Federation (-1 per cent) and Brazil (-2.5 per cent). International transport emissions rapidly increased (+11.4 per cent), but remain below pre-pandemic levels. Total emissions of the G20 also increased (+1.2 per cent).

The top seven global emitters remain the same as in 2021: Brazil, China, India, Indonesia, the European Union, the Russian Federation and the United States of America (figure 2.2). Collectively, and with the addition of international transport, these emitters accounted for a total of 33 $GtCO_2e$ in 2021, or 65 per cent of global emissions on a territorial basis, including national inventory-based LULUCF CO_2. Combined, the G20 accounted for 76 per cent of global emissions. By contrast, least developed countries accounted for 3.8 per cent of global emissions, while small island developing States contributed less than 1 per cent. Generally, global emissions have shifted from high-income to low- and middle-income countries in the past two decades. High-income countries, which include eight members of the G20 (Australia, Canada, the European Union, Japan, Saudi Arabia, the Republic of Korea, the United Kingdom of Great Britain and Northern Ireland and the United States of America) contributed 43 per cent of GHG emissions in 2000, but 28 per cent in 2021. Conversely, low- and middle-income countries, which include nine members of the G20 (Argentina, Brazil, China, India, Indonesia, Mexico, the Russian Federation, South Africa and Türkiye) contributed 53 per cent in 2000 and 69 per cent in 2021.

There is some evidence that the global energy crisis and the international sanctions following the war in Ukraine have impacted regional economic activity and emissions, with highly uncertain long-term implications (International Energy Agency 2022). Direct emissions from military operations, vehicles and installations are likely non-trivial, but remain insufficiently accounted under UNFCCC reporting conventions, and there is limited evidence in the literature on the scope, scale, composition or trend of these emissions (Rajaeifar *et al.* 2022). The energy crisis has driven efforts towards a clean energy transition, with increased investments in renewables and support for clean energy policies and phasing out fossil fuels in some countries (Steffen and Patt 2022; Tollefson 2022). At the same time, some countries have expanded domestic fossil fuel extraction, citing energy security concerns (United Kingdom 2022). There is evidence of an increase in energy prices and a shift in regional energy supplies, particularly in Europe, which took active measures to decrease fossil imports from the Russian Federation (Steffen and Patt 2022). Rising costs of energy and products dependent on fossil fuels could push millions of people globally into poverty, in addition to the hundreds of millions already living under hardship (Guan *et al.* 2023).

Net LULUCF CO_2 emissions, especially from deforestation and land-use change, continue to be concentrated in tropical regions, with Brazil, Indonesia and the Democratic Republic of the Congo contributing 58 per cent of the global total in 2021 – albeit with extremely high uncertainties (Friedlingstein *et al.* 2022). Countries such as these that have a higher contribution from LULUCF CO_2 also tend to experience larger annual fluctuations in GHG emissions due to policy-induced land-use changes, deforestation, wildfires on managed land or shifts towards forest protection (figure 2.2).

Figure 2.2 Emissions trends of major emitters



Sources: World Bank (2023) for population; Crippa *et al.* (2023) for GHG emissions; Grassi *et al.* (2023) for inventory-based LULUCF CO_2.

Note: The top panel depicts total GHG emissions in 2021 and their trends since 2000 for the top seven emitters and international transport. Insufficient LULUCF CO_2 data prevents an update of these trends to 2022 and before 2000. The lower panel depicts per capita GHG emissions in 2021 for these countries and their trends since 2000. Both include inventory-based net LULUCF CO_2 emissions. Non-CO_2 gases are converted to CO_2 equivalents using global warming potentials with a 100-year time horizon from the IPCC WGI AR6 (Forster *et al.* 2021).

2.4 Some countries have peaked in emissions, meanwhile global per capita levels remain highly unequal

Per capita territorial-based GHG emissions in the United States of America and the Russian Federation are over double the world average of 6.5 tons of CO_2 equivalent (tCO_2e), while those in India remain under half of it (figure 2.2). The G20 as a whole averaged 7.9 tCO_2e, whereas least developed countries averaged 2.2 tCO_2e and small island developing States averaged 4.2 tCO_2e. In general, per capita GHG emissions are highly unequally distributed across countries, with emissions as low as 1.3 tCO_2e in Nepal and as high as 73 tCO_2e in Qatar. By comparison, global median estimates of per capita emissions by 2050 consistent with 2°C and 1.5°C scenarios are 2.2 tCO_2e and 1.0 tCO_2e respectively (see chapter 3).

An increasing number of countries have peaked and reduced absolute emissions for more than 10 years (Le Quéré *et al.* 2019; Hubacek *et al.* 2021; Lamb *et al.* 2021a). As of 2022, 36 countries have now sustained emissions reductions for longer than 10 years, in terms of both fossil CO_2 and total GHG emissions, excluding LULUCF CO_2. Of these, 22 are countries in the European Union, while a further eight are high-income countries: Australia, Israel, Japan, Norway, Switzerland, Ukraine, the United Kingdom, the United States of America. Six middle-income countries have also reduced emissions over this time period: Albania, Cuba, Jamaica, Mexico, North Macedonia and South Africa. Generally, while these countries have succeeded in reducing power sector and industry emissions, success in reducing transport, buildings and agriculture emissions has so far been limited (Lamb *et al.* 2021a).

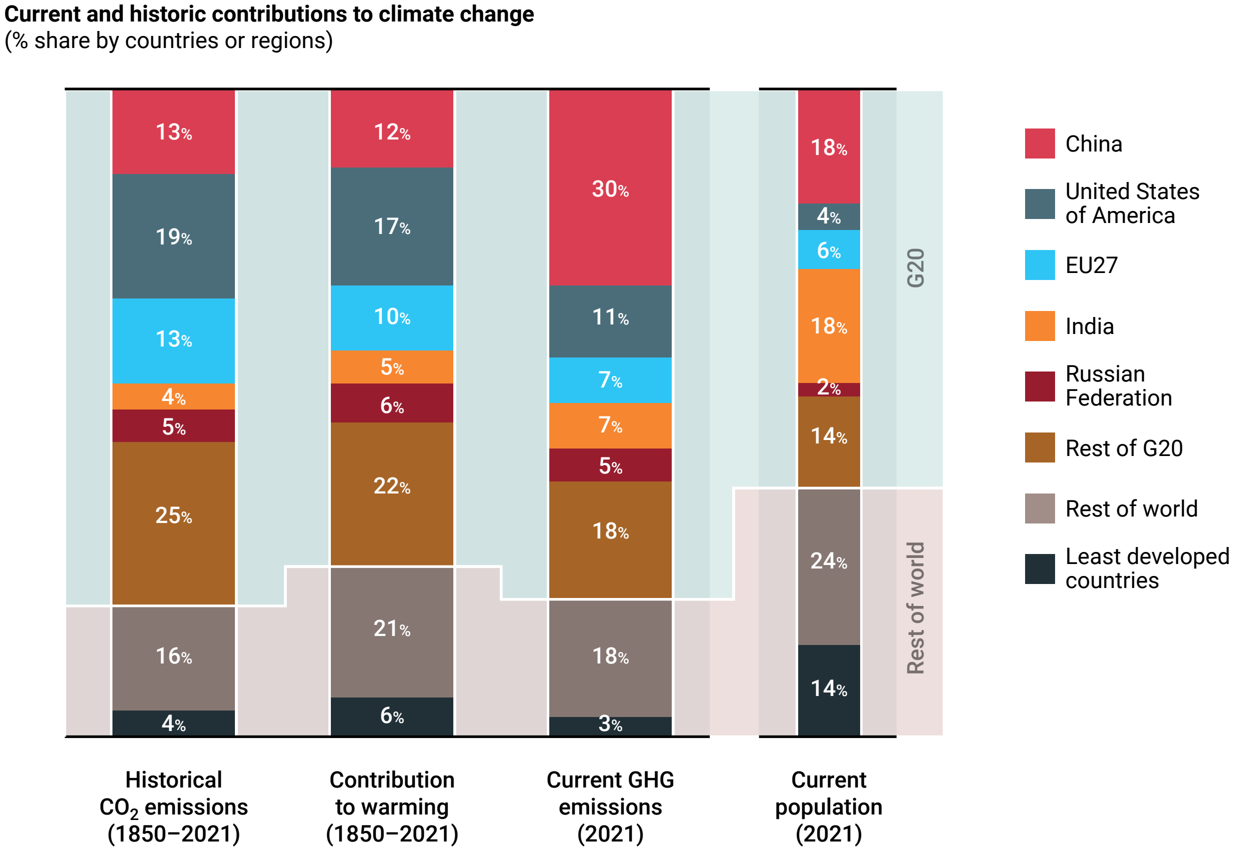
2.5 Contributions to climate change are unequal

2.5.1 A minority of countries have contributed the majority of historical emissions and warming

Cumulative emissions between 1850 and 2021 vary across regions (IPCC 2022). The United States of America is responsible for the largest share of these emissions, followed by the European Union and China (figure 2.3). Collectively, the United States of America and the European Union contributed nearly a third of the total cumulative emissions from 1850 to 2021. Consequently, emissions from these countries have also contributed significantly to warming, including the impact of methane and nitrous oxide emissions, since industrialization (Jones *et al.* 2023). In comparison, least developed countries contributed 4 per cent of historical cumulative fossil and LULUCF CO_2 emissions (figure 2.3).

The G20 as a whole is responsible for approximately three quarters of warming to date, and an even greater proportion of historical cumulative fossil CO_2 emissions (figure 2.3). However, the G20 is itself diverse in terms of economic and social development stages, including population, level of urbanization, industrialization and resource endowments.

Figure 2.3 Current and historical contributions to climate change



Sources: World Bank (2023) for population; Crippa *et al.* (2023) for current GHG emissions; Friedlingstein *et al.* (2022) for historic CO_2 emissions; Jones *et al.* (2023) for historic contributions to warming.

Note: This figure contrasts the distribution of global population in 2021 (total = 7.86 billion), GHG emissions in 2021 (total = 51.6 $GtCO_2e$), cumulative CO_2 emissions (total = 2,200 $GtCO_2$) and historic contributions to warming (total = 1.61°C). Historic contributions to warming result from cumulative CO_2 emissions, but also estimated CH_4, N_2O and F-gas emissions (cooling from aerosols is excluded, leading to a higher estimate of warming than currently observed). Note that due to missing data, these totals are not complete for all categories and exclude, for example, international transport. Current GHG and cumulative CO_2 emissions include net LULUCF CO_2 emissions (global bookkeeping approach) to align with historical emissions estimates (note that this leads to differences with section 2.3.1 where national inventories are used). Non-CO_2 gases are converted to CO_2 equivalents using global warming potentials with a 100-year time horizon from the IPCC AR6 (Forster *et al.* 2021).

2.5.2 Wealthy households contribute nearly half of consumption-based emissions worldwide

Globally, emissions inequality exists among households across and within countries, reflecting underlying inequalities in wealth and income (Bruckner *et al.* 2022). A consistent finding in the literature is that households with the highest income or wealth contribute a disproportionate amount of emissions worldwide. Emissions of the global top 10 per cent of individuals (ranked according to income, wealth or emissions) contributed 45 per cent to 49 per cent of total global emissions, while the global bottom 50 per cent emitted 7 per cent to 13 per cent of the total (Chancel and Piketty 2015; Kartha *et al.* 2020; Chancel 2022; Bruckner *et al.* 2022;).

Estimates of household-level emissions can include those associated with the direct consumption of energy for heating, cooling and transportation, as well as the indirect emissions associated with the consumption of goods and services, or with financial investments (Starr *et al.* 2023).

There are high emitters in all regions and countries. However, emissions of the high-income households in South and Southeast Asia and sub-Saharan Africa appear to be significantly lower compared to other regions (figure 2.4). The emissions of the top 1 per cent households in the United States of America, the Russian Federation and China far exceed their counterparts from developing countries such as Brazil, India and Indonesia.

Emissions trends also vary across income groups. For the United States of America, Starr *et al.* (2023) found that the top 1 per cent consumption-based per capita emissions increased over the recent period, while they decreased for other groups of the population. Zheng *et al.* (2023) found that emissions of the top 20 per cent declined less rapidly than that of other groups in most high-income countries. At the global level, the top 1 per cent contributed to a quarter of the growth in per capita emissions over 1990–2019 (Chancel 2022).

These inequalities in consumption-based emissions reflect income and wealth inequality, and unequal consumption and savings patterns both within and between countries (Cheng *et al.* 2021; Duarte, Miranda-Buetas and Sarasa 2021). Drivers of high energy consumption in wealthier countries include living space (very large homes or secondary homes), the use of large vehicles such as sport-utility vehicles, leisure and work that involve driving and air travel, and the high consumption of meat, dairy and fast fashion (Wiedmann *et al.* 2020; Hickel and Slamersak 2022). Emissions from investments can also lead to significant inequalities between high- and low-income households (Starr *et al.* 2023). Evidence from China shows a positive relationship between income and wealth inequality, and high-consumption lifestyles and emissions (Liu *et al.* 2019; Mi *et al.* 2020; Qin *et al.* 2022). In the United States of America, emissions from high-income households are due to higher energy needs resulting from lifestyle choices such as preference for larger homes and higher dependence on private transport (Feng, Hubacek and Song 2021). Evidence of emissions inequalities between high- and low-income households has been reported for India, Mexico and the Philippines (Santillán Vera and de la Vega Navarro 2020; Seriño 2020; Sri and Banerjee 2023). Climate policy instruments have not always been successful in reducing emissions-intensive consumption or investments, and in many cases have increased the burden on low- and middle-income households (Chancel 2022).

Materials and energy are also required to sustain decent living standards, such as shelter, mobility, nutrition and healthcare – however, the estimated impact of satisfying these needs is relatively small (Pachauri 2014; Rao, Min and Mastrucci 2019; Vélez-Henao and Pauliuk 2023; see also chapter 5). Achieving targets of the Sustainable Development Goals including eradicating extreme poverty, providing clean energy access and providing decent living standards to these regions are consequently global priorities alongside deep emissions reductions (chapters 5 and 6).

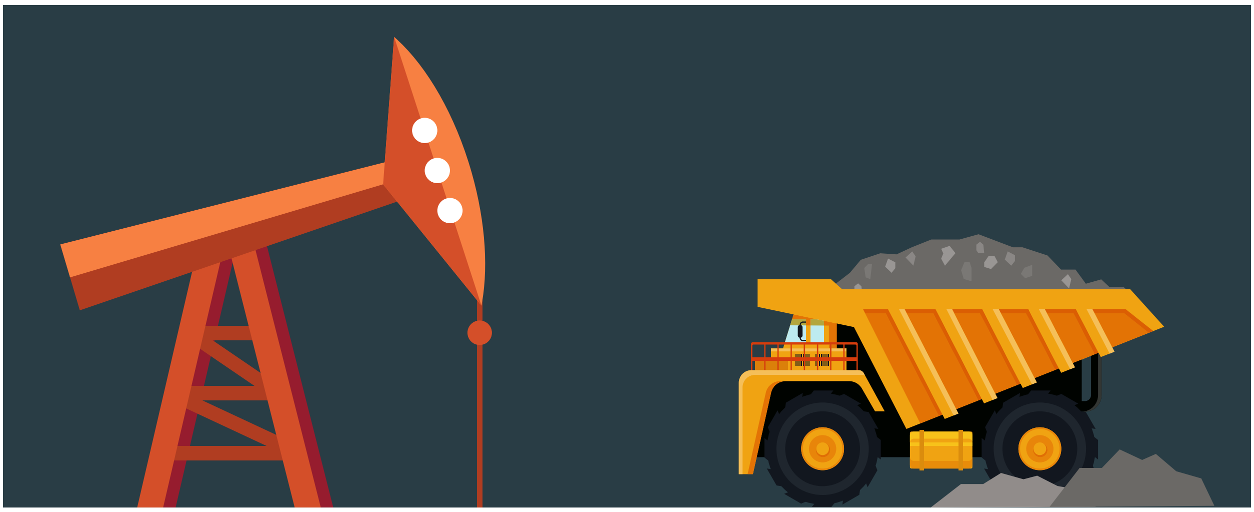
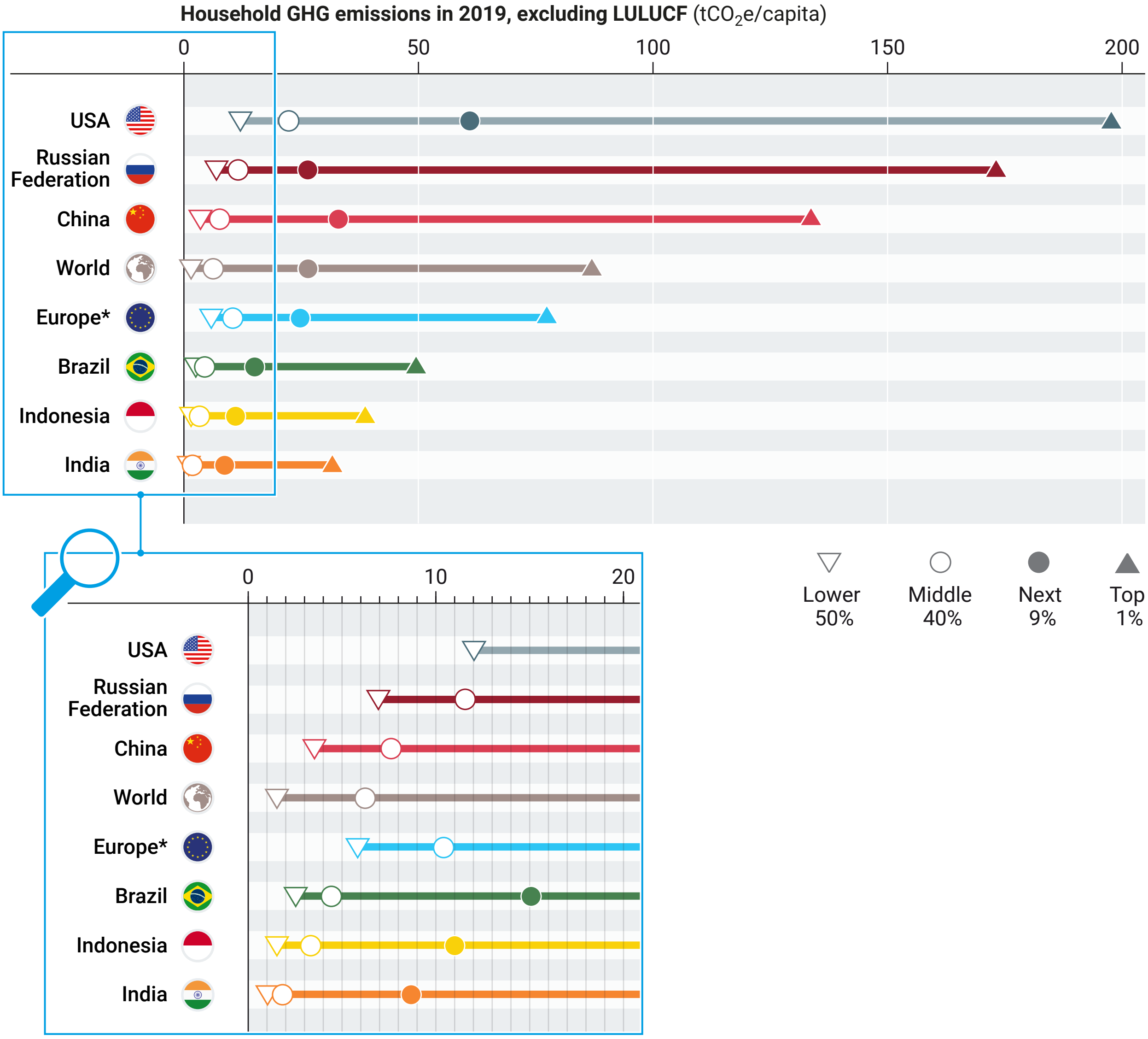


Figure 2.4 GHG emissions across different groups of households (2019)



Source: World Inequality Database (2023).

Note: Emissions include those from domestic direct and indirect consumption, and public and private investments, imports and exports of carbon embedded in goods and services traded. In these estimates, emissions associated with the formation of capital (i.e. investments) are attributed to the owners of capital. This excludes LULUCF CO_2 emissions. Emissions are split equally within households.

* In this table, Europe refers to, and is calculated as the weighted average, of France, Germany, Italy, Poland, Spain, Sweden and the United Kingdom.

3 Nationally determined contributions and long-term pledges: The global landscape and G20 member progress

Lead authors:

Takeshi Kuramochi (NewClimate Institute, Germany), Michel den Elzen (PBL Netherlands Environmental Assessment Agency, the Netherlands) and Taryn Fransen (World Resources Institute, United States of America)

Contributing authors:

Jesse Burton (University of Cape Town and E3G, South Africa), Ioannis Dafnomilis (PBL Netherlands Environmental Assessment Agency, the Netherlands), Ipek Gençsü (Overseas Development Institute [ODI], United Kingdom), Archie Gilmour (ODI, United Kingdom), Mariana Gutiérrez Grados (Climate Transparency, Germany), Frederic Hans (NewClimate Institute, Germany), Sarah Heck (Climate Analytics, Germany), Niklas Höhne (NewClimate Institute, Germany), Camilla Hyslop (Oxford University, United Kingdom), Anna Kanduth (Canadian Climate Institute, Canada), Ben King (Rhodium Group, United States of America), Hannah Kolus (Rhodium Group, United States of America), Ho-Mi Lee (Korea Energy Economics Institute, Republic of Korea), Jared Lewis (Climate Resource, Australia), Swithin Lui (NewClimate Institute, Germany), Natasha Lutz (Oxford University, United Kingdom), Andrew Marquard (University of Cape Town, South Africa), Silke Mooldijk (NewClimate Institute, Germany), Leonardo Nascimento (NewClimate Institute, Germany), Analuz Presbítero (Iniciativa Climática de México [ICM], Mexico), Jazmín Rocco Predassi (Farn, Argentina), Joeri Rogelj (Imperial College London, United Kingdom; International Institute for Applied Systems Analysis [IIASA], Austria), Clea Schumer (World Resources Institute, United States of America), Alister Self (Climate Resource, Australia), Kentaro Tamura (Institute for Global Environmental Strategies, Japan) and Jorge Villarreal (ICM, Mexico)

Data contributors:

Johannes Gütschow (Potsdam Institute for Climate Impact Research, Germany), Christopher Henderson (World Resources Institute, United States of America), Elena Hooijschuur (PBL Netherlands Environmental Assessment Agency, the Netherlands), Kimon Keramidas (European Commission, Joint Research Centre, Spain), Mia Moisio (NewClimate Institute, Germany), Mika Pflüger (Climate Resource, Germany) and Claire Stockwell (Climate Analytics, Germany)

3.1 Introduction

This chapter provides a global update of greenhouse gas (GHG) emissions reduction pledges for 2030 and beyond, as well as an assessment of G20 members' implementation progress. The chapter addresses the following three questions:

1. How have the nationally determined contributions (NDCs) evolved since the twenty-seventh session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 27) and since the Paris Agreement was adopted, and what does this imply for global GHG emissions in 2030? (section 3.2)

2. What progress have G20 members made towards achieving their NDC targets since COP 27, and what new policies are they implementing? (section 3.3)

3. To what extent have net-zero targets been strengthened and moved towards implementation since COP 27? (section 3.4)

The cut-off date for the literature and data assessed in this chapter is 25 September 2023. In line with the other chapters of this report, all GHG emissions numbers are expressed using the 100-year global warming potentials from the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6). For historical emissions, this chapter refers to the national inventory reports submitted to the United Nations Framework Convention on Climate Change (UNFCCC), unless otherwise noted. The methodology and preliminary findings of this chapter were made available to the Governments of the G20 members to provide them with the opportunity to comment on the findings.

According to the Paris Agreement, its implementation should "reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of differing national circumstances" (UNFCCC 2015). An assessment of the extent to which countries' 2030 and long-term pledges are ambitious in light of equity, responsibility, capability and other burden-sharing principles is beyond this chapter. These are highly contested and normative issues. However, the chapter showcases the wide variation in per capita emissions implied by current NDCs and policies. Moreover, it notes that the ambition of an NDC is one of the factors likely to influence whether a country is on track to achieving it, as a less ambitious target for 2030 will be easier to implement than a more ambitious target. Similarly, a country not currently on track to achieve its NDCs might nevertheless be taking substantially more mitigation action than a country that is on track. The chapter should be read with this context in mind.

3.2 Global progress of NDCs is negligible since COP 27, but there is some progress since the adoption of the Paris Agreement

3.2.1 A growing number of NDCs contain GHG reduction targets, and more of these are economy-wide

The Conference of the Parties (COP) decision that accompanied the Paris Agreement invited countries to communicate new NDCs or to update their current NDCs by 2020, while subsequent COP decisions have asked countries to revisit and strengthen their targets "as necessary to align with the Paris Agreement temperature goal". The Emissions Gap Report tracks the number of countries communicating new or updated NDCs, as well as key characteristics related to the emissions reduction targets included in these NDCs.

Since COP 27, nine countries have submitted new or updated NDCs. Of these, four propose to reduce 2030 emissions further than the country's prior NDCs (Egypt, Türkiye, the United Arab Emirates and Uruguay), two are unclear or not comparable to the prior NDCs (Kiribati and Turkmenistan), one does not further reduce emissions (Kazakhstan) and one is the country's first NDC (the Holy See) (Climate Watch 2023). These submissions bring the total number of Paris Agreement parties that have replaced or updated their NDCs as at 25 September 2023 to 149 (counting the European Union and its 27 Member States as a single party). The mitigation content of these NDCs has evolved over time, in several ways (table 3.1).

First, more NDCs now contain GHG reduction targets, and more of these targets are economy-wide – that is, they cover a country's entire economy as opposed to certain sectors. The Paris Agreement stipulates that developed countries should adopt "economy-wide absolute emissions reduction targets" and encourages developing countries to "move over time" to economy-wide emissions targets. Now, 148 NDCs contain GHG reduction targets, up from 122 at COP 21 where the Paris Agreement was adopted. Of these targets, 97 are economy-wide, versus 55 in the initial NDCs. The share of NDCs with targets covering all seven GHGs listed in the Kyoto Protocol, in contrast, has remained modest at only 23, up from 20 at COP 21.[1]

Second, the number of NDCs noting that they may use international market mechanisms to achieve their targets has increased to 121, up from 92 at COP 21. Article 6 of the Paris Agreement provides that parties may cooperate with other parties to achieve their targets by trading emissions credits or offsets. The increase in targets that may incorporate these mechanisms might reflect greater certainty regarding the modalities of these mechanisms since they were clarified at COP 26.

Finally, developing country parties often specify that all or part of their NDCs are conditional on international finance, technology transfer or other provisions. The number of NDCs containing elements that are not conditional on such measures has increased to 135, compared with 108 at COP 21.

3.2.2 The effect on global emissions of new and updated NDCs submitted since COP 27 is negligible, while the aggregate effect of new and updated NDCs since the Paris Agreement is more pronounced

If all the latest unconditional NDCs[2] are fully implemented, they are estimated to reduce global GHG emissions in 2030 by about 5.0 gigatons of CO_2 equivalent ($GtCO_2e$) (range: 1.6–8.1) annually compared with the initial NDCs (see appendix B.2 for details on the impacts of various country contributions). The combined effect of the nine NDCs submitted since COP 27 amounts to about 0.1 $GtCO_2e$ of this total.[3] Thus, while progress since COP 27 is negligible, progress since the adoption of the Paris Agreement is more pronounced.

1 There are 136 NDCs that contain targets covering methane.

2 Through 25 September 2023.

3 The data comes from three model groups with updated NDCs, with cut-off dates ranging from November 2022 to September 2023 across studies (Keramidas *et al.* 2022; den Elzen *et al.* 2023; Meinshausen *et al.* 2022; Meinshausen *et al.* 2023) and two open-source tools (Climate Action Tracker 2023a; Fransen *et al.* 2022, as updated using Climate Watch 2023).

Table 3.1 Trends in global NDC characteristics since the Paris Agreement

NDC characteristics	COP 28 (2023)	COP 27 (2022)	COP 26 (2021)	COP 21 (2015)
Number of NDCs	Number (percentage of global emissions)			
That reduce 2030 emissions relative to initial NDCs	81 (79%)	79 (79%)	65 (63%)	N/A
That contain a GHG reduction target	148 (90%)	147 (90%)	143 (89%)	122 (85%)
That contain a GHG target covering all sectors (energy, industry, waste; agriculture, forestry and other land-use change; or agriculture and land use, land-use change and forestry [LULUCF])	97 (54%)	96 (53%)	91 (52%)	55 (44%)
That contain a GHG target covering all GHGs listed in the Kyoto Protocol (carbon dioxide [CO_2], methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride and nitrogen trifluoride)	23 (30%)	23 (30%)	23 (30%)	20 (29%)
That may be achieved using international market mechanisms	121 (39%)	120 (39%)	120 (37%)	92 (24%)
That contain elements not conditional on international support	135 (82%)	134 (82%)	131 (81%)	108 (77%)

Note: Numbers in parentheses refer to the share of global GHG emissions from countries communicating NDCs with the characteristic shown in the first column. The last day of each COP is used as the cut-off date for each column, except for COP 28, for which the cut-off date is 25 September 2023.

3.3 Implementation progress of G20 members continues, but must be accelerated

This section provides an update on the progress of G20 members towards their latest NDC targets. It assesses collective and individual progress of G20 members in bridging the implementation gap, defined as the difference between projected emissions under current policies and projected emissions under full implementation of the NDCs (section 3.3.1). This is accompanied by consideration of recent major policy developments that are not yet fully reflected in emissions projection studies (section 3.3.2). To take stock, box 3.1 concludes on the predecessor of the NDCs (the Cancun Pledges for 2020) against which the Emissions Gap Reports (until 2015) assessed the emissions gap for 2020.

Box 3.1 Did the G20 achieve the Cancun Pledges for 2020?

As part of the 2010 Cancun Agreements, developed country parties communicated emissions reduction targets for 2020 and developing country parties communicated nationally appropriate mitigation actions, many of which also contained 2020 emissions targets (UNFCCC 2011). Thirteen of the G20 members made such pledges (counting the European Union Members – France, Germany, Italy and the United Kingdom – as a single entity), while three countries (Argentina, Saudi Arabia and Türkiye) did not. GHG inventory data for 2020 are now available for all Annex I countries and some non-Annex I countries, making it possible to assess whether these pledges were achieved.

Collectively, G20 members achieved the Cancun Pledges (see appendix B.1). Ten G20 members (Australia, Brazil, China, the European Union [including the United Kingdom], India, Japan, Mexico, South Africa, the Russian Federation and the United States of America) achieved their Cancun Pledges, while two members (Canada and the Republic of Korea) did not achieve them. Some countries, such as Indonesia, need to update their national data and information to enable tracking progress towards their pledges.

However, the achievement of the Cancun Pledges still resulted in a large emissions gap in 2020. The failure to bridge the 2020 emissions gap has added further to the present mitigation challenge and the feasibility of bridging the 2030 emissions gap.

The assessment is based on a comparison of 2020 GHG emissions with the trajectories associated with the achievement of these parties' pledges (see appendix B.1 for further detail). Emissions data is sourced from official GHG inventories (where available) or from independent data sources (chapter 2).

3.3.1 Progress of G20 members towards the 2030 NDC targets varies

Collectively, the G20 members are projected to fall short of their latest NDCs by 1.2 $GtCO_2e$ (central estimate) annually by 2030. This is 0.6 $GtCO_2e$ lower than last year's assessment. For two G20 members, the projected emissions under the NDC have, from the time they were submitted, significantly exceeded current policies projections (the Russian Federation and Türkiye), thereby lowering the implementation gap compared with what can be reasonably expected. If NDC projections for these two members are substituted by current policies scenario projections, the G20 members would collectively fall short of achieving their NDCs in 2030 by an annual 1.8 $GtCO_2e$ in 2030, which is 0.8 $GtCO_2e$ lower than in last year's assessment. The impact of newly implemented policies is the driver of the lower projections. Other factors include that the scenario dataset has been updated to reflect the latest emissions trends and socioeconomic developments and circumstances, and that there have been methodological updates to scenario models (see box 3.2 and chapter 4).

Box 3.2 Methodology underlying the assessment of G20 member progress

The updated assessment of progress towards 2030 targets is based on a synthesis of emissions projection studies by independent research groups. The studies considered in the assessment are mostly published between 2021 and 2023. A list of the studies as well as the criteria for their inclusion is available in appendix B.3. In line with previous Emissions Gap Reports, the assessment follows the methodology of den Elzen *et al.* (2019). NDC targets are compared to emissions projections under a current policies scenario, which reflects all policies adopted and implemented up to specific cut-off dates, and which, for the purposes of this report, are defined as legislative decisions, executive orders or their equivalent. This implies that officially announced plans or strategies alone would not qualify, while individual executive orders to implement such plans or strategies would qualify. It is important to note that some of the most recently adopted policies, some of which are presented in section 3.3.3, may not be considered in the scenario studies reviewed as they were prepared before the adoption of these policies. Many studies reviewed this year reflect the impact of the COVID-19 pandemic on both historical and projected emissions.[4] Additionally, a few studies published in 2022 and 2023 partially reflect the impact of the energy crisis and the war in Ukraine.

To evaluate the conditionality of NDCs, the categorization of the World Resources Institute (Climate Watch 2023) is adopted. According to this categorization, Indonesia and Mexico have both unconditional and conditional NDCs, while India and South Africa have only conditional NDCs (see appendix B.2). The assessment based on independent studies is compared with official projections published by national Governments. Many of the "with existing measures" scenario projections in the latest UNFCCC submissions are considered as current policies scenario projections. Methodological limitations of the assessment are similar to those described in previous Emissions Gap Reports (see appendix B.4). The assessment is based on "point in time" emissions projections for the NDC target year.[5] European Union Member States are not assessed individually. The assessment is based on emissions including LULUCF.

4 Earlier studies suggest that the economic rescue and recovery measures would not lead to substantive additional future emission reductions (Hans *et al.* 2022; Nahm, Miller and Urpelainen 2022).

5 Some countries also set an emissions budget for a multi-year period; an assessment of these targets may lead to different conclusions.

Progress of individual G20 members towards their latest NDC targets is shown in more detail in table 3.2, organized by the likelihood of achieving the targets with existing policies. There are no major changes to the overall assessment of whether individual G20 members are on track to meet their 2030 targets with existing policies, compared with last year's assessment. Overall, ten G20 members are assessed to fall short of achieving their NDC targets with existing policies.

It should be noted that many of these countries have submitted stronger NDC targets in 2020 or later, and are in the midst of their implementation efforts to meet their new targets. G20 members that are projected to meet their latest NDC targets based on policies currently in place are those that did not strengthen, or only moderately strengthened, their target levels in their new or updated NDCs.

Table 3.2 Assessment of progress towards achieving the current NDC targets

Assessment of progress towards the latest NDC target					
LIKELY to meet the target with existing policies*		**LESS LIKELY** to meet the target with existing policies		**UNCERTAIN**	
China	●●●●●●○○	Argentina	○○○	Indonesia	●○○
India (Conditional NDC)	●●●●○○○	Australia	●○○○ [1]		
Saudi Arabia	●○	Brazil	●◐◐○		
Türkiye	●●●	Canada	●○○○ [1]		
Russian Federation	●●●● [1]	EU27	◐◐○ [1] [2]		
Mexico	●●○	Japan	●○○		
		Republic of Korea	●○○		
		South Africa (Conditional NDC)	●○○		
		UK	○○ [1]		
		USA	○○○○○○○ [1]		

Number of studies indicating:

● Target will be achieved

◐ Target within reach

○ Target will be missed

Conditional NDC (shaded)

*** Indicated by bold font, if overachieved by more than 15%.**

Note: All NDCs considered in this assessment are unconditional NDCs, unless otherwise mentioned. The assessment is based on independent studies mainly published in 2021 or later. See appendix B.3 for the list of studies reviewed. The number of independent studies that project a country to meet its current NDC targets are compared with the total number of studies. The assessment is based on the middle of the projection range for each independent study. "Within reach" is applied when the lower bound estimate of a current policies scenario projection is within the NDC target range, even though the assessment based on the middle of the projection range suggests that the country will not achieve its target. In the case of Indonesia, "uncertain" is mainly due to the variations in LULUCF emissions and uncertainty of LULUCF emissions projections as a result of peat fires.

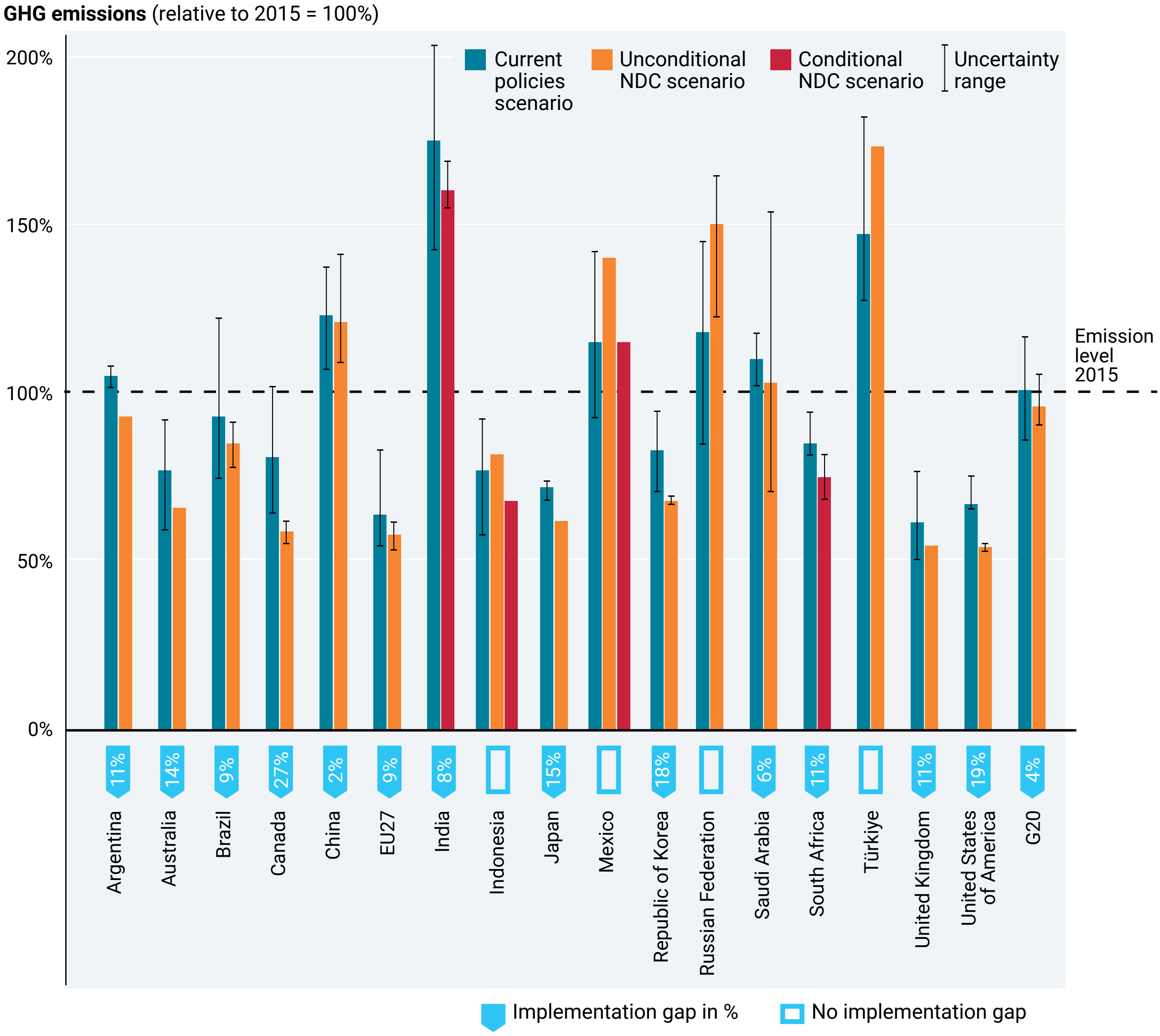
1 Current policies scenario projections from official publications were also examined. The official publications for five G20 members (Australia, Canada, the European Union, the United Kingdom and the United States of America) show that they do not yet project to meet their "point in time" NDC target under their current policies scenarios (European Environment Agency 2023; European Commission, Directorate-General for Energy, Directorate-General for Climate Action, Directorate-Generate for Mobility and Transport 2021; UNFCCC 2023a). For the Russian Federation, official projections of the fourth biennial report indicate that the country would achieve its NDC with existing policies.

2 Both independent studies and official projections do not account for the impact of some recently adopted policies, most notably the REPowerEU plan.

However, for most G20 members, central estimates of projected emissions in 2030 under current policies are lower than in last year's assessment. Based on the scenario modelling, the largest reductions (8–14 per cent) are observed for Australia, the European Union, Japan, Mexico, the Republic of Korea and the United Kingdom. Figure 3.1

illustrates the collective and individual implementation gaps of the G20 members and shows them relative to emissions levels in 2015, the year the Paris Agreement was adopted. The figure illustrates a wide variation in implementation gaps as well as projected emissions in 2030 relative to 2015 levels. The aggregate emissions of the G20 members in 2030 under current policies are projected at 36.1 $GtCO_2e$ (central estimate), which is slightly above 2015 levels. The impact of newly implemented policies is a main driver of the lower emissions projections for 2030 for G20 members. Other factors include an updated scenario dataset reflecting the latest emission trends, and socioeconomic developments and circumstances.

Figure 3.1 Implementation gaps between current policies and NDC pledges for the G20 members collectively and individually by 2030, relative to 2015 emissions



Note: The 2015 emissions are based on national inventory data and provided in table B.2 of appendix B.2. For the G20 total, the bar for unconditional NDCs also includes the conditional NDCs of India and South Africa. The error bars show the uncertainty range across studies, which reflects model variations as well as interpretation of policies and targets.

Per capita emissions are highly unequal across G20 members, and far from levels consistent with the Paris Agreement

To supplement the findings presented above and complement chapter 2, table 3.3 presents per capita GHG emissions in 2015 and projections for 2030 under current

NDC targets and current policies scenario.[6] There are only small changes compared with last year. The average per capita emissions in 2030 of G20 members under the latest NDCs are projected to be only marginally lower (6.8 tons of CO_2 equivalent [tCO_2e]) than under the current policies scenario (7.1 tCO_2e). They are still very far from the median estimates implied by 2°C and 1.5°C scenarios by 2050, which are 2.2 tCO_2e (fifth and ninety-fifth percentile range: 1.4–2.8) and 1.0 tCO_2e (0.1–1.6), respectively.[7]

Echoing the findings of chapter 2, table 3.3 shows that per capita emissions range widely across G20 members. Australia, the European Union, the United Kingdom and the United States of America are projected to reduce their per capita emissions by more than one-third between 2015 and 2030 under current policies, and by between 40 per cent and 50 per cent under unconditional NDCs. For five G20 members (China, India, Mexico, the Russian Federation and Türkiye), per capita emissions are projected to increase between 2015 and 2030 under both current unconditional NDC targets and current policies. Furthermore, per capita emissions are projected to stay above 10 tCO_2e in 2030 for several G20 members, both under current policies and under full implementation of the unconditional NDCs.

Table 3.3 G20 member per capita emissions implied by current policies and unconditional NDCs

Country	Unconditional NDC: Per capita GHG emissions [1]		Current policies scenario: Per capita GHG emissions [1]	
	tCO_2e/cap in 2030 [2, 3]	vs. 2015 levels	tCO_2e/cap in 2030 [2, 3]	vs. 2015 levels
G20 [4]	6.8	-10%	7.1	-6%
Argentina	7.5	-16%	8.4	-5%
Australia	12.7	-44%	14.7	-35%
Brazil	6.1	-23%	6.7	-15%
Canada	10.5	-49%	14.5	-30%
China	10.0	+19%	10.2	+21%
EU27	4.6	-42%	5.0	-37%
India [4]	2.8	+40%	3.1	+52%
Indonesia	6.9	-28%	6.5	-32%
Japan	6.5	-35%	7.6	-23%
Mexico	5.8	+25%	4.8	+3%
Republic of Korea	8.7	-32%	10.6	-18%
Russian Federation	15.8	+54%	12.4	+21%
Saudi Arabia	16.1	-16%	17.2	-11%
South Africa [4]	6.0	-35%	6.8	-27%
Türkiye	7.9	+55%	6.7	+31%
United Kingdom	4.0	-49%	4.5	-43%
United States of America	9.4	-50%	11.7	-38%

Notes: The figures presented here may not exactly match those presented in other chapters of this report (including figure 2.2) and official estimates by the national Governments, due to the differences in data sources.

1 Emissions estimates include LULUCF.

2 Central estimates are the median value when five or more studies were available, otherwise they are average values.

3 Data on historical and projected (medium fertility variant) population per country are taken from the United Nations World Population Prospects 2022 (United Nations 2022).

4 To estimate G20 total emissions for the NDC pledges scenario, emissions projections under the current policies scenario were used for India, the Russian Federation and Türkiye.

6 Note that the 2015 estimates are not identical to those of chapter 2, due to the differences in data sources and the consideration of LULUCF emissions.

7 Estimated based on the IPCC AR6 scenario database (Byers *et al.* 2022; Riahi *et al.* 2022) and United Nations population projections, medium fertility variant (United Nations 2022).

3.3.3 Recently adopted policies in G20 economies shows mixed progress

The projections in section 3.3.2 do not include all the most recent policy updates, as some of these are not yet reflected in the underlying models. Therefore, this section provides recent policy updates (mid-2022 to mid-2023) of the G20 members.

Responding to the climate emergency requires rapid policy implementation in all countries with discernible progress each year. However, this chapter finds that recent developments in national policies has been mixed with some steps forward, while some imply a standstill or even deterioration.

3.3.3.1 Some recent policies of G20 members could have substantial effects on GHG emissions in 2030

This section provides examples of recently adopted policies in the G20 member states that are quantified or analysed to have positive or negative effects in reducing global or national implementation gaps in recent studies. It is acknowledged that these policies cover only a fraction of G20 policy developments, and that other policies may still result in substantial emissions reductions or support the implementation of more stringent policies.

Inflation Reduction Act (IRA) – United States of America: The United States of America's federal Government has advanced several important regulations implementing the IRA, which was passed in August 2022. These regulations propose or finalize requirements for claiming electric power generation, clean vehicles and home energy tax credits (United States of America, Internal Revenue Service 2023); provide funding to reduce methane emissions (United States of America, Environmental Protection Agency 2023); and implement new lease sales and royalty rates for oil and gas leasing on public lands and in public waters (United States of America, Department of the Interior, Bureau of Land Management 2023; United States of America, Department of the Interior, Bureau of Ocean Energy Management 2023), among others. More and more analyses confirm that the act will bring the United States of America roughly two thirds of the way to meet its NDC targets for 2030, with reductions of up to 1 $GtCO_2e$ over a scenario without that policy (Bistline *et al.* 2023). While a big step forward, the IRA also received criticism as it, for example, allows for more oil and gas exploration, potentially increasing emissions, but not overcompensating reductions elsewhere. The name of the IRA suggests that it is more an economic policy than a climate policy. It has significant knock-on effects on other countries, as many industries are considering whether to place their production lines in the United States of America or abroad. The potential impact of the IRA on 2030 emissions has been considered in all national-level scenarios reviewed in the United Nations Environment Programme (UNEP) Emissions Gap Report since the 2022 edition; the projected 2030 emissions range presented in section 3.3.2 is therefore similar to that of the 2022 assessment.

Fit for 55 and REPowerEU – European Union: In the last 12 months, the European Union significantly advanced several policy packages to achieve its 2030 emissions reduction target and accelerate the European Union transition away from fossil fuels (European Commission 2021; European Commission 2022). These include the expansion of the current European Union Emissions Trading System, updates to regulation on emissions from transport and buildings, improvements in the renewables and energy efficiency targets and a carbon border adjustment mechanism, which will ensure that carbon-intensive imports are subject to a carbon price equivalent to that of products from within the European Union, and at the same time a gradual phase-out of free allocations to those industries within the European Union Emissions Trading System. Still, increased investments in fossil gas infrastructure and a temporary shift from gas to coal pose a threat to the European Union's climate ambition. Many elements of the Fit for 55 package and REPowerEU plan have now been adopted. The emission scenario studies reviewed in section 3.3.1 show a range of interpretation (or lack thereof) on the implementation status of these policies. The elements adopted in the last 12 months result in roughly 0.5 $GtCO_2e$ lower emissions in 2030. If all packages are adopted, the European Union could overachieve its 2030 target (Climate Action Tracker 2023c).

Just Energy Transition Partnership (JETP) – Indonesia: In November 2022, a JETP to support limiting Indonesia's power sector emissions was agreed between the Indonesian Government and an international partner group. It secures approximately US$20 billion to support investments in grid and transmission, early coal power retirement, accelerated uptake of dispatchable and variable renewables, as well as supply chain build-out for renewable energy technologies. It also helps to mitigate adverse effects on communities. It reinforces the commitment established in a presidential regulation to stop the addition of new coal-fired power plants to the electricity grid (Indonesia 2022). However, the presidential regulation still allows for off-grid power plants where the electricity is directly used by industry to be built, which results in increasing emissions up to 2030. The deal stipulates that Indonesia caps its power sector emissions to 290 megatons of CO_2 equivalent ($MtCO_2e$) in 2030 (Edianto 2023). Estimates indicate that the emissions cap constitutes a reduction of emissions in the order of up to 100 $MtCO_2e$ in 2030 over current policies (International Energy Agency 2022; Edianto 2023). This alone may be small on a global scale, but if the concept of JETP proves successful, it can lead to similar agreements in other countries.

Emissions Reduction Plan – Canada: Many recent developments in Canada advance the implementation of its Emissions Reduction Plan, which is the federal Government's first comprehensive roadmap for how to achieve the 2030 target (Canada, Environment and Climate Change Canada

2022). The federal Government's Clean Fuel Regulations were finalized in June 2022 and came into effect in July 2023 (Canada 2022). The regulations require all fuel importers or producers to gradually reduce the life-cycle emissions intensity of their fuels. Beginning in 2023, the federal carbon price rose from CA\$50/tCO_2e to CA\$65/tCO_2e, and is scheduled to increase linearly to CA\$170/tCO_2e in 2030. Additionally, the 2023 budget made significant investments to expand clean electricity and accelerate low-carbon growth. The federal budget contained over CA\$40 billion in new or reallocated funds for emissions-reducing actions by 2034/2035, including a number of new investment tax credits for carbon capture, utilization and storage, clean electricity, clean hydrogen, clean technology and clean technology manufacturing. While some of the tax credits are not yet in force, once legislated, many of the credits will be retroactively available to businesses. The implementation of legislated and developing policies in Canada results in emissions at approximately 520 MtCO_2e in 2030, bringing Canada more than halfway through meeting its 2030 target (Sawyer *et al.* 2022) and roughly 100 MtCO_2e lower than last year without the policies (Climate Action Tracker 2022a).

Fossil fuel expansion in the G20: Although many policies constitute progress in the past year, an opposite trend of fossil fuel infrastructure expansion is at odds with global climate goals. Over the past year, many countries increased their plans for fossil fuel extraction and production. Several major G20 economies, such as Australia, Canada, the United Kingdom and the United States of America issued new licences for oil and gas explorations, and Argentina pursued expansion (NewClimate Institute and Climate Analytics 2023; International Energy Agency 2023). In addition, rather than declining, fossil fuel subsidies have increased significantly. The International Monetary Fund reports that explicit subsidies more than doubled globally from 2020 to 2022 (Black *et al.* 2023). The United States of America is now the largest fossil fuel producer in the world, with oil production doubling and gas production increasing by around 60 per cent since 2010 (United States of America, Energy Information Administration 2023). The recent increase in fossil fuel production and exports of the G20 members result in domestic emissions and undermine global GHG emission reductions. This year's edition of the Production Gap Report (Stockholm Environment Institute *et al.* 2023) shows that globally, Governments still plan to produce more than double the amount of fossil fuels in 2030 than would be consistent with the collective goals of the Paris Agreement. G20 Governments account for the majority of current fossil fuel production (73 per cent on an energy basis [International Energy Agency 2023]).

3.3.3.2 The effect of other selected policy developments cannot yet be quantified

Several other policies have been adopted by G20 members, but in many cases their impacts remain unclear. Some of the key policy developments since the last edition of the UNEP Emissions Gap Report are described below.

Argentina: In December 2022, Argentina published its new National Climate Change Adaptation and Mitigation Plan (Argentina, Ministry of Environment and Sustainable Development 2022). This strategy includes targets for the decarbonization of the transport sector, incentives to increase energy efficiency in buildings, and measures to reduce food loss and waste. It also includes agroecological practices measures, which affect one of Argentina's biggest productive sectors. The plan, however, does not include any new renewable energy targets, nor does it include a plan to reduce absolute emissions from livestock, one of Argentina's major emissions sources. Additionally, the plan proposes measures related to oil and gas expansion (focusing on the Vaca Muerta shale fields), as well as hydrogen production without clarifying if the hydrogen is produced from electricity (Argentina, Ministry of Environment and Sustainable Development 2022).

China: Policy developments in China go both ways. On one hand, the Government is rapidly implementing its double strategy of overarching carbon peaking before 2030 and carbon neutrality before 2060 goals, and has issued supporting sectoral peaking plans. The Central Comprehensively Deepening Reforms Commission of China announced in 2023 the transition of the economy from targeting energy consumption and intensity reduction to limiting carbon (intensity and reduction) – a clear sign of support for clean energy (Xinhua 2023). Non-fossil energy capacity has surpassed 50 per cent of all installed capacity, reaching a 2025 milestone target early, and was forecasted to grow in 2023 by another 180 gigawatts (GW) off the back of a strong year for solar and wind (China Electricity Council 2023; Xinhuanet 2023). On the other hand, energy security concerns are leading to the continued expansion and overcapacity of the coal-fired power fleet: 243 GW of coal-fired power plants are currently either permitted or in construction (Global Energy Monitor *et al.* 2023). Energy demand has increased in 2023, with domestic production and consumption of coal, gas and oil up compared to last year (China, National Energy Administration 2023).

Japan: A new law that proposes a carbon levy, an emissions trading scheme and issuance of new government bonds was adopted in June 2023 (Japan 2021). However, its impact on emissions remains unclear due to lack of clarity on the level of carbon pricing. The Government will mobilize JP¥20 trillion through the issuance of the Green Transformation (GX) Economy Transition Bonds (Japan, Ministry of Economy, Trade and Industry 2023). The Basic Hydrogen Strategy was also revised and now sets new hydrogen supply targets for 2030, 2040 and 2050, and an investment plan of US\$107.5 billion over the next 15 years (Japan, Cabinet Secretariat 2023).

Mexico: In February 2023, Mexico announced a renewables energies plan – the Sonora Plan – aiming at deploying renewable energy as well as low-carbon investments in the north of the country (Conan 2023). The Sonora Plan is a step in the right direction to accelerate the energy transition, but is the only new renewable energy project announced by this administration. In May 2023, the Energy Regulatory Commission revised the criteria to calculate clean energy. The Commission states that a portion (30 per cent) of the electricity generation from combined cycle power plants using fossil gas could be legally considered as "clean" energy. Clean Energy Certificates could also be granted to fossil fuel-based power plants (Mexico, Secretariat of the Government 2023). This regulation has been provisionally suspended, and further legal processes are expected to address environmental concerns. The Government has also updated the new light vehicle fleet's fuel efficiency standard (NOM-163), but captured only half of the potential. The adopted standard lowers emissions by 9 $MtCO_2$ by 2030 (Jiménez and Pineda 2022), while a more ambitious standard could have achieved up to 19.5 $MtCO_2$ by 2030 (Iniciativa Climática de México 2022).

Republic of Korea: In April 2023, the Government of the Republic of Korea released its National Basic Plan for Carbon Neutrality and Green Growth (the Basic Plan) (Republic of Korea, Climate Change Strategy Division 2023). The new plan reaffirmed the Republic of Korea's commitment to carbon neutrality by 2050 and a 40 per cent reduction of GHG emissions below 2018 levels by 2030. The plan introduces 12 measures to realize carbon neutrality, including making the most of domestically available low-carbon energy sources and transitioning to low-carbon industry structure and circular economy. In line with the tenor of the Basic Plan, several sectoral targets in the national 2030 scenario were revised (for power generation and industry, among others). Among the major changes are an increased role of nuclear energy in power generation mix and expanded use of overseas carbon offset programmes.

South Africa: In response to the supply pressure facing the state-owned utility Eskom, South Africa opened the electricity market in 2022, enabling generation at large-scale for own-use or sale to others. The pipeline of new privately developed generation is significant, especially considering new wind and solar. A total of 33 GW of variable renewable energy and batteries either has approval or is in the process of applying for environmental licencing (i.e. is relatively advanced). Overall, there are 66 GW of new wind, solar, battery and gas projects under development, albeit at varying stages of project development and certainty, up to 2028 (Eskom, South African Photovoltaic Industry Association and South African Wind Energy Association 2023). This constitutes a major projected increase compared to the 6 GW of renewable installed capacity operational in 2022. The uptake is driven largely by supply insecurity and declining costs – exemplified in recent auctions where the average cost of the portfolio, across technologies, was approximately US$0.026 per kilowatt-hour, similar to Eskom's coal plant fuel costs (Independent Power Producers Office 2023). South Africa's Just Energy Transition Investment Plan, which supports South Africa's transition away from coal and towards clean energy with US$8.5 billion, is the first of its kind and if successful, can lead the way to similar partnerships. But its success depends on the partners spelling out the exact detail of what they are offering and how the local political dynamics can be overcome.

United Kingdom: The United Kingdom Government made a U-turn on climate policies in September 2023 and announced the country is to delay in phasing out new petrol and diesel cars, to delay in phasing out gas boilers and to eliminate the requirement for landlords to improve the energy efficiency of their homes, among other measures. This undermines progress made, for example, on emissions standards for cars and in heavy industry. As a response, the United Kingdom's Climate Change Committee (the national scientific oversight body) remains "concerned about the likelihood of achieving the United Kingdom's future targets, especially the substantial policy gap to the United Kingdom's 2030 goal" (Dooks 2023).

3.4 Developments in long-term and net-zero pledges: The number continues to increase, but confidence in their implementation remains low

3.4.1 The number of net-zero targets has inched upwards

As at 25 September 2023, 97 parties representing 101 countries and covering approximately 82 per cent of global GHG emissions had adopted net-zero pledges either in law (27 parties), in a policy document such as an NDC or a long-term strategy (54 parties), or in an announcement by a high-level government official (16 parties).[8] This is up from 88 parties as at last year's report. An additional nine parties covering an additional 2 per cent of global GHG emissions have another (non-net zero) GHG mitigation target as part of their long-term strategy. A total of 37 per cent of global GHG emissions are covered by net-zero targets for 2050 or earlier, while 44 per cent of global emissions are covered by net-zero pledges for years later than 2050.

Net-zero targets vary in their scope, with some applying to all GHGs and sectors of the economy and others applying to a subset of sectors and gases. A total of 69 net-zero targets cover all sectors, while the remainder do not specify sectoral coverage. A total of 48 cover all gases, 11 cover fewer than all gases and 38 do not specify. The vast majority of countries with net-zero targets fail to specify whether their targets cover international shipping and aviation, and whether they permit the use of international offsets.

Likewise, few net-zero strategies yet clarify the role of CO_2 removal in achieving their net-zero targets, with only

8 These figures do not count parties where net-zero pledges are under discussion but do not yet take one of the forms listed above.

six countries having set separate goals for emissions and removals. These countries are Australia, Colombia, Slovakia, Slovenia, Spain and Sweden, and together account for less than 3 per cent of global emissions. Long-term strategies, likewise, contain limited detail on the role of CO_2 removal in counterbalancing residual emissions (Buck *et al.* 2023; Lebling, Schumer and Riedl 2023).

3.4.2 Overall, confidence in the implementation of G20 members' net-zero pledges remains low

Responsible for three quarters of current global emissions, G20 members will have an outsized impact on when global emissions reach net zero. Encouragingly, all G20 members except Mexico have set net-zero targets, and since the 2022 Emissions Gap Report, some members have taken important steps towards strengthening and implementing their targets. Argentina and India, for example, communicated long-term low-emissions development strategies, formalizing their previously announced targets.

Overall, however, limited progress has been made on key indicators of confidence in net-zero implementation, including legal status, the existence and quality of implementation plans, and alignment of near-term emission trajectories with net-zero targets (Rogelj *et al.* 2023). Nine G20 members have legally binding net-zero targets – the same as last year. Implementation planning has seen further progress, with 10 G20 members now having published an implementation plan, counting new or more detailed plans from the Republic of Korea and Türkiye. A majority of these plans, however, still lack concrete details and milestones to guide implementation at a granular level. Most concerningly, no G20 members are currently reducing emissions at a pace consistent with net-zero scenarios in the published literature. Reflecting the principle of common but differentiated responsibilities and respective capabilities, some countries will need more time than others to align their emissions trajectories with their net-zero targets. Most countries' long-term strategies and other net-zero plans do not robustly justify their targets in light of fairness and equity. The Paris Agreement recognizes that peaking emissions – a prerequisite to aligning emissions trajectories with net zero – will take longer for developing countries. For those countries that have peaked emissions, it will be necessary to accelerate reductions to match net-zero trajectories. For those countries that have not yet peaked emissions, it will be especially important to develop clear plans to peak and then align emissions with net-zero trajectories.

Table 3.4 presents a meta-analysis of key characteristics of G20 members' net-zero targets, based on three independent trackers (Climate Action Tracker 2022b; Climate Watch 2023; Net Zero Tracker 2023). The indicators and criteria by which they are assessed are as follows:

- **Source:** Refers to whether the net-zero target is established in law, in a policy document (including an NDC or a long-term strategy), or via a political announcement or pledge, such as those made at the 2020 Climate Ambition Summit.
- **Target year:** Refers to the year by which the source indicates net-zero emissions will be achieved.
- **Covers all sectors and gases:** Receives green checkmark if the source specifies that the target applies to all economic sectors (as opposed to, for example, the energy sector only) as well as all Kyoto greenhouse gases.
- **Transparent information on carbon removal:** Receives green checkmark if the source contains transparent assumptions for both domestic LULUCF and domestic removals and storage; receives yellow checkmark if source contains information on domestic LULUCF, removals and storage, but assumptions are not transparent.
- **Published plan:** Receives green checkmark if source meets all Climate Action Tracker and Net Zero Tracker criteria for information on anticipated pathway or measures for achieving net-zero target, and a yellow checkmark if source meets some, but not all, criteria.[9]
- **Review process:** Receives a green checkmark if source establishes a legally binding process to review progress against the target at regular intervals; receives a yellow checkmark if the process is not legally binding, is still being established, or lacks detail or tracking of progress.
- **Annual reporting:** Receives a green checkmark if source establishes a process to report at least annually on progress towards the target.

All indicators receive an "X" if the criteria for either a green or yellow checkmark are not met, a question mark where no information is available, an "inconclusive" if the data sources reach differing conclusions regarding the indicator and a "no data" if none of the data sources track the indicator for the G20 member. The European Union is evaluated according to its long-term strategy, while individual European Union Member States are evaluated according to the laws, policies and plans specific to the respective States. Further detail on the methods underlying each indicator can be found at Climate Action Tracker, Climate Watch and Net Zero Tracker.

A number of overall conclusions can be drawn from this chapter. While G20 members are making collective progress towards achieving the NDC targets with policy

9 The yellow category is new for this year's report. According to the 2022 coding criteria, the yellow checkmarks would have been green.

implementation, there is wide variation and the speed of progress needs to be accelerated. Few countries have responded to the calls of the COP 27 decision, the COP 28 presidency and the recently published synthesis report from the technical dialogue of the global stocktake process (UNFCCC 2023b) to put forward more ambitious NDCs for 2030. As the next chapter shows, this results in a large emissions gap in 2030. Relentlessly strengthening implementation is key to go beyond the existing 2030 targets, open the way for more ambitious targets for both 2030 and 2035, and ultimately achieve long-term net-zero goals.

Table 3.4 Key characteristics of G20 members' net-zero targets

Sources: Climate Action Tracker 2022b, Climate Watch 2023; Net Zero Tracker 2023.

Countries	Source	Target year	Covers all sectors and gases	Transparent information on carbon removal	Published plan	Review process	Annual reporting
High-income G20 members							
Australia	law	2050	Fulfilled	Partially fulfilled	inconclusive	Partially fulfilled	Fulfilled
Canada	law	2050	Fulfilled	Partially fulfilled	Partially fulfilled	Fulfilled	Fulfilled
European Union	law	2050	Fulfilled	Fulfilled	Fulfilled	Fulfilled	Fulfilled
France	law	2050	Fulfilled	Partially fulfilled	Fulfilled	Fulfilled	Fulfilled
Germany	law	2045	Fulfilled	Partially fulfilled	inconclusive	Fulfilled	Fulfilled
Italy	policy	2050	Fulfilled	Partially fulfilled	Partially fulfilled	not evaluated	Fulfilled
Japan	law	2050	Fulfilled	Not fulfilled	inconclusive	Fulfilled	Fulfilled
Republic of Korea	law	2050	No information	Fulfilled	inconclusive	Partially fulfilled	Fulfilled
Saudi Arabia	announcement	2060	No information	Not fulfilled	Not fulfilled	No information	Not fulfilled
United Kingdom	law	2050	Fulfilled	Fulfilled	Fulfilled	Fulfilled	Fulfilled
United States of America	policy	2050	Fulfilled	Fulfilled	Partially fulfilled	Partially fulfilled	Fulfilled
Lower- and upper-middle-income G20 members							
Argentina	policy	2050	Fulfilled	Not fulfilled	Not fulfilled	No information	Not fulfilled
Brazil	policy	2050	No information	Not fulfilled	Not fulfilled	No information	Not fulfilled
China	policy	2060	No information	Not fulfilled	Partially fulfilled	Partially fulfilled	Not fulfilled
India	policy	2070	No information	Not fulfilled	Not fulfilled	No information	Not fulfilled
Indonesia	policy	2060	Not fulfilled	Not fulfilled	inconclusive	No information	Not fulfilled
Mexico	no net-zero target						
Russian Federation	law	2060	Fulfilled	Partially fulfilled	Partially fulfilled	Partially fulfilled	Not fulfilled
South Africa	policy	2050	Not fulfilled	Not fulfilled	Not fulfilled	No information	Not fulfilled
Türkiye	policy	2053	No information	Not fulfilled	Partially fulfilled	No information	Not fulfilled

Fulfilled · Partially fulfilled · Not fulfilled · No information

4 The emissions gap in 2030 and beyond

Lead authors:

Joeri Rogelj (Imperial College London, United Kingdom; International Institute for Applied Systems Analysis [IIASA], Austria), Michel den Elzen (PBL Netherlands Environmental Assessment Agency, the Netherlands) and Joana Portugal-Pereira (Graduate School of Engineering, Universidade Federal do Rio de Janeiro, Brazil)

Contributing authors:

Taryn Fransen (World Resources Institute, United States of America), Jarmo Kikstra (Imperial College London, United Kingdom), Robin Lamboll (Imperial College London, United Kingdom), Malte Meinshausen (University of Melbourne, Australia) and Isabela Tagomori (PBL Netherlands Environmental Assessment Agency, the Netherlands)

Data contributors:

Ioannis Dafnomilis (PBL Netherlands Environmental Assessment Agency, the Netherlands) and Kimon Keramidas (European Commission, Joint Research Centre, Spain)

4.1 Introduction

This chapter provides an updated assessment of the emissions gap, which is the difference between the estimated global greenhouse gas (GHG) emissions resulting from the full implementation of the latest country pledges, and those under least-cost pathways aligned with the Paris Agreement's long-term temperature goal to limit the global average temperature increase to well below 2°C, while pursuing efforts to limit it to 1.5°C compared with pre-industrial levels. Put simply, the emissions gap represents the discrepancy between pledged GHG emission reductions and the reductions required to align with the Paris Agreement. This chapter also assesses the discrepancy between pledged GHG emission reductions and those associated with current policies or a continuation thereof. This is referred to as the implementation gap.

This year's assessment is particularly relevant as 2023 marks the conclusion of the first global stocktake. To inform the stocktake and the next round of nationally determined contributions (NDCs) to be put forward by 2025 (which should include emission reduction targets for 2035), this update addresses the following questions:

- What is the emissions gap in 2030 under the latest NDCs and various policy assumptions?
- What are the implications for the emissions gap in 2035 and for the global level of ambition required in the next round of NDCs?
- What are the implications of delayed stringent mitigation action for the emissions gap and global warming over the century?

The scenarios that form the basis for assessing the emissions gap are described in section 4.2, with a summary of the implications of delayed mitigation action provided in section 4.3. The assessment of the emissions gap in 2030 and beyond is presented in section 4.4, while section 4.5 assesses the implications for global temperature projections.

4.2 A set of scenarios is needed to assess the emissions gap and global temperature outcomes

The emissions gap assessment draws on a set of scenarios (table 4.1) that are updated in this section. These scenarios are organized into four categories: a current policies reference scenario, NDC scenarios, mid-century scenarios and least-cost mitigation scenarios starting in 2020 and aligned with specific temperature limits. These scenarios form the basis for estimating the emissions gap in 2030 and the global temperature outcomes in section 4.5.

It is worth noting that emissions projections, especially beyond 2030, rely on the assumptions and choices of modelling teams in how to interpret scenarios in the longer term.

Table 4.1 Summary of scenarios selected for the emissions gap assessment

Category	Scenario cases	Cut-off year	Scenario description
Reference scenario	Current policies	2022	This scenario projects the GHG implications of climate mitigation policies that have been adopted and implemented as at November 2022, including the short-term and midterm socioeconomic impacts of COVID-19. Where necessary, these implications have been adjusted to account for the impact of recent policies, such as the Inflation Reduction Act of the United States of America.
NDC scenarios	Unconditional NDCs	2023	This scenario projects the GHG implications of the full implementation of the most recent NDCs that do not depend on explicit external support (cut-off date: 25 September 2023). When extended beyond 2030, the scenario assumes a continuation of efforts at a similar level of ambition.
	Conditional NDCs	2023	Additional to the unconditional NDCs, this scenario encompasses the most recent NDC targets for which implementation is contingent on receiving international support, such as finance, technology transfer and/or capacity-building (cut-off date: November 2022). When extended beyond 2030, it assumes a continuation of efforts at a similar level of ambition.
Mid-century scenarios	Current policies continuing	2022	This scenario projects GHG implications per the current policies scenario and assumes mitigation policies continue similar reduction efforts when extended beyond 2030 (see appendix C.1).
	Unconditional NDCs plus net-zero pledges using strict criteria	2022	This scenario assumes an extension of the unconditional NDC scenario plus net-zero pledges (including those made in long-term low emissions development strategies) after 2030 that live up to strict criteria regarding the comprehensiveness of implementation plans and current emission trajectories (see also appendix C.1).
	Conditional NDCs plus all net-zero pledges	2022	This is the most optimistic scenario included. It assumes the achievement of the conditional NDC scenario until 2030 and all net-zero or other long-term low emissions development strategy pledges thereafter.
Mitigation scenarios consistent with limiting global warming to specific levels	Below 2°C	N/A	A least-cost pathway starting from 2020 and consistent with keeping global warming below 2°C throughout the twenty-first century with at least a 66 per cent chance.
	Below 1.8°C	N/A	A least-cost pathway starting from 2020 and consistent with keeping global warming below 1.8°C throughout the twenty-first century with at least a 66 per cent chance.
	Below 1.5°C	N/A	A least-cost pathway starting from 2020 and ensuring that global warming is kept below 1.5°C with at least a 33 per cent chance throughout the entire century and is brought below 1.5°C with at least a 50 per cent chance by 2100. This pathway reaches net-zero GHG emissions in the second half of the century.

Note: Details are available in the subsequent sections and in table C.1 in appendix C.

4.2.1 The current policies scenario is a reference scenario

The current policies scenario projects global GHG emissions based on the assumption that currently adopted and implemented policies (defined as legislative decisions, executive orders or equivalent) are achieved but with no further measures undertaken since 2022. Typically, selected policies are based on literature research, input from the Climate Policy Database (NewClimate Institute 2023) and country expert reviews of the policies identified, and are then implemented in global models following a detailed protocol, which is continuously updated and builds on the work of Roelfsema *et al.* (2020; 2022). The data for this scenario are based on the four modelling estimates that underpin the current policies assessment of the Intergovernmental Panel on Climate Change Working Group III *Sixth Assessment Report* (IPCC WGIII AR6) (Lecocq *et al.* 2022), and have been updated by the respective research teams. These data updates use a policy cut-off date of November 2022 and apply the most recent AR6 global warming potentials over 100 years (Riahi *et al.* 2021; Climate Action Tracker 2022; den Elzen *et al.* 2022; Keramidas *et al.* 2022; Nascimento *et al.* 2022; den Elzen *et al.* 2023; Schmidt Tagomori, Hooijschuur and Muyasyaroh 2023; van Ruijven *et al.* 2023). The scenario considers the effects of the COVID-19 pandemic and the impact of recent policies, such as the expected emission reductions from the Inflation Reduction Act introduced in the United States of America. The scenarios do not include the impact of the energy crisis and the war in Ukraine on energy flows and related emission levels. The resulting median estimate of global GHG emissions in 2030 and 2035 under current policies is 56 gigatons of carbon dioxide equivalent ($GtCO_2e$) (range: 52–60 $GtCO_2e$) and 57 $GtCO_2e$ (range: 46–61 $GtCO_2e$), respectively (see table C.4 in appendix C). The median 2030 estimate is about 1.5 $GtCO_2e$ lower than the median estimate of the Emissions Gap Report 2022, which is due to multiple factors, including updated polices first and foremost, but also latest emission trends, socioeconomic projections and methodological updates. In line with the findings on the emission trends of G20 members (see chapter 3), the current policies projections have shown a flattening trend since 2019, and are now significantly lower than those at the time of the Paris Agreement's adoption (United Nations Environment Programme [UNEP] 2015), which indicated that 2030 emissions would increase by 16 per cent.

4.2.2 NDC scenarios project emissions based on the full achievement of NDCs

The NDC scenarios project global GHG emissions based on the full achievement of the latest unconditional and conditional NDCS submitted by Parties to the United Nations Framework Convention on Climate Change (UNFCCC). The estimates are derived using an approach similar to that used in Lecocq *et al.* (2022) and reflect the latest updates available as at November 2022. The scenarios are based on findings from four modelling exercises: Climate Action Tracker (2022), Keramidas *et al.* (2022), den Elzen *et al.* (2023) and Meinshausen *et al.* (2023). The unconditional and conditional NDC scenario estimates result in median global GHG emissions in 2030 of 55 $GtCO_2e$ (range: 54–57 $GtCO_2e$) and 52 $GtCO_2e$ (range: 50–55 $GtCO_2e$), respectively (see table 4.3; further information is provided in appendix C). The ranges mainly stem from uncertainty in socioeconomic baselines and current policies projections, as well as uncertainty from the conditionality or range of NDC targets (den Elzen *et al.* 2023). The projected emissions in 2030 assuming the full achievement of NDCs are similar to the median estimates of the Emissions Gap Report 2022 (UNEP 2022).

4.2.3 Mid-century scenarios are subject to much larger uncertainty

The mid-century scenarios describe how GHG emission trajectories might evolve in the longer term. Since GHG projections to mid-century are subject to much larger policy uncertainty than projections to 2030, three scenarios are presented to reflect the range of possible outcomes. The least ambitious mid-century scenario involves a simple extension of current policies continuing at the current level of climate policy effort after 2030. The most optimistic scenario assumes the full achievement of all conditional NDCs and all net-zero pledges, including those made as part of long-term low emissions development strategies and announced by 25 September 2023. Finally, a scenario that uses the unconditional NDC scenario as a base and also includes net-zero pledges that fulfil strict criteria on operationalization and implementation progress is considered.

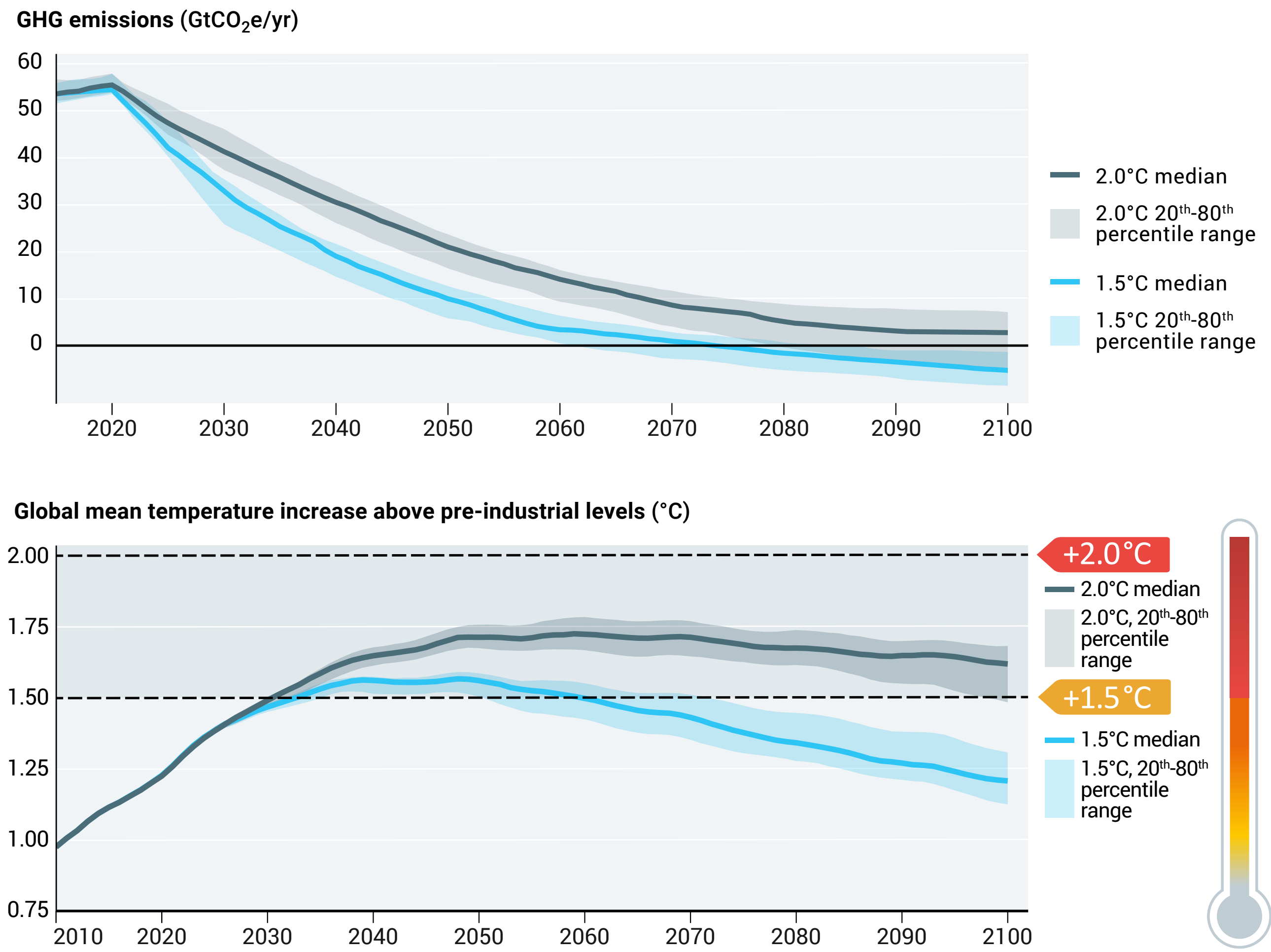
The assessment of progress towards net-zero pledges is based on a set of criteria as defined in Rogelj *et al.* (2023): (i) whether the long-term target is legally binding; (ii) whether a credible policy plan has been published supporting its implementation; and (iii) whether short-term emissions under current policies are on a downward path over the next decade (at least 10 per cent below 2019 levels) (for further information, see appendix C). Only net-zero pledges that live up to the second and third criteria on credible policy plans and downward emission trajectories are considered in the scenario based on unconditional NDCs plus net-zero pledges that comply with strict criteria. Relatively few net-zero pledges fulfil these two criteria, with those made by New Zealand, the United States of America and the European Union among the few that do (see table 3.4 in chapter 3). Currently, more than 80 per cent of global emissions are not covered by long-term pledges that fulfil these criteria (see table C.4 in appendix C). It is important to note that compliance with the strict operationalization and implementation criteria does not necessarily mean that the net-zero pledges will be achieved. As chapter 3 (section 3.4) illustrates, all countries need to enhance the operationalization and implementation of their net-zero pledges to increase their credibility and feasibility. Similarly, it should be noted that non-compliance with these criteria does not imply that net-zero pledges cannot be achieved or that progress is not being made. Rather, it reflects that some countries are further along with operationalizing and implementing their net-zero pledges than others.

Emissions projections for all mid-century scenarios are provided in appendix C (table C.5), including a comparison with the ranges from the corresponding four individual modelling studies used for the current policies and NDC scenarios (Climate Action Tracker 2022; Keramidas *et al.* 2022; Dafnomilis den Elzen and van Vuuren 2023; van Ruijven *et al.* 2023).

4.2.4 Mitigation scenarios that keep warming below specified temperature limits

This category of scenarios reflects least-cost mitigation pathways starting in 2020 for different global warming outcomes relative to pre-industrial levels over the course of this century. Consistent with previous Emissions Gap Reports, three scenarios have been chosen to represent warming limits relevant in the context of the Paris Agreement's long-term temperature goal, 2°C, 1.8°C and 1.5°C, noting that these limits are not intended to offer a specific interpretation of the goal. The GHG emissions of the scenarios were drawn from the IPCC WGIII AR6 scenario database (Byers *et al.* 2022; Riahi *et al.* 2022) and grouped according to characteristics as described in table 4.1. Their corresponding temperature projections are based on IPCC WGI AR6 (Nicholls *et al.* 2021; Kikstra *et al.* 2022; Smith 2023) and are consistent with recent updates to the remaining carbon budget (Forster *et al.* 2023). Table 4.2 provides an overview of the scenarios' emissions and temperature characteristics. The no or limited overshoot pathways in the 1.5°C category have at least a 33 per cent chance of keeping warming below 1.5°C over the course of the entire century, and at least a 50 per cent chance of doing so by 2100.[1] In many cases, median warming under these scenarios will temporarily reach and exceed 1.5°C of global warming as part of projected temperature developments (figure 4.1). As figure 4.2 shows, pathways in the 1.5°C category achieve net-negative GHG emissions in the second half of the century through the use of carbon dioxide removal (see chapter 7).

Figure 4.1 Global GHG emissions and corresponding median temperature projections of 1.5°C and 2°C scenarios



Notes: The ranges show the twentieth to eightieth percentile range across each category's scenarios. GHG emissions are aggregated using AR6 global warming potentials over 100 years. The thick lines in each range represent the category median.

1 The global warming characteristics for the 1.5°C pathways are chosen to be consistent with category C1a from the IPCC AR6 Working Group 3 assessment. The 2022 edition of the Emissions Gap Report also applied a 33 per cent of limiting warming to 1.5°C over the entire century, but a 66 per cent chance of limiting warming below 1.5°C in 2100. Until mid-century, this change results in no or little difference in projected emission levels, as these are constrained by the minimum 33 per cent chance limit. Achieving a higher chance in 2100 relies on realizing net-negative emissions in the second half of the century through the use of carbon dioxide removal (see chapter 7).

Table 4.2 Global GHG emissions in 2030, 2035 and 2050, and global warming characteristics of least-cost pathways starting in 2020 consistent with specific temperature limits

Least-cost pathways consistent with limiting global warming to specific levels	Number of scenarios	Global total GHG emissions ($GtCO_2e$)			Estimated temperature outcomes			
		In 2030	In 2035	In 2050	50% chance	66% chance	90% chance	Closest IPCC WGIII AR6 scenario class
Below 2°C (66% chance throughout the century)	195	41 (37–46)	36 (31–39)	20 (16–24)	Peak: 1.7–1.8°C In 2100: 1.4–1.7°C	**Peak:** **1.8–1.9°C** **In 2100:** **1.6–1.9°C**	Peak: 2.2–2.4°C In 2100: 2–2.4°C	C3a
Below 1.8°C (66% chance throughout the century)	139	35 (28–41)	27 (21–31)	12 (8–16)	Peak: 1.5–1.7°C In 2100: 1.3–1.6°C	**Peak:** **1.6–1.8°C** **In 2100:** **1.4–1.7°C**	Peak: 1.9°C–2.2°C In 2100: 1.8–2.2°C	N/A
Below 1.5°C (50% chance in 2100 and minimum 33% chance throughout the century)	50	33 (26–34)	25 (20–27)	8 (5–13)	Peak: 1.5–1.6°C In 2100: 1.1–1-3°C	**Peak:** **1.6–1.7°C** **In 2100:** **1.2–1.5°C**	Peak: 1.9–2.1°C In 2100: 1.6–1.9°C	C1a

* Values represent the median and twentieth to eightieth percentile range across scenarios. The likelihood levels refer to peak warming at any time during the twenty-first century for the below 1.8°C and below 2°C scenarios. When achieving net-negative carbon dioxide (CO_2) emissions in the second half of the century, global warming can be further reduced from these peak warming characteristics, as illustrated by the 'Estimated temperature outcomes' columns. For the below 1.5°C scenario, the likelihood applies to the global warming level in 2100, while the 'no or limited overshoot' characteristic is captured by ensuring that the lowest likelihood of warming being limited to 1.5°C throughout the twenty-first century is never less than 33 per cent. This definition is similar to the C1a category definition of IPCC WGIII AR6. The Emissions Gap Report analysis uses scenarios that assume immediate action from 2020 onward.

Note: GHG emissions in this table have been aggregated using IPCC AR6 global warming potentials over 100 years.

Source: Based on underlying data from Byers *et al.* (2022) and Riahi *et al.* (2022).

4.3 Pathways matter for the carbon budget, the interpretation of emissions gaps and the chance of achieving the Paris Agreement's temperature goal

Global warming is almost linearly proportional to the total net amount of CO_2 that has ever been emitted into the atmosphere from human activities. Limiting global warming to a specified level therefore requires the total amount of CO_2 emissions ever emitted to be kept within a finite carbon budget (Canadell *et al.* 2021). Until global CO_2 emissions reach net-zero levels, the carbon budget will continue to be depleted with each passing year. IPCC AR6 reported remaining carbon budgets of 500 $GtCO_2$ for a 50 per cent chance of limiting global warming to 1.5°C from 2020 onward, and 1,150 $GtCO_2$ for a 67 per cent chance of limiting warming to 2°C (Canadell *et al.* 2021). A recent update that considers further warming until 2022 shows a reduction of these budgets to 250 $GtCO_2$ from 2023 onward for a 50 per cent chance of limiting warming to 1.5°C and 950 $GtCO_2$ for a 67 per cent chance of limiting warming to below 2°C.

These values can be compared with the cumulative CO_2 emissions implied by the current policies and NDC scenarios. Under current policies, the carbon budget for a 50 per cent chance of limiting warming to 1.5°C is expected to clearly be exceeded by 2030. Even the budget for a 66 per cent chance of limiting warming to 2°C is expected to be reduced by more than a third by 2030, leaving very little room for warming to be kept well below 2°C if emissions continue at current rates.

This highlights the importance of the pathways followed to reach net-zero CO_2 emissions. As figure 4.1 and table 4.1 show, the 1.5°C and 2°C pathways assume stringent emission reductions from 2020, which current trends contradict, resulting in implications for the achievability of significant reductions by 2030. Emissions are now higher than in 2020, which implies a commitment to slightly higher global warming than the least-cost pathways indicate, unless there is further acceleration of emission reductions after emissions levels consistent with the least-cost pathways are met. The emissions gap estimates are therefore likely to be a lower bound as they do not account for the excess emissions since 2020 compared with the least-cost pathways.

The emissions gap estimates in section 4.4 should be read with this caveat in mind, while section 4.5 shows that following a delayed path compared with 1.5°C and 2°C pathways is associated with higher warming and a lower likelihood of achieving the Paris Agreement's long-term temperature goal.

4.4 The emissions gap in 2030 and 2035 must be bridged through action in this decade

This section provides an updated assessment of the emissions gap in 2030 based on the scenarios described in section 4.2, findings on the global level of ambition needed in the next round of NDCs (which will contain targets for 2035) and implications for emissions by 2050.

Action in this decade will not only determine the ambition required in the next round of NDCs, but also the feasibility of achieving the Paris Agreement's long-term temperature goal. Unless current NDC targets are over-complied with globally, it will become impossible to limit warming to 1.5°C with no or limited overshoot, and strongly increase the challenge of limiting warming to well below 2°C. Furthermore, the feasibility and credibility of net-zero emission pledges must be enhanced.

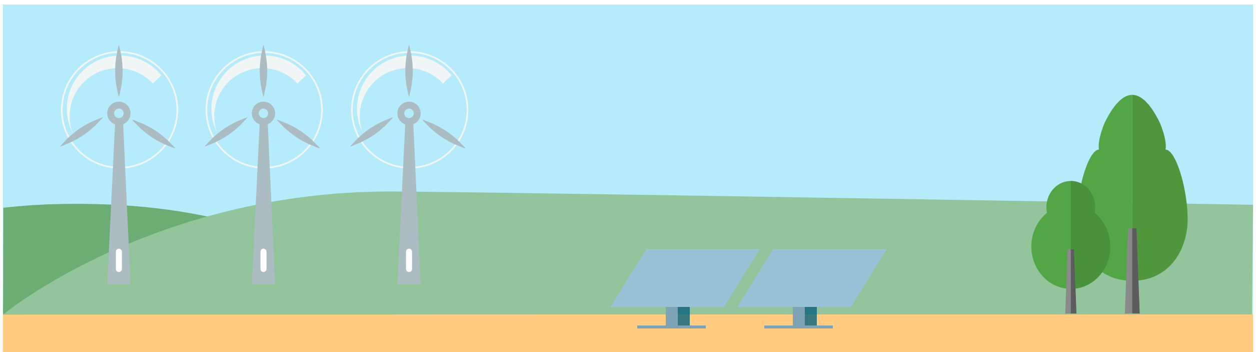
4.4.1 The emissions gap in 2030 remains significant

The emissions gap for 2030 is defined as the difference between the estimated total global GHG emissions resulting from the full implementation of NDCs and the total global GHG emissions from least-cost scenarios that keep global warming to 2°C, 1.8°C or 1.5°C, with varying levels of likelihood. As noted in section 4.3, this is an underestimate as it does not account for excess emissions since 2020 compared with the least-cost pathways.

Figure 4.2 shows the emissions gap in 2030, with table 4.3 providing further information. Current NDCs remain highly insufficient to bridge the emissions gap in 2030. Full implementation of unconditional and conditional NDCs for 2030 reduces expected emissions in 2030 under current policies by only 2 per cent and 9 per cent, respectively, whereas 28 per cent and 42 per cent is needed for 2°C or 1.5°C, respectively (table 4.2 and table 4.3). These estimates are two percentage points lower than the 2022 assessment, illustrating the progress in narrowing the implementation gap (defined as the difference between projected emissions under current policies and projected emissions under the full implementation of NDCs) (chapter 3). This difference is now around 1.5 $GtCO_2e$ for unconditional NDCs (down from 3 $GtCO_2e$ in the 2022 assessment) and 5 $GtCO_2e$ for conditional NDCs (down from 6 $GtCO_2e$ in the 2022 assessment) in 2030.[2] Nonetheless, unprecedented annual emission cuts are required from now to 2030 to achieve the reductions required.

Full implementation of the latest unconditional NDCs is estimated to result in an 1.5°C emissions gap of 22 $GtCO_2e$ (range: 21–24 $GtCO_2e$) with at least a 66 per cent chance (table 4.3 and figure 4.2). If conditional NDCs are also fully implemented, the 1.5°C emissions gap reduces to 19 $GtCO_2e$ (range: 17–23 $GtCO_2e$). The emissions gap for the below 2°C pathways is about 14 $GtCO_2e$ (range: 13–16 $GtCO_2e$), assuming the full implementation of unconditional NDCs. If conditional NDCs are also fully implemented, the below 2°C emissions gap reduces to 11 $GtCO_2e$ (range: 9–15 $GtCO_2e$). These figures remain largely unchanged compared with the 2022 assessment, with some small differences due to rounding.

In conclusion, immediate and unprecedented mitigation action is needed in this decade to reduce total global GHG emissions compared with levels implied by the current NDCs, and to ultimately narrow the emissions gap.



2 These estimates are based on original, unrounded scenario figures and therefore differ from those that can be derived from table 4.3.

Figure 4.2 GHG emissions under different scenarios and the emissions gap in 2030 and 2035 (median estimate and tenth to ninetieth percentile range)

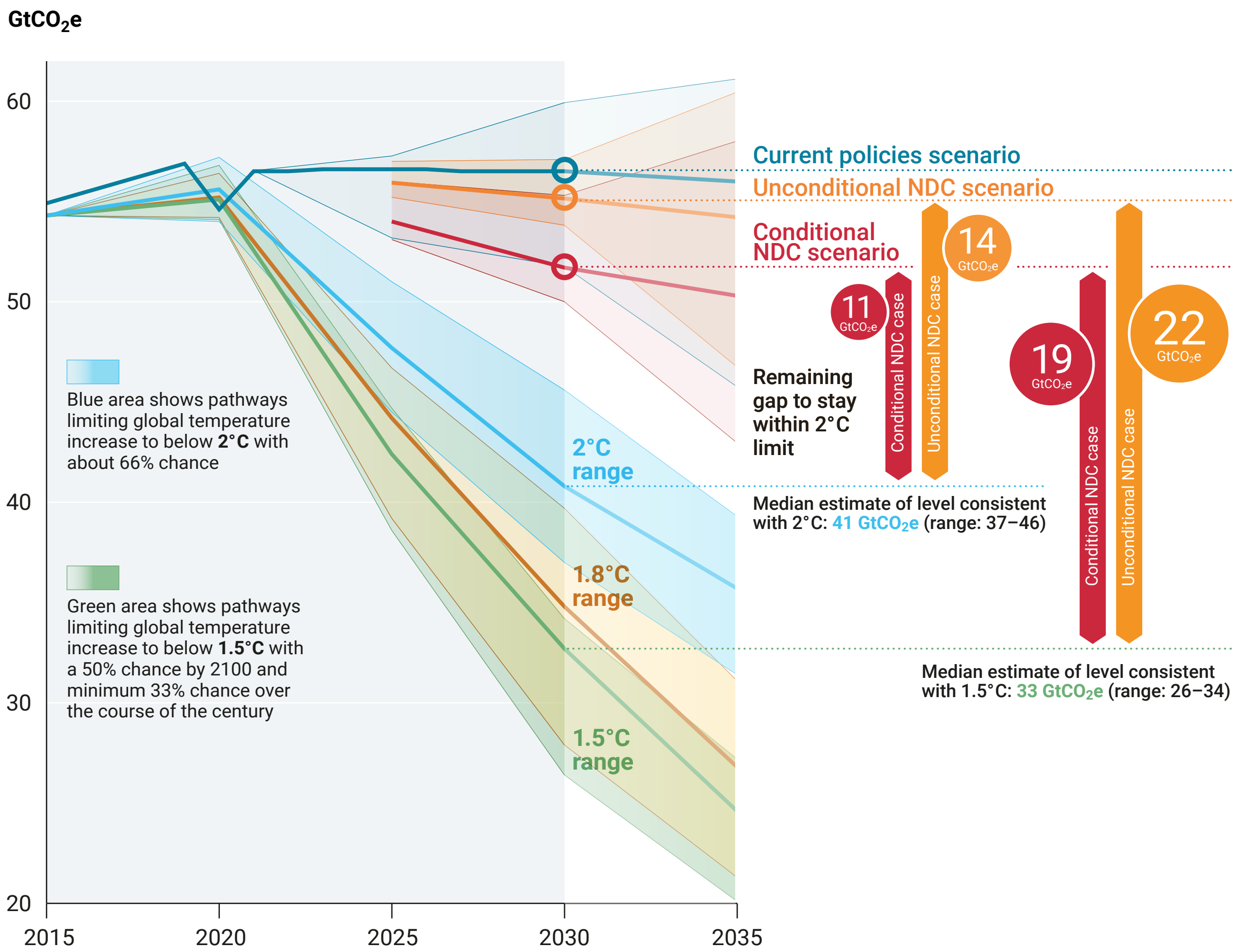


Table 4.3 Global total GHG emissions in 2030, 2035 and 2050, and estimated gaps under different scenarios

Scenario	GHG emissions ($GtCO_2e$)	Estimated gap to least-cost pathways consistent with limiting global warming to specific levels ($GtCO_2e$)		
	Median and range	Below 2°C	Below 1.8°C	Below 1.5°C
2030				
Current policies	56 (52–60)	16 (11–19)	22 (17–25)	24 (19–27)
Unconditional NDCs	55 (54–57)	14 (13–16)	20 (19–22)	22 (21–24)
Conditional NDCs	52 (50–55)	11 (9–15)	17 (15–20)	19 (17–23)
2035				
Current policies continued	56 (45–64)	20 (9–28)	29 (18–37)	31 (20–39)
Unconditional NDCs continued	54 (47–60)	18 (11–25)	27 (20–34)	29 (22–36)
Conditional NDCs continued	51 (43–58)	15 (8–22)	24 (17–31)	26 (19–33)
2050				
Current policies continued	55 (24–72)	35 (4–52)	43 (12–60)	46 (16–63)
Unconditional NDCs and net-zero pledges using strict criteria	44 (26–58)	24 (6–38)	32 (14–46)	36 (18–49)
Conditional NDCs and all net-zero pledges	21 (6–33)	1 (-14–13)	9 (-6–21)	12 (-2–25)

Notes: The GHG emission ranges for 2035 and 2050 show the minimum–maximum range across different projection-model assumptions, including 2030 current policy/NDC assessment uncertainty (see appendix C). The gap figures and ranges are calculated based on the original figures (without rounding), which may differ from the rounded figures in the table. Figures are rounded to full $GtCO_2e$. GHG emissions have been aggregated using IPCC AR6 global warming potentials over 100 years.

4.4.2 Action in this decade will determine the ambition required in the next round of NDCs and the emissions gap for 2035

The first global stocktake under the Paris Agreement, which will conclude at the twenty-eighth session of the Conference of the Parties to the UNFCCC (COP 28), is envisaged to inform the next round of NDCs (with targets for 2035) that countries are requested to submit by 2025. Although there are no pledges for 2035 yet to enable an estimation of the emissions gap for 2035, it is possible to provide information about the global level of ambition that will be required in the next round of NDCs.

Overall, global ambition in the next round of NDCs must be sufficient to bring global GHG emissions in 2035 to levels consistent with the below 2°C and 1.5°C pathways. These are 36 $GtCO_2e$ (range: 31–39 $GtCO_2e$) and 25 $GtCO_2e$ (range: 20–27 $GtCO_2e$), respectively (table 4.2).

In contrast, a continuation of current policies and current NDC scenarios would result in widened and likely unbridgeable gaps in 2035 (table 4.3). A continuation of current policies is projected to result in global GHG emissions of 56 $GtCO_2e$ in 2035, which is 36 per cent and 55 per cent higher than the levels consistent with below 2°C and 1.5°C pathways, respectively, even without compensating for excess emissions.

Again, these findings imply that immediate and unprecedented mitigation action in this decade is essential. Overcompliance of NDC targets for 2030 is not only necessary to maintain the possibility of limiting global warming to 1.5°C with no or limited overshoot, it will also enable countries to put forward more ambitious mitigation targets for 2035 in their next NDCs and will make the achievement of such ambitious targets more feasible.

4.4.3 Looking beyond 2035 reinforces these findings and points to the essential need to enhance the credibility and feasibility of net-zero pledges

The mid-century scenarios allow for an exploration of developments later in this century (table 4.1 and table 4.3). Considering these scenarios strengthens the findings of the previous sections that action in this decade is critical, and also highlights the crucial importance of increasing the steps and policies that make the achievement of net-zero pledges more likely.

Total global GHG emissions in 2050 will only be brought closer to 1.5°C and 2°C pathways if conditional NDCs are fully implemented and combined with the achievement of all net-zero pledges. Again, this does not account for excess emissions under this scenario compared with the 1.5°C and 2°C pathways. Furthermore, and as table 4.3 illustrates, the uncertainties around GHG emissions and gap estimates are vast the further into the future projections are made.

4.5 The emissions gap has severe implications for global warming projections

The global failure to bridge the emissions gap to date has various consequences. This section provides the consequences for annual average global GHG emission reduction rates until 2030 consistent with limiting warming to 1.5°C or 2°C, and the global warming implications under the scenarios considered in this chapter.

4.5.1 Unprecedented annual emission cuts are required from now to 2030

The consequences of the continued delay in stringent emission reductions are evident when examining the past decade of Emissions Gap Reports. As highlighted in the Emissions Gap Report 2019 (UNEP 2019) the underlying data from the reports reveal that had serious climate action been initiated in 2010, the annual emission reductions necessary to achieve emission levels consistent with the below 2°C and 1.5°C scenarios by 2030 would have been only 0.7 per cent and 3.3 per cent on average, respectively (Höhne *et al.* 2020). The lack of stringent emission reductions means that the required emission cuts from now to 2030 have increased significantly. To reach emission levels consistent with a below 2°C pathway in 2030, the cuts required per year are now 5.3 per cent from 2024, reaching 8.7 per cent per year on average for the 1.5°C pathway. To compare, the fall in total global GHG emissions from 2019 to 2020 due to the COVID-19 pandemic was 4.7 per cent (UNEP 2022).

4.5.2 Temperature implications depend strongly on scenarios

Temperature implications of the emissions gap are estimated by projecting emissions over the twenty-first century and assessing their global warming implications with the Finite Amplitude Impulse Response (FaIR) reduced-complexity climate model, which is calibrated to the IPCC AR6 assessment (Nicholls *et al.* 2021; Kikstra *et al.* 2022; Smith 2023; see also section C.1 in appendix C). Projections until the end of the century are inherently uncertain and subject to scenario assumptions, such as the level at which climate action continues or technology costs. These uncertainties are reflected in the large ranges around the central warming projections indicated in table 4.4.

A continuation of the level of mitigation effort implied by global warming under the current policies scenario is projected to limit global warming to 3°C (range: 1.9–3.8°C)[3]

3 The range captures uncertainty in the near-term (2030) assessment of current policies, as well as the uncertainty in the continuation of policies over the course of the twenty-first century.

with a 66 per cent chance (table 4.4). A continuation of the unconditional NDC scenario lowers this estimate to 2.9°C (range: 2.0–3.7°C), whereas the additional achievement and continuation of conditional NDCs lowers this by around 0.4°C to 2.5°C (range: 1.9–3.6°C).

Table 4.4 Global warming projections under the scenarios assessed

Peak warming throughout the twenty-first century (°C)			
Scenario	**50% chance**	**66% chance**	**90% chance**
Current policies continuing	2.7°C (range: 1.8–3.5)	**3.0°C** (range: 1.9–3.8)	3.5°C (range: 2.3–4.5)
Unconditional NDCs continuing	2.6°C (range: 1.8–3.4)	**2.9°C** (range: 2.0–3.7)	3.4°C (range: 2.3–4.4)
Conditional NDCs continuing	2.3°C (range: 1.7–3.3)	**2.5°C** (range: 1.9–3.6)	3.0°C (range: 2.2–4.2)
Unconditional NDCs and net-zero pledges using strict criteria	2.5°C (range: 1.8–3.2)	**2.7°C** (range: 1.9–3.5)	3.2°C (range: 2.3–4.1)
Conditional NDCs and all net-zero pledges (most optimistic case)	1.8°C (range: 1.6–2.3)	**2.0°C** (range: 1.8–2.5)	2.4°C (range: 2.0–3.0)
Likelihood of limiting warming to below a specific warming limit (%)			
Scenario	**1.5°C**	**2°C**	**3°C**
Current policies continuing	0% (range: 0–16)	4% (range: 0–73)	68% (range: 16–99)
Unconditional NDCs continuing	0% (range: 0–12)	6% (range: 0–69)	75% (range: 24–99)
Conditional NDCs continuing	0% (range: 0–20)	19% (range: 0–78)	90% (range: 30–100)
Unconditional NDCs and net-zero pledges using strict criteria	0% (range: 0–16)	11% (range: 0–74)	83% (range: 42–99)
Conditional NDCs and all net-zero pledges (most optimistic case)	14% (range: 1–27)	69% (range: 22–85)	99% (range: 89–100)

Notes: The range between brackets reflects the scenario uncertainty, taking into account the range of emission estimates for 2030 and the variations in their extensions (see section C.1 in appendix C). The Emissions Gap Report typically presents temperature projections with a 66 per cent chance. Other likelihoods are included for completeness. Values for 2100 are given in table C.6 in appendix C.

Under the scenario where unconditional NDCs are combined with the net-zero pledges that currently comply with strict criteria on implementation progress, global warming is estimated to be limited to 2.7°C (range: 1.9–3.5°C) with a 66 per cent chance over the course of this century.

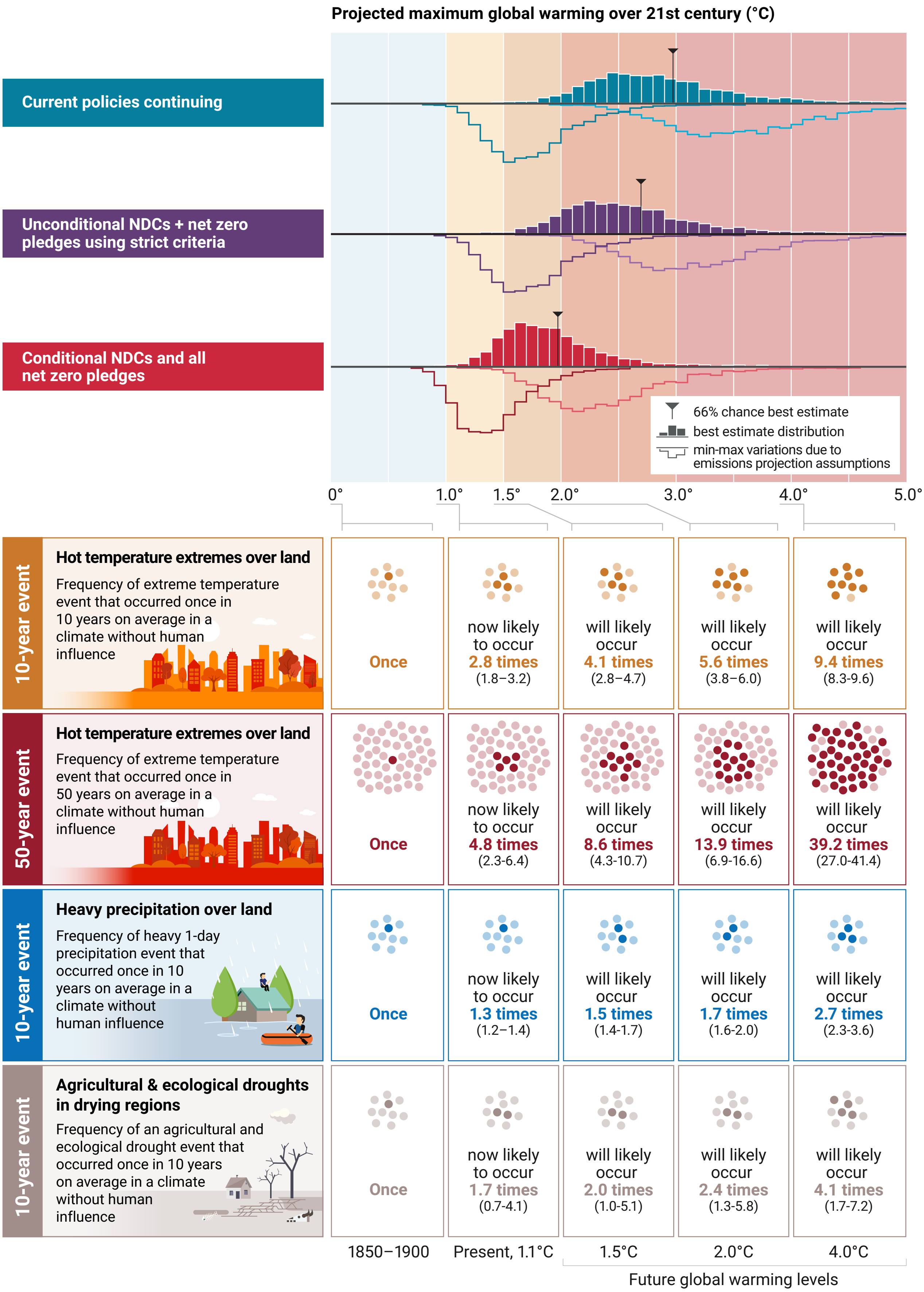
In the most optimistic scenario, where conditional NDCs and all net-zero pledges (including those specified in long-term low emissions development strategies) are assumed to be achieved, global warming is projected to be limited to 2°C (range: 1.8–2.5°C) with a 66 per cent chance over the course of this century. However, as chapter 3 shows, the achievement of net-zero pledges remains highly uncertain.

Values for other likelihoods and for 2100 are provided in table 4.4 and table C.6 in appendix C. Central temperature projections are slightly higher than in the Emissions Gap Report 2022, but uncertainty ranges strongly overlap.[4] This is because a larger number of models has been included in the estimation of future emissions for the 2023 assessment (see section C.1 in appendix C). The Emissions Gap Report's best estimated temperature projections are consistent with those from other major assessments, such as the 2023 Announced Pledges Scenario of the International Energy Agency, Climate Action Tracker and the 2023 UNFCCC NDC synthesis report (all of which report temperature projections with a 50 per cent chance).[5]

4 Current policies and unconditional and conditional NDC scenarios in the Emissions Gap Report 2022 were estimated to keep warming with a 66 per cent chance to 2.8°C (range: 1.9–3.3°C), 2.6°C (range: 1.9–3.1°C) and 2.4°C (range: 1.8–3.0°C), respectively. The most optimistic case, combining unconditional and conditional NDCs with all long-term net-zero targets, resulted in an estimate of 1.8°C (range: 1.7–1.9°C).

5 See appendix C and the joint technical note by UNFCCC and UNEP, both available online, for more detailed comparisons.

Figure 4.3 Temperature implications of key scenarios assessed in this chapter and the associated risks of extreme events



Notes: Peak global warming outcomes for emissions projections following the best estimate (solid histograms) and variations across different models and projection assumptions and including 2030 current policy/NDC assessment uncertainty (line histograms). The thin horizontal lines indicate the median estimate. Projections of extremes are taken from figure SPM.6 of IPCC WGI AR6 (IPCC 2021).

Even in this most optimistic scenario, the likelihood of limiting global warming to 1.5°C is only 14 per cent (table 4.4), and the various scenarios leave open a large possibility that global warming will exceed 2°C or even 3°C (table 4.4 and figure 4.3). This further illustrates the need to reduce global emissions by 2030 to less than the levels associated with the full implementation of current NDCs, as well as the need to expand the coverage of net-zero pledges to all GHG emissions and to achieve these pledges. Climate impacts and extremes increase with every increment of global warming, emphasizing the significant risks that result from insufficient near-term mitigation action (figure 4.3).

5 Global energy transformation in the context of the Paris Agreement

Lead authors:

Jesse Burton (University of Cape Town and E3G, South Africa) and Greg Muttitt (International Institute for Sustainable Development [IISD], United Kingdom)

Contributing authors:

Fatima Denton (United Nations University Institute for Natural Resources in Africa, Ghana), Sivan Kartha (Stockholm Environment Institute, United States of America), Narasimha Rao (Yale School of the Environment, Yale University, United States of America), Joeri Rogelj (Imperial College London, United Kingdom; International Institute for Applied Systems Analysis [IIASA], Austria), Saritha Sudharmma Vishwanathan (Indian Institute of Management Ahmedabad, India; National Institute for Environmental Studies, Japan), Dan Tong (Tsinghua University, China), Marta Torres Gunfaus (IDDRI, France) and William Wills (Centro Brasil no Clima and Eos Consulting, Brazil)

5.1 Introduction

Previous chapters document the continued delay in strong mitigation action and the implications for the carbon budget and projected global warming. The second part of the report focuses on two issues which result from these findings and that are central for the possibility of achieving the long-term temperature goal of the Paris Agreement (United Nations 2015).

First, all countries must accelerate economy-wide, low-carbon transformations. Energy sector transformation is essential, as energy is the dominant source of greenhouse gas (GHG) emissions. Accelerated mitigation by high-income countries is urgent and a priority to reflect the United Nations Framework Convention on Climate Change (UNFCCC) principle of common but differentiated responsibilities and respective capabilities. However, this will not be sufficient, given that low- and middle-income countries already account for more than two thirds of global greenhouse gas emissions today (see appendix A). Thus, energy sector transformation is also necessary in low- and middle-income countries, but must be aligned with meeting pressing development needs (chapter 6).

Second, all pathways consistent with meeting the Paris Agreement long-term temperature goal require a growing quantum of carbon dioxide removal in the longer term, alongside rapid and immediate GHG emission reductions. Chapter 7 explores the implications of this.

Energy transformation and development of approaches to carbon dioxide removal will need to be pursued in parallel, rather than more of one justifying less of the other. Action on both must be consistent with the UNFCCC principle of common but differentiated responsibility and respective capabilities, and requires global collaboration.

This chapter outlines some of the major issues related to global energy transformation, setting the scene for the subsequent chapter on energy transition in low- and middle-income countries (chapter 6).

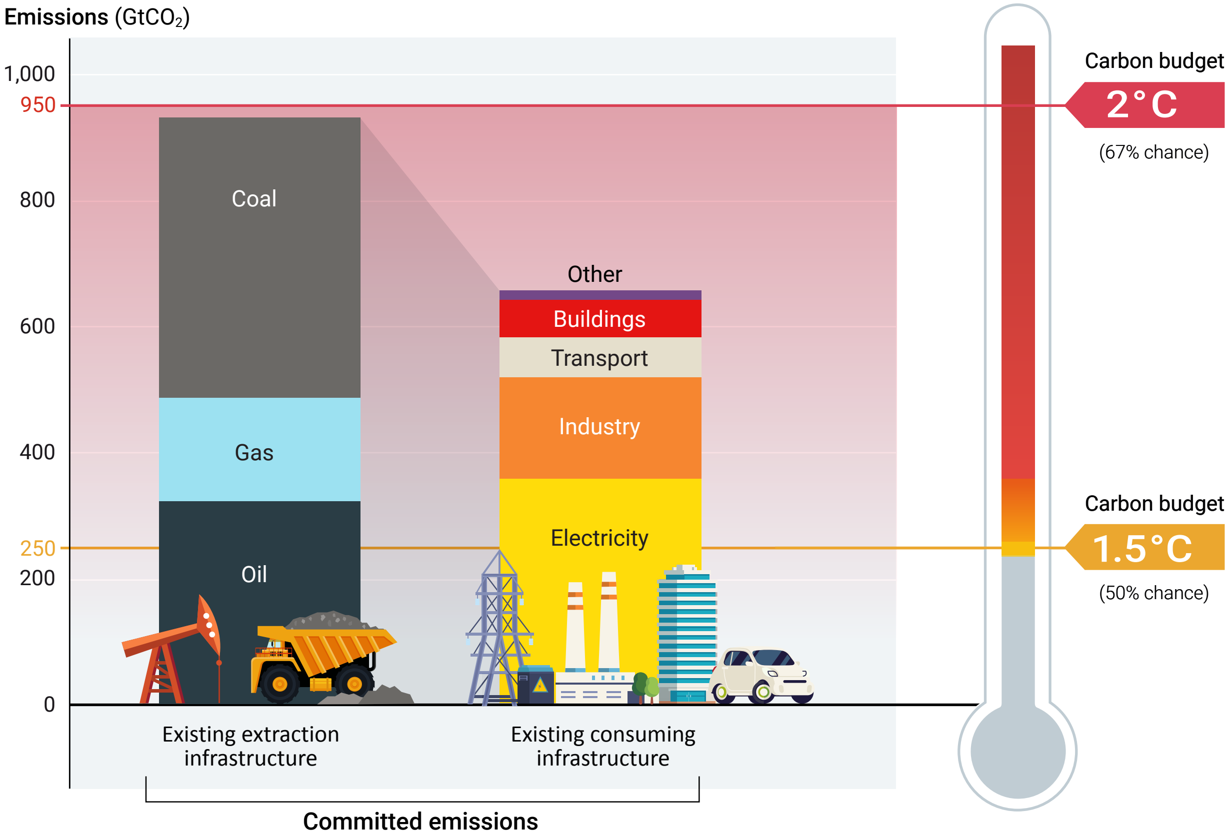
5.2 Avoiding new fossil fuel capacity will limit the existing infrastructure that must be retired early to achieve Paris Agreement goals

Energy consumption and production account for 86 per cent of global carbon dioxide (CO_2) emissions, comprising 37 per cent from coal, 29 per cent from oil and 20 per cent from gas (Friedlingstein *et al.* 2022; see also chapter 2). Achieving the Paris Agreement goals thus requires a policy-driven transformation of the global energy system.

The coal, oil and gas extracted over the lifetime of producing and under-construction mines and fields, as at 2018, would emit 936 gigatons of CO_2 if fully used (Trout *et al.* 2022) – around 3.5 times the carbon budget available to limit warming to 1.5°C with 50 per cent probability, and almost the size of the budget available for 2°C with 67 per cent probability (figure 5.1). Yet as described in chapter 3, new fields and mines continue to be opened.

Similarly, at the other end of the supply chain, the CO_2 emissions from full-lifetime operation of power stations, industrial plants, transportation and buildings already in existence exceed the budget available for 1.5°C warming by a factor of 2.5, and amount to around two thirds of the budget for 2°C (Tong *et al.* 2021; figure 5.1). Again, new energy-consuming infrastructure continues to expand (chapter 3).

Figure 5.1. Committed CO_2 emissions from existing fossil fuel infrastructure, compared to carbon budgets reflecting the long-term temperature goal of the Paris Agreement



Source: Adapted from Bustamente *et al.* (2023).

Note: Bars show future emissions implied by full-lifetime operation of fossil fuel-extracting infrastructure (Trout *et al.* 2022) and of fossil fuel-consuming infrastructure (Tong *et al.* 2019). These are compared with carbon budgets remaining at the start of 2023 (chapter 4). "Existing" generally means that infrastructure has been invested or committed, as at the start of 2018 (see previously cited sources for further details on methods). Since that time, while full data are not available, more infrastructure has been added than retired; hence this figure is an underestimate of the committed emissions problem.

In contrast, carbon budgets aligned with the long-term temperature goal of the Paris Agreement require that much of the existing capital stock will need to be retired early, retrofitted with carbon capture and storage, and/or operated below capacity (Trout *et al.* 2022; Intergovernmental Panel on Climate Change [IPCC] 2022; IEA 2023), while ensuring a just transition for workers and affected communities (International Labour Organization 2015; Smith 2017; McCauley and Heffron 2018). Globally, this leaves no room for new fossil fuel infrastructure, unless an even greater quantity of existing stock is stranded. Instead, new energy investments should focus on clean energy supply and end-use electrification to avoid further increasing committed emissions (International Energy Agency [IEA] 2021; IISD 2022; IEA 2023; Stockholm Environment Institute *et al.* 2023).

As low-carbon technology costs have fallen, wind and solar now offer the lowest-cost means of generating electricity in most of the world (UNEP 2019). The fall in the cost of renewables generally means that the "transition fuel" argument for higher-emissions and higher-cost gas is becoming increasingly invalid. However, there can be barriers to immediate transitions, including where finance for renewable remains prohibitively expensive in poorer countries (see chapter 6).

All this creates a dilemma for poorer countries with fossil fuel resources, between trying to use those resources to meet their development needs, versus avoiding the economic risk of stranded assets as the world decarbonizes (United Nations University Institute for Natural Resources in Africa 2019; see also chapter 6).

While all countries face stranded asset risk, stranded assets are likely to intensify existing systemic inequities and related vulnerabilities, including fiscal deficits, indebtedness, high borrowing costs and currency devaluation, especially in poorer countries (Sokona *et al.* 2023).

5.3 Meeting the basic energy needs of people living in poverty would have a limited impact on global GHG emissions

Access to affordable, reliable and modern energy services is critical to human welfare and livelihoods, linking together social equity, economic development and environmental sustainability (United Nations Department of Economic and Social Affairs 2022; see also chapter 6). Energy access enables food security and improved nutrition; reduces drudgery for women and girls from the collection of traditional fuels; provides light and frees time for education and studying; improves health and well-being, both through access to medicines and by reducing the burden of air pollution; and is a critical input for small business and for economic development.

Yet energy poverty persists, with women and children disproportionately affected. In 2022, the number of people without electricity access increased for the first time in a decade (Cozzi *et al.* 2022), while annual investments would need to triple to achieve universal access by 2030 (IEA *et al.* 2023; see also chapter 6).

Increasing consumption among the poorest to achieve developmental outcomes would have limited impact on GHG emissions (IPCC 2022; Wollburg *et al.* 2023). This is because at very low levels of development, measured by the Human Development Index, gains can quickly be made through small increases in energy access and use (Garg 2020; Clarke *et al.* 2022).

The energy that is required to deliver the basic elements of living standards that enable well-being – including thermal comfort, nutritious food, health and education, mobility, and civic engagement (IPCC 2022) – ranges from 12 to 40 gigajoules per person (taking into account differences in climate, geography, economic structure and culture), well below the average global energy consumption of 47 gigajoules per person (Kikstra *et al.* 2021). Considering the unequal distribution of emissions across income groups within and between countries documented in chapter 2, the energy needed to achieve the basic elements of living standards that enable well-being worldwide could even be supplied while decreasing aggregate global energy use (Millward-Hopkins *et al.* 2020), if increases for some people and countries were counterbalanced by decreases in the high per capita energy consumption of the world's wealthiest people (Rao *et al.* 2019; UNEP 2020; Kikstra *et al.* 2021).

5.4 Delivering change requires global cooperation that reflects the equity and fairness principles of the Paris Agreement

Limiting global warming to well below 2°C, while pursuing efforts to limit the increase to 1.5°C, requires an unprecedented degree of global cooperation. Fairness of effort-sharing is central to the intergovernmental trust-building that is essential to the bottom-up process of the Paris Agreement (Holz *et al.* 2023). Reflecting this, the Paris Agreement builds on the principle of common but differentiated responsibilities and respective capabilities in light of national circumstances.

This principle implies that countries with greater capacity and greater historic responsibility for emissions – particularly high-income countries– will need to take more ambitious and rapid action, setting the course and demonstrating the viability of fossil-free development. For example, the Climate Solidarity Pact, proposed by the United Nations Secretary-General, calls on all big emitters to make extra efforts to cut emissions, and wealthier countries to provide financial and technical resources to support low- and middle-income countries. Specifically, the Pact calls on developed countries to reach net zero as close as possible to 2040, and emerging economies to commit to reaching net zero as close as possible to 2050 (United Nations Secretary-General 2023).

Differentiated timelines are important for the feasibility of pathways aligned with the long-term temperature goal of the Paris Agreement, which is an aspect that global modelling tends to overlook. To illustrate, the median of 1.5°C pathways reviewed by the IPCC sees unabated coal power decline by 88 per cent from 2020 to 2030 (Muttitt *et al.* 2023), which in coal-dependent countries such as China, India and South Africa would require transition at a historically implausible rate, effectively replacing almost the entire fleet of power stations within a decade, likely making a just transition impossible (Vinichenko *et al.* 2021). This is compared to a 14 per cent reduction in gas power and 10 per cent for all uses of oil (primary energy), implying slower transition rates for most high-income countries, which generally depend more on oil and gas than on coal. Adjusting to a more feasible coal phase-out pace in all countries would require correspondingly faster declines in oil and gas use, and greater efforts by high-income countries (Muttitt *et al.* 2023). Thus, while global modelling is important to align overall ambition, it needs to be complemented by national models, which are better positioned to understand societal feasibility constraints, national realities, enabling conditions, and integration with national development strategies (La Rovere *et al.* 2018; Waisman *et al.* 2019; Deep Decarbonization Pathways 2021; Gunfaus and Waisman 2021; Svensson 2023).

The Paris Agreement furthermore recognizes that international support of at least three types is crucial for climate action: finance, technology transfer and capacity-building (UNFCCC 2015). This includes access to sufficient, affordable and quality finance that addresses sectoral transformations in different contexts (Ameli *et al.* 2021; Pachauri *et al.* 2022; Svensson 2023), access to clean technology that has been proven through deployment by the North; and technical assistance to drive nationally-defined and investment-ready low-carbon development pathways (Dubash 2023). Decarbonization will require affordable finance, considerably above current levels: limiting warming to 1.5°C while achieving the Sustainable Development Goals will require several trillion US$ per year (Organisation for Economic Co-operation and Development 2020; UNFCCC Standing Committee on Finance 2022; UNEP 2022; IEA and International Finance Corporation 2023).

Pressing development needs, existing resource profiles, political economy constraints, and limited political and institutional capacity all constrain and challenge countries to achieve transformations in power, transport and demand sectors at pace, and avoid new emissions as they develop. Thus, as discussed in chapter 6, a country's capacity to initiate the transformation of its energy system and the pace of transition that can be achieved will depend strongly on national circumstances, in the context of national developmental priorities (Mulugetta *et al.* 2022).

6 Energy transitions for low-carbon development futures in low- and middle-income countries: Challenges and opportunities

Lead authors:

Narasimha Rao (Yale School of the Environment, Yale University, United States of America) and Yacob Mulugetta (University College London, United Kingdom)

Contributing authors:

Jesse Burton (University Cape Town and E3G, South Africa), Joisa Dutra Saraiva (Getulio Vargas Foundation, Brazil), Ashwin Gambhir (Prayas Energy Group, India), Jessica Omukuti (University of Oxford, United Kingdom), Nadia S. Ouedraogo (United Nations Economic Commission for Africa, Ethiopia), Setu Pelz (International Institute for Applied Systems Analysis [IIASA], Austria), Fei Teng (Tsinghua University, China) and Meron Tesfamichael (University College London, United Kingdom)

6.1 Introduction

This chapter focuses on the relationship between energy transitions[1] and low-carbon development futures in low- and middle-income countries,[2] whose emissions account for more than two thirds of global greenhouse gases (see chapter 5). Globally, the role for low- and middle-income countries in climate action is framed by historical patterns of development, as recognized by the Paris Agreement principle of common but differentiated responsibility and respective capabilities in light of national circumstances. Low- and middle-income countries share the challenge of bringing millions out of poverty, including through energy demand growth, while shifting to a clean energy system. Even as they face some common challenges, their pathways will vary, driven by different starting points, economic structures and natural resource endowments. The objective of this chapter is to place these countries' future opportunities for energy transition in the context of their heterogeneous starting points and development priorities, while exploring the scope for an internationally supported energy transition.

6.2 Development and energy are interlinked

Energy transitions in low- and middle-income countries are shaped by the overarching objective of pursuing development. The historical expansion of the energy sector has enabled development by providing energy services to households and industry, and in some cases generating export revenues. Low- and middle-income countries' future energy transitions, and their low-carbon implications, will in turn be shaped by their development context. This section examines past and likely future links between development and energy trends, and the importance of local context in shaping these links.

6.2.1 Development drives energy transitions

Energy transitions have historically been driven by the requirements of providing clean cooking and electricity services to homes, and infrastructure needed to improve living standards. In low- and middle-income countries, climate mitigation measures have frequently been adopted as part of development policies that offer multiple environmental and social benefits (Ürge-Vorsatz *et al.* 2014). For example, the policies database of the International Energy Agency (IEA) illustrates that policies often target achieving a mix of energy efficiency, green growth, air pollution reduction and affordability objectives (IEA undated).

1 Consistent with IPCC usage, the term "transition" is used here to denote the process of changing from one state or condition to another in a given period of time. Transitions are related to achieving a "transformation", or a change in the fundamental attributes of natural and human systems, but emphasize the process of this change (IPCC 2023).

2 Low-and-middle-income countries are defined as countries with an annual per capita gross national income of less than US$13,205 in 2022 (Hamadeh *et al.* 2022). This includes low-, lower-middle- and upper-middle-income countries. In this chapter, "middle-income countries" refers to both lower- and upper-middle-income countries together.

The cooking transition is a good example of how energy transitions are development-driven. Driven by health objectives and national context, electric or biogas stoves offer the most attractive long-term pathways for the sector, effectively leading to decarbonizing cooking and heating (Pachauri *et al.* 2021). Driven by this logic, about 600 million people have transitioned from solid fuel to liquid petroleum gas and electric stoves since 2012, resulting not only in mitigation but in fewer premature deaths and diseases among women and children (World Health Organization [WHO] 2014; WHO 2022) and easing the burden on women in carrying out their productive activities (Maji *et al.* 2021). However, the transition is yet incomplete; close to 2.4 billion people continue to use solid fuels.

Electricity access through off-grid systems has been enabled by steeply decreasing costs of solar photovoltaics (PV), albeit offset in low-income countries to an extent by high borrowing costs (section 6.5). Over 100 million people, half of whom reside in sub-Saharan Africa, and 29 per cent in South Asia, had solar-based access through off-grid systems by 2019 (IEA *et al.* 2021). However, about 775 million people still lack electricity access (Cozzi *et al.* 2022); over 3.5 billion suffer unreliable supply and electricity consumption remains low (Ayaburi *et al.* 2020); and the share of renewables in total energy consumption is only 17 per cent, and scarcely keeping up with energy demand growth. Moreover, services from off-grid systems are typically limited to basic lighting and phone charging, neglecting longer-term energy services and productive uses that would have transformative local development benefits (Groenewoudt and Romjin 2022). Notwithstanding these concerns, the scale-up of affordable renewable-based access solutions offers an opportunity for stimulating development and raising living standards, while avoiding emissions growth from the power sector.

National energy needs for broader human development, including for poverty eradication and further quality of life improvements, will require significant energy demand growth (Kikstra *et al.* 2021). In 2021, average per capita energy demand in sub-Saharan Africa and South Asia was 19 and 16 gigajoules respectively, in contrast to 51 gigajoules in China, 83 gigajoules in Western Europe and 181 gigajoules in North America. However, as discussed in section 6.4.1, there is scope for meeting energy demand more efficient and equitable, and meet energy needs with low-carbon energy as renewables get cheaper (see chapter 5).

6.2.2 Countries have different starting points and priorities for future clean energy transitions

The challenges faced by countries in bringing about clean energy transitions are shaped by differing national circumstances (Mulugetta *et al.* 2022). Yet, these challenges fall into patterns based on countries' stage of development, economic structures, and fuel resource endowments, as mapped out in figure 6.1. Low-income countries not only contribute the least to global greenhouse gas emissions but also face acute development challenges that limit their ability to invest in clean energy opportunities without affordable finance. Middle-income countries with a manufacturing and services base may require a greater focus on decarbonizing industry, while those with a services and agriculture and silviculture base may give precedence to reducing deforestation. Fuel endowments also matter: countries with renewable (e.g. hydro) capacity, those with abundant fossil reserves for domestic use and/or exports, and those dependent on energy imports, will all face different sets of challenges and opportunities.

The overarching economic context in low-income countries and some lower middle-income countries, is low human development and high levels of debt. With underdeveloped power sectors and industry, clean energy access for cooking and electricity to reduce traditional biomass dependence is a priority (Chen *et al.* 2022). However, financing energy access expansion has been a challenge. Many low-income countries have depleted public savings either to counter the economic fallout of the COVID-19 pandemic, to cope with volatile commodity prices or to service external debt. In 2021, Governments in sub-Saharan Africa spent 16.5 per cent of their revenues servicing external debt, up from less than 5 per cent in 2010 (World Bank, Office of the Chief Economist for the Africa Region 2023). Today, 60 per cent of low-income countries are in or at high risk of debt distress, up from 49 per cent in 2019 (World Bank 2022).

The risks from undertaking a clean energy transition, and its implications for broader economic outcomes, varies by resource base. For instance, in net fuel importing low-income countries, such as Mali, threats to fossil fuel supply may exacerbate trade deficits and debt burdens. Consequently, they are likely to prioritize energy security, and value clean energy investments to replace imports (de Hoog, Bodnar and Smid 2023).

Low-income countries with cheap energy due to abundant hydro resources, such as Ethiopia or Nepal (recently classified as lower-middle-income), may choose to export low-carbon electricity to earn revenues while easing their foreign exchange bottlenecks. They also have more flexibility to accelerate emission reductions because they do not face stranded fossil fuel asset costs. Bhutan, for example, is among the few countries that have pledged to achieve carbon neutrality in its second nationally determined contribution (NDC) targets, based on its significant hydropower potential and over 70 per cent forest cover (Yangka *et al.* 2019).

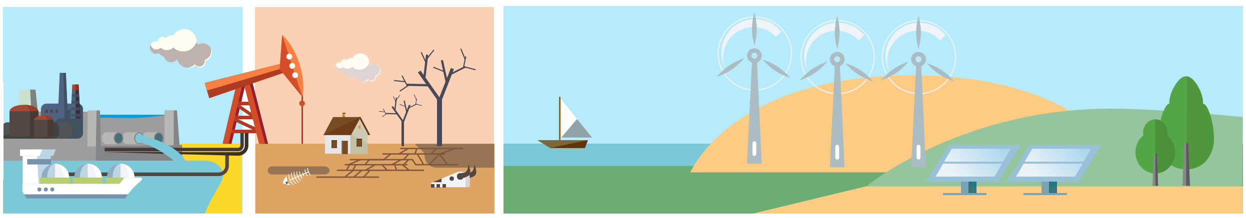
Figure 6.1 Country groups based on development stage and fuel endowments share these challenges in the energy transition, among other country-specific circumstances

Energy sources	Risks	Low-income countries	Lower- and upper-middle income countries: Agriculture and forestry	Lower- and upper-middle income countries: Manufacturing and services
Fossil fuel producer (export-dependent)	Stranded sector risks	Democratic Republic of the Congo	Cameroon Equatorial Guinea	Algeria Ecuador Nigeria
Fossil fuel producer (domestic use)	Stranded sector risks	Burkina Faso	Brazil Indonesia	China India Viet Nam
Renewable producer (mainly hydro)	Climate risks for energy supply	Afghanistan	Costa Rica Bhutan	Kenya
Energy importer (low resources)	Energy security risks	Mali	Senegal Myanmar Côte d'Ivoire	Morocco Jamaica Mauritius

Common barriers

Debt and lack of affordable finance

Land-use conflict



Some low-income countries and a few middle-income countries already do or plan to rely on fossil fuel exports, and could benefit from economic diversification. These countries face common risks, such as fuel price volatility and locking into future stranded assets. For example, a 50 per cent decline in oil prices during the pandemic contracted revenues and depleted foreign currency reserves in oil exporting countries (Akinola *et al.* 2022; Gerval and Hansen 2022). These circumstances pose a considerable threat to countries such as Angola and South Sudan, where energy accounts for up to 90 per cent share of their export earnings (International Monetary Fund [IMF] 2022; IMF 2023). In addition to incumbent producers in North and West Africa, several African countries including, Mozambique, Namibia, Senegal and Uganda, have made new discoveries of significant oil and gas reserves. Countries such as these seeking new sources of growth will avoid fossil fuel expansion only if they have credible alternative choices.

At the same time, oil and gas projects are capital-intensive, difficult to execute, and often face cost and time overruns (Mihalyi and Scurfield 2020). Because of long lead times to develop their industries, countries will be in a race against time to reap the economic benefits of the oil and gas trade. As renewables and other low-carbon technologies become competitive, the prospects of declining future demand could risk lock-in and asset stranding over the long term (Anwar, Neary and Huixham 2022). These fossil fuel-dependent low-income countries may benefit from economic diversification. Angola is an example of a country that has sought to diversify exports, as reflected in the country's 2025 Strategy and 2018–2022 Sector Development Plan.

Most middle-income countries, in contrast, typically have larger urban centres, more developed energy infrastructure, and better access to capital. Those that are major coal producers, such as China, India and South Africa, face the risk of stranded assets, large-scale unemployment and energy insecurity if coal is rapidly phased down. The speed of transition required poses a particular challenge. Energy transition consistent with Intergovernmental Panel on Climate Change (IPCC)-modelled pathways to 1.5° would require declines in coal generation at historically unprecedented rates (Muttit *et al.* 2023). However, the clean energy transition also offers opportunities, contingent on international support. Notably, all three of the countries mentioned have developed ambitious plans for mainstreaming climate into long-term development strategies (South Africa 2019; India, Ministry of Environment, Forest and Climate Change [MoEFCC] 2022).

In China, for example, to meet the projected rate of emissions decline, the country's energy infrastructure investment could triple compared to the NDC scenario. In one 1.5° scenario, these investments account for more than 2.6 per cent of its gross domestic product (GDP) (He *et al.* 2022). Since much of China's energy infrastructure, including coal plants, has been constructed in the past two decades, a rapid phase-out of coal could result in trillion-dollar stranded assets (Cui 2019). Conversion to peaking plants (Cui 2021), and retrofits with CCS or biomass co-generation (Xing *et al.* 2021), are partial solutions to this challenge.

South Africa, a coal-producing and -exporting economy, has rapidly expanded renewable energy development, yet faces a long road to replace its coal dependence. In 2019, South Africa had planned for 30 GW of variable renewable energy in its Integrated Resource Plan (South Africa, Department of Mineral Resources and Energy 2019), and by 2022 had 18 GW in the grid connection queue and 33 GW of variable renewable energy and batteries at an advanced stage of approval (South African Photovoltaic Industry Association 2023). Yet to meet South Africa's ambitious NDC targets would require adding over 6 GW of variable renewable energy every year to 2030, an amount equivalent to the current installed capacity of variable renewable energy, as well as investments in grid backbone (South Africa, Presidency 2022). Without enhanced international financial support, the country risks short-term negative impacts on growth, exacerbating poverty and inequality, and failing to capture future low-carbon industrial opportunities (World Bank Group 2022).

India faces the challenge of mobilizing investment to achieve its ambitious clean energy transition plans. These plans include increasing non-fossil fuel capacity in the power sector to 65 per cent by 2030 (India, Ministry of Power, Central Electrical Authority 2023), exceeding its NDC commitment of 50 per cent, implementing building and industrial energy efficiency standards and markets, and undertaking electric vehicle, biofuels and green hydrogen promotion programmes (India, MoEFCC 2022; India, Ministry of New and Renewable Energy 2023). To fully achieve this transition will require complementary measures such as a smooth transition away from coal, strengthening an already stretched electric grid, and decarbonizing the fertilizer, cement and steel industries. There is also scope to exploit potential linkages between social development and climate mitigation (Bhatia 2023), such as through electric public transit and two- or three-wheeler vehicles, passive designs for affordable housing (the Pradhan Mantri Awas Yojana programme) and efficient cooling solutions.

In industrializing middle-income countries with strong agriculture and forestry sectors, like Brazil and Indonesia, curbing deforestation through forest management reform may be a critical lever, though also with political challenges. For example, Brazil had success in reducing deforestation from 2004 to 2012 through stronger monitoring and enforcement and incentive programmes, such as conditional access to credit in rural areas with illegal practices (Assunção, Gandour and Rocha 2015), but some regression has occurred with changes in political cycles. Such reforms have had to contend with the conflict between conservation and the protection of indigenous rights, and land-grabbing for agriculture (Brito *et al.* 2019).

6.3 The political economy of clean energy transitions is challenging

Ensuring rapid, smooth and just national clean energy transitions will require addressing many political and institutional challenges at the national and global levels. Central to these challenges is the reality that greenhouse gas emissions contributions and the capacity to mitigate them have been, and will likely continue to be, highly unequal (see chapters 2 and 5). Global inequalities carry implications for financing and other means of international support for energy transitions, as discussed in section 6.5. National inequalities reflect unequal access to institutions and resources, concentration of power among elites and contestation among rival political interests. This section focuses on the implications for energy transitions of national development challenges, in particular capacity constraints, weak institutions and complex political economies.

6.3.1 Clean energy transitions are limited by capacity constraints

Ensuring that clean energy transition processes account for national circumstances requires deep capacity, including autonomy to take decisions in the national interest, inclusive processes, and the building and sharing of required knowledge (Klinsky and Sagar 2022). Yet differences in wealth mirror differences in capacities to undertake a clean energy transition. Low-income countries typically have limited resources and are often saddled with weak institutions and governance mechanisms to plan and manage their transitions (Sokona 2021).

Yet, capacity-building processes are often shaped more by the interests of international actors than by local needs (Nago and Krott 2020). For example, mitigation actions focused on climate outcomes may privilege training and knowledge acquisition on climate transparency, such as emissions reporting, over knowledge on social benefits or assessing needs for international support (Klinsky and Sagar 2022). Such "knowledge politics" also require attention in capacity-building processes.

6.3.2 Institutional requirements are substantial

Clean energy transition processes are characterized by lock-ins and path dependence (Sovacool 2016), and require structural changes including building new industries, infrastructure and human capital (Muttitt and Kartha 2020). Climate institutions, notwithstanding political challenges in establishing them, can help shape policy and serve governance functions needed for low-carbon transitions (Dubash *et al.* 2021).

Institutions that enable coordination across sector areas are necessary because multiple and competing institutions operating in silos are often in charge of energy- and development-related sectors, with implications for carbon outcomes (Newell 2019). Enhancing policy coherence through coordination between energy and the rest of the economy is critical to capitalize on the systemic benefits from the energy transition (Shawoo *et al.* 2021). For example, finance ministries are well placed to introduce development- and climate-related conditionalities to the use of public funds.

The careful design of decarbonization processes can help build consensus for complex transitions and broaden the knowledge base on which they are built. For example, Costa Rica put in place a data-driven, stakeholder-co-designed National Decarbonization Plan, which has also been an important foundation on which significant international concessional finance was mobilized (Jaramillo *et al.* 2023). Elements of this approach include a deliberative process, and carefully crafted long-term scenarios based on open-source models with scope for input from broad research, practice and policy communities.

6.3.3 Political economy challenges include entrenched fossil fuel interests

Undertaking clean energy transitions requires structural changes in political economy, with impacts on existing economic structures and interests as well as new political constituencies. For example, in South Africa, the historically powerful alliance of coal mining and the main electricity utility Eskom have maintained their defence of incumbent fossil fuel, while new alliances composed of parts of the State and civil society have lined up in favour of expanding renewables (Hochstetler 2020). The chasm between these coalitions has made it difficult for policymakers to commit fully to either climate action or renewable energy. In Latin American countries where livestock cultivation contributes to deforestation, mitigation may threaten the political influence of the cattle industry and increase the importance of food policies to reduce beef demand (Dumas *et al.* 2022).

The political acceptability of sustaining transitions depends on how their economic impacts are distributed through labour shifts, energy price and macroeconomic impacts. Labour retrenchment is a concern in coal-dependent economies such as China, India, Indonesia, and South Africa. Because the coal sector supports millions of people directly and indirectly, a phase-down from coal would also cause spillover effects in local economies and community well-being (Ruppert Bulmer *et al.* 2021). Similarly, Algeria employs 350,000 workers directly and 1.7 million people indirectly in its oil and gas sector. Not least, the transition out of fossil fuels could bring macroeconomic shocks with political economy implications. For example, countries that seek to exploit fossil fuel reserves for future economic growth face the risk of dwindling revenues as the rest of the world transitions to renewables-based economies (Solano-Rodriquez *et al.* 2021).

6.4 Clean energy transitions also bring opportunities

In addition to challenges, low emission energy transitions bring potential opportunities for low- and middle-income countries, including multiple social and environmental co-benefits. Many mitigation options bring both synergies and trade-offs with the Sustainable Development Goals, but the prevalence of synergies is greater than of trade-offs (Allan *et al.* 2021 p. 22). For example, sustainable transport strategies could yield co-benefits such as air quality and health improvements, equitable access to transportation services including enhanced gender equality, and improved access to education (Doblas-Reyes *et al.* 2021, p. 1389). Widening access to clean cooking options could improve health outcomes considerably, especially for women, while reducing forest degradation and deforestation. Realizing these co-benefits also depends on policy choices that intentionally maximize co-benefits and minimize trade-offs.

The scope for these sectoral co-benefits is well recognized. This section focuses on the complementary question of how broader structural economic changes could help generate opportunities, across a wide spectrum of low- and middle-income countries, while keeping their specific national contexts in mind. It discusses two such sets of opportunities: demand-side changes that result in more efficient growth; and moving up the clean energy supply chain.

6.4.1 Demand-side changes bring efficiency and social benefits

Demand-side changes could bring social benefits and, through enhanced efficiency, reduce the need for supply expansion (Creutzig *et al.* 2018). The most energy-intensive demand sectors include housing, transport and food (Rao *et al.* 2019). Avoiding lock-in in these sectors require shifting how low- and middle-income countries develop urban areas where the most energy demand growth and lock-in is expected. Given that future demand growth is dominated by urban areas, the potential for avoided emissions is greatest there.

Because urban and industrial infrastructure is still being built in low- and middle-income countries, these countries can avoid locking into energy- and carbon-intensive infrastructure, thereby avoiding future emissions (Lwasa *et al.* 2022). Urban planning and housing policies that encourage more dense and affordable multifamily housing can reduce commuting needs and building energy demand. Building energy efficiency measures, coupled with financial support to maintain affordability, such as for appliances and housing construction practices, can save households money and reduce emissions. In the transport sector, shifts from investments in road infrastructure to facilitate shared transit, such as buses, mass transit rail or even car-sharing, can significantly reduce transport-related emissions, with numerous social and environmental benefits (McCollum *et al.* 2018).

In the food sector, energy investments at scale are essential to support expected growth in food production of 70 per cent by 2050 to meet the needs of a growing population, increased urbanization, and dietary changes (International Renewable Energy Agency [IRENA] and Food and Agriculture Organization of the United Nations [FAO] 2021). For example, improved access to modern energy for cooling and mechanical power in the agrifood supply chain can reduce waste in storage and increase productivity in agroprocessing. Policies that support diets with healthy coarse grains (Davis *et al.* 2019) and less meat (Willet *et al.* 2019) can have nutritional, environmental and economic benefits.

Shifts in development strategies that prioritize the poor or broad public interests over private consumption can reduce emissions growth. In South Africa, models show that macroeconomic policies that prioritize energy security and employment can favour renewables over fossil investments in the power sector (Winkler *et al.* 2022). Shifts in investments towards shared infrastructure that serve basic needs, such as health or education facilities, and water and sanitation, would reduce inequality in human development and limit emissions growth (Kikstra *et al.* 2021; Millward-Hopkins and Oswald 2023).

6.4.2 Participating in clean energy supply chains can bring jobs and revenue

Moving from mineral extraction to the final product end of the clean energy supply chain provides considerable opportunities to low- and middle-income countries. Doing so can create new revenue opportunities for the industry and new jobs for the public, and, in some cases, help fossil fuel-dependent economies to diversify.

The rise in the electric vehicle industry will require a material shift from a liquid-based to a minerals-intensive energy system, estimated to result in a six-fold increase in mineral inputs in 2040 relative to today (IEA 2021a). By 2025, the six segments of the US$8.8 trillion global electric vehicle batteries value chain will include mineral exploitation (US$11 billion), minerals-to-metals transformation (US$44 billion), production of precursors (US$217 billion), battery cell manufacture (US$387 billion), cell assembly (US$1.8 trillion) and electric vehicle manufacture (at least US$7 trillion). Moving from the first segment to the third would allow countries in Central Africa to capture gains beyond the very first and least profitable stage of the chain (BloombergNEF 2021; Ouedraogo and Gasser 2022).

Low- and middle-income countries today are competitive in exploration and mining of critical minerals, but lack capacity for processing or refining operations, cell assembly, and manufacturing of components necessary for electric vehicle production. For example, almost all the cobalt mined in the Democratic Republic of the Congo is exported to Belgium or China for refining, with insignificant economic benefits accruing to the country (Bridle *et al.* 2021). Achieving the transformative potential of lower- and middle-income countries' resources requires a new way of thinking about minerals and their place in the industrialization and diversification of economies.

Low- and middle-income countries that have been successful in taking advantage of downstream opportunities in the renewables value chain have done so through the support of robust institutions, cross-sectoral coordination, industrial policies to strengthen local manufacturing capabilities, and development of export partnerships. China's PV programme, for example, has established an industrial ecosystem with strong synergy between upstream and downstream sectors. China's PV industry promoted sustained cooperation between local firms, universities and industry associations across the PV value chain. Starting from portable lighting devices, then moving to solar PV panels, and ultimately creating domestic cell and wafer industry for export, the Chinese PV industry has gradually become one of the pillars of the Chinese manufacturing sector (Huang *et al.* 2016; Zhang and Gallagher 2016). Conversely, India's National Solar Mission prioritized low-cost deployment of PV over building domestic manufacturing capability, paying insufficient attention to training and research and development (R&D) (Behuria 2020). India's relatively limited success in creating opportunities for localizing manufacturing has therefore resulted in high dependence on solar PV imports.

Prior expertise in related industries matters. For instance, Viet Nam has had substantial experience producing internal combustion engine based two-wheelers for several decades, and has become the second-largest electrical two-wheelers market worldwide, second only to China (Hiep *et al.* 2023). As part of the effort for upscaling electric vehicles, the Government of Viet Nam agreed to reduce the excise tax on domestically manufactured, assembled and imported electric cars. A preferential import tax on raw materials and components is currently under review (Le, Posada and Yang 2022). However, Viet Nam still lacks a clear and comprehensive e-mobility policy and regulatory framework to plan for significant future investment.

Starting down the pathway to harness gains from the energy supply chain may require taking early bold steps. For instance, Peru reformed its copper royalty regime in 2021 to increase government revenue from the mining sector. Indonesia has banned the export of unprocessed nickel to encourage value-added activities within its borders. Namibia has also been actively exploring the development of green hydrogen, mainly for export. Although it lacks the industrial capacity and sectoral system capabilities of countries further ahead, Namibia has established strong international R&D interactions and collaborations to ensure the social benefits of employment and local learning take place (United Nations Conference on Trade and Development 2023). The initiative is expected to create an additional 600,000 jobs by 2040 in Namibia, but the social, political and resource-related risks would need to be carefully assessed.

6.5 Adequate international finance is an essential enabler of clean energy transitions

Decarbonizing energy systems in low- and middle-income countries requires mobilizing capital at an unprecedented scale. Without affordable external climate finance assistance, the majority of low- and middle-income countries will struggle to achieve their development objectives and reduce emissions. Global clean energy investment stands at US$1.3 trillion today, and is projected to rise to US$2 trillion by 2030 (though US$4 trillion is needed to stay on track with the net-zero scenario) (IEA 2021b). Low- and middle-income countries account for two-thirds of the global population, yet received only a fifth of all energy transitions investments (IEA 2021c). The implementation of the NDCs alone, for instance in Africa, are projected to require close to US$3 trillion of conditional and unconditional finance for implementation, a sum close to one year of Africa's GDP in current terms (UNECA 2020).

Enabling an energy transition in low- and middle-income countries will require scaling up financial flows in strained financial systems. In many cases, challenges of food sovereignty, energy sovereignty, and the low value-added content of exports relative to imports (Sokona *et al.* 2023) contribute to structural trade deficits, weakened currencies and persistent indebtedness. In low- and middle-income countries with fossil fuel industries, affordable finance is important not only for scaling clean energy, but also to manage the economic shocks from retiring fossil fuel assets. For example, coal-fired power plants support the viability of India's rail system through coal freight charges and finance state budgets (Tongia, Sehgal and Kamboj [eds.] 2020). Moreover, reduction in fossil fuel exports could threaten fiscal solvency in countries such as Algeria, where oil and gas revenues accounted for 38 per cent of government revenue between 2016 and 2021, increasing to more than 50 per cent in 2022 and 2023 (Oxford Analytica 2023).

Against this challenging backdrop, energy transitions in low- and middle-income countries are impeded by nominal financing costs that are up to seven times higher than those in the United States of America and Europe (IEA 2021c). The weighted average cost of capital varied between 5 and 21 per cent for solar and wind projects in lower- and middle-income countries (see figure 6.2). The regional weighted average cost of capital for solar PV in 2021 was 7 per cent in Africa and Asia and 4 per cent in Europe (IRENA 2022). Some low- and middle-income countries face a climate investment trap, where the high costs of capital that limit financial flows are due in part to limited experience with these markets. Perceived risks of investment are exacerbated by sovereign credit scores and ratings, and the lack of concessional finance, catalytic finance and guarantees (Mithatcan *et al.* 2022).

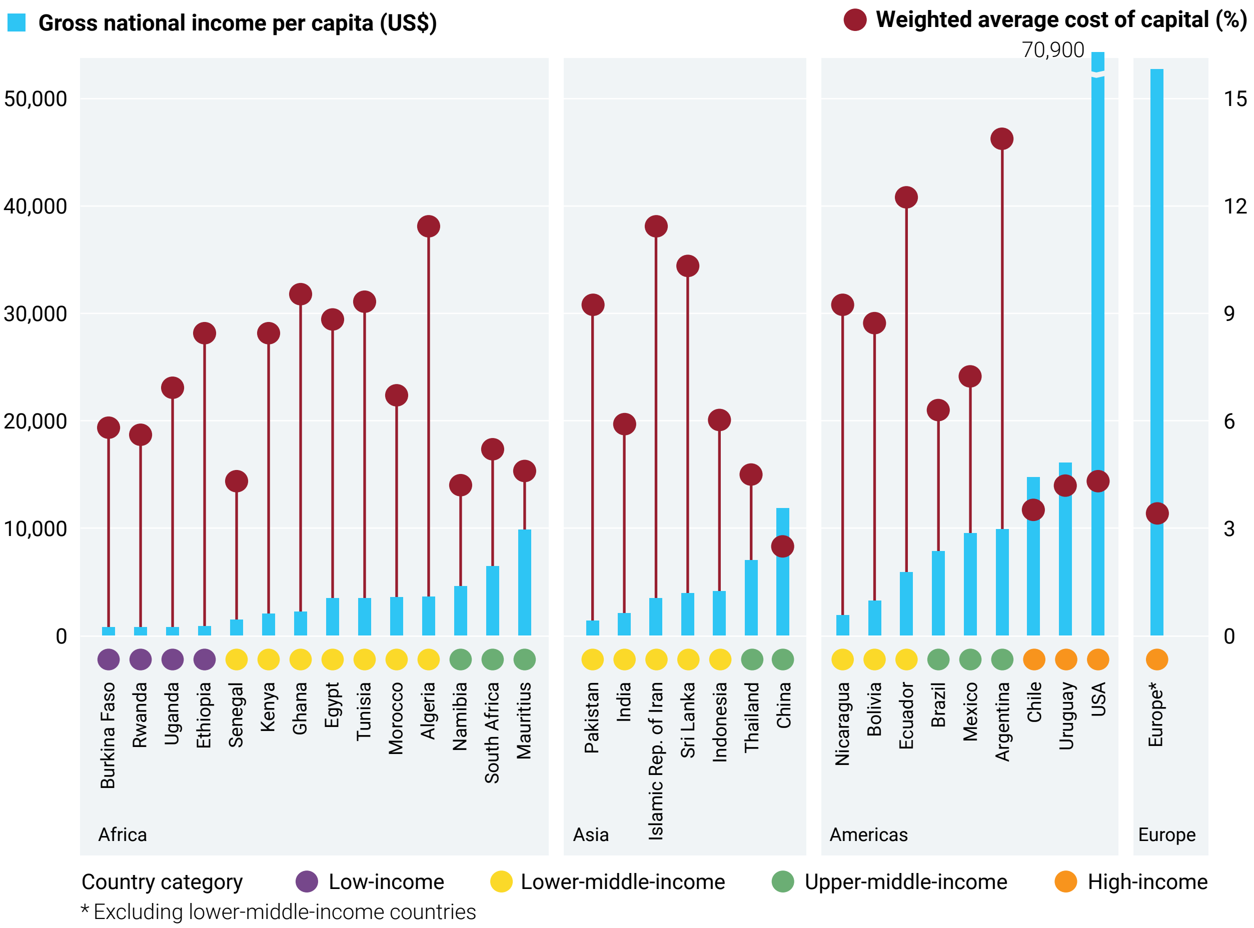
Reducing costs of capital can significantly increase the scope for low-carbon energy investments to provide affordable energy services to wider populations (Ameli *et al.* 2021). To do so, reforms are needed in international finance as well as in domestic markets where clean energy is sold. International climate finance needs to be re-oriented towards long-tenor and low-interest concessional finance, guarantees and catalytic finance need to be provided, and new public and private sources of finance should be encouraged. New innovative models for finance are needed that restore debt sustainability and restructure the rules of international financial institutions (United Nations 2023). In domestic markets, risks of energy off-take need to be reduced by improving the financial viability of purchasing utilities, developing reliable market design and rules, and strengthening electric grids to ensure reliable delivery.

Further, climate finance is less forthcoming for countries that need it the most. The 46 least developed countries received 2.8 billion in energy transition investments in

2018, an amount lower than in previous years. Despite the enormous renewable potential and need to meet energy access needs in Africa, only 2 per cent of global investment flowed into Africa between 2000 and 2020, of which 75 per cent was concentrated in Egypt, Kenya, Morocco and South Africa (IEA, IRENA, United Nations Statistics Division, World Bank and WHO 2021).

The emerging Just Energy Transition Partnerships (JETPs) between international finance providers and low- and middle-income countries are finance packages intended to support country-led decarbonization strategies consistent with national development priorities. They show promise, but require considerable additional investment mobilization and further assessment of their ability to address development objectives. The amount of funding in a JETP is small compared to the scale required for clean energy transition. However, they offer a process to help develop capacity and governance. For example, in South Africa the JETP catalysed the development of a comprehensive country investment plan that is much bigger (US$98 billion) than what was on offer (South Africa, Presidency 2022). Indonesia and Viet Nam have agreements to increase their commitment to renewable energy and reduce their pipeline of coal generation expansion with international assistance (Southeast Asia Energy Transition Partnership 2022).

Figure 6.2 Weighted average cost of capital for solar PV projects against per capita gross national income for select countries in 2021.



Source: Adapted from IRENA (2022). Gross national income (current US$, World Bank Atlas method).

6.6 Low- and middle-income countries can take concrete steps towards clean energy transitions

The challenges on the path to clean energy transition in low- and middle-income countries are considerable. However, there are concrete steps that this large group of countries can take towards accelerated energy transition. The starting point is to develop nationally owned and context-specific visions and strategies for energy futures that bring together development and clean energy imperatives. To do so requires low- and middle-income countries to undertake institutional strengthening. And to realize these ambitious visions will require mobilizing international support. This section lays out concrete measures towards each of these steps. Taken together, these steps can assist lower- and middle-income countries' Governments in preparing investment-ready climate and development plans that scale up mitigation ambition through articulated policies and strategies, and their investment needs.

6.6.1 Develop domestic strategies towards equitable, efficient and clean growth

Shifting development pathways towards sustainability allows mitigation considerations to be incorporated alongside a broad set of developmental objectives (Winkler *et al.* 2022). But to do so requires developing energy transition strategies that account for both synergies and trade-offs across development and emissions outcomes in specific national contexts. At least three areas may be particularly salient to lower- and middle-income countries' strategies: encouraging energy-efficient and well-being-enhancing demand growth; developing economic and social transition plans for fossil dependence; and exploiting clean energy supply chains.

6.6.2 Avoid emissions through demand-side measures

Because many low- and middle-income countries have not fully locked into infrastructure or consumption patterns, focused attention to the following aspects of energy demand could avoid future emissions: in emerging urban areas, preemptive urban planning with electric public transit, affordable, efficient housing and compact design; social service expansion through shared infrastructure such as health, education, water and sanitation; and supporting efficient food systems with diverse grains, which likely entails less emissions-intensive growth, and potentially contributes to gender equality and youth employment (IRENA and FAO 2021).

Develop a strategic plan around fossil fuel use: Because of the need for rapid global phase-down of all fossil fuels, low- and middle-income countries should develop strategic plans for existing or planned fossil fuel use – domestic or exports. These plans should examine the scope for economic diversification and alternatives to fossil fuel expansion, the economic risks associated with stranding existing assets, and the need for social protection mechanisms to manage transition shocks such as unemployment and higher energy prices. The process of formulating these strategic plans should be inclusive and gender-responsive, to identify and involve affected communities.

Foster green industrial opportunities: Capturing economic and social gains from the large-scale deployment of renewable energy and storage technologies is a key development objective (United Nations Environment Programme 2019). To do so, extraction-dependent low- and middle-income countries could broaden their involvement in clean energy supply chains from ore exports to higher-margin activities such as processing and manufacturing technologies. This requires identifying value chain activities that can feasibly be picked up by local firms and introducing enabling measures such as local content incentives, business incubation initiatives, domestic R&D and human capital investments, and promotion of low-carbon industrial clusters (Lema *et al.* 2021). Regional coordination may enable low- and middle-income countries to build on comparative strengths in raw materials, manufacturing, and trade routes. For example, entities such as the African Continental Free-Trade Area can help develop an efficient regional low-carbon industrial ecosystem by providing an impetus for African Governments to address infrastructure gaps, improve and streamline supply chains, improve manufacturing capacity, and foster cross-border cooperation.

6.6.3 Develop institutions to support energy transitions

To enable low- and middle-income countries' Governments to take ownership of their mitigation strategies, developing appropriate domestic institutions at national and subnational levels is necessary (Dubash *et al.* 2021). Institutions can enable strategic thinking, ensure coordination for implementation, and strengthen gender-responsive inclusive processes for designing, assessing, and implementing policies that safeguard people's interests during transition. Appropriate institutional development is a precondition for countries to exploit new green economy opportunities, as discussed above. Identifying strategic opportunities, coordinating and harnessing domestic capabilities to move down the supply chain, working in partnership with domestic industry, and establishing partnerships and markets globally, all require considerable State capacity. Because of their cross-sectoral nature, managing energy transitions will require coordinating across government departments and jurisdictions. And because they risk creating winners and losers, they require open processes that ensure the interests of the poor are represented. This calls for lower- and middle-income countries' Governments to take greater responsibility for setting up transparent and accountable governance systems with improved public administration.

6.6.4 Create improved conditions for international financial assistance

A clean energy transition requires international support, consistent with operationalizing the principle of common but differentiated responsibilities and respective capabilities (Klinsky *et al.* 2017). In practical terms, global climate mitigation financial flows from North America and Europe to other regions would have to increase to hundreds of billions to reconcile development needs and fair effort sharing (Pachauri *et al.* 2022). To facilitate such an increase in international flows, the structure of international finance needs reform, domestic market conditions need to be improved, and country platforms for facilitating dialogue need to be developed, as laid out below.

Fundamental to the goal of restructuring international finance is to reduce costs of capital. This will require de-risking early-stage investment, enabling long-tenor and low-cost concessional finance, introducing catalytic finance and guarantees, and creating market conditions that provide long-term certainty (Mithatcan *et al.* 2022). Mobilizing capital at the scale required may require attracting private capital through blended capital with international or domestic financial institutions (IEA 2021c).

Domestic market conditions need to provide investor confidence. In some low- and middle-income countries, market design rules and regulations that enable the private sector to invest in clean energy need to be put in place (Fazekas *et al.* 2022). Stable and robust legal and regulatory institutions are important to investors. Domestic financial institutions can provide support to enhance the financial viability of projects. The India Infrastructure Project Development Fund is an example of such an institution that bore early-stage risk in large infrastructure projects.[3] As discussed in section 6.5, the viability of clean energy investments in electricity production also depends on reliable electricity policies, grid reliability and on the financial viability of utilities.

Matching reformed and scaled up international finance with domestic mitigation strategies requires appropriate mechanisms to facilitate international cooperation.

The preparation of the next round of NDCs due in less than two years, which will include mitigation targets for 2035, provides an opportunity in this context. Most of the NDCs for 2030 are unconditional. However, some low- and middle-income countries have submitted conditional NDCs – i.e. commitments with more ambitious emission reduction targets for 2030 than those of unconditional NDCs, but which are contingent on the provision of support. Current NDCs often lack specificity on policies and on investment needs (Pauw *et al.* 2018). A few countries list policies associated with higher ambition, while some others have merely listed sectoral policies in their NDC. The next round of NDCs offers the opportunity for low- and middle-income countries to develop road maps for more ambitious low-carbon development futures that include policies with accompanying targets and investment needs, against which finance and technology support can be negotiated and implementation progress can be measured. The twenty-eighth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 28) is a timely opportunity to call on low- and middle-income countries to lead the preparation of such plans, and for industrialized countries to commit financial and technical support towards them.

In addition, JETPs offer a semi-structured approach to link support to low-carbon development outcomes. However, they are likely to be more useful if they embrace a broad domestic vision for national economic transformation and fund broader programmes rather than individual projects for coal or other fossil-fuel phase-down. Moreover, they can offer a process to help develop capacity and governance in key areas, such as project tracking, data management and outcome measurement, and identify needs in line with national goals and a vision of a just transition.

3 See https://ppp.worldbank.org/public-private-partnership/library/india-project-development-fund-ipdf.

7 The role of carbon dioxide removal in achieving the Paris Agreement's long-term temperature goal

Lead authors:

Oliver Geden (German Institute for International and Security Affairs, Germany), Matthew Gidden (International Institute for Applied Systems Analysis [IIASA], Austria), Mai Bui (Imperial College London, United Kingdom) and Mercedes Bustamante (Universidade de Brasília, Brazil)

Contributing authors:

Holly Buck (State University of New York at Buffalo, United States of America), Sabine Fuss (Mercator Research Institute on Global Commons and Climate Change, Germany), Gaurav Ganti (Climate Analytics, Germany), Jan Minx (Mercator Research Institute on Global Commons and Climate Change, Germany), Gregory Nemet (University of Wisconsin-Madison, United States of America), Julia Pongratz (University of Munich and Max Planck Institute for Meteorology, Germany), Joana Portugal-Pereira (Graduate School of Engineering [COPPE], Universidade Federal do Rio de Janeiro, Brazil), Stephanie Roe (World Wide Fund for Nature [WWF], United States of America) and Stephen M. Smith (University of Oxford, United Kingdom)

7.1 Introduction

Under current or planned emission reduction efforts, as presented in chapter 4, the expanded use of carbon dioxide removal (CDR) is unavoidable if the Paris Agreement long-term temperature goal is to remain within reach.

CDR is already being deployed, mainly in the form of conventional land-based methods and mostly in the developing countries. As described in section 7.1.1, there are various current and emerging approaches for CDR. These approaches are at varying levels of maturity and have different types of risks that are either method- or implementation-specific (e.g. relating to land competition, sustainability, biodiversity, durability or high energy requirements) or of a more systemic nature, such as the potential to undermine the priority of emission reductions or overestimating the future efficacy of CDR.

It is important to note that all mitigation scenarios assessed by the Intergovernmental Panel on Climate Change (IPCC) (Riahi *et al.* 2022) that are aligned with the Paris Agreement temperature goal make use of CDR to some extent, especially to achieve and even go beyond net-zero carbon dioxide (CO_2) emissions and eventually all greenhouse gas (GHG) emissions. The gigaton-level application of CDR in these scenarios imply a need for substantial growth in nascent technologies. For this to happen, both national and international policy and governance regimes will need to be developed to better incorporate CDR constraints and opportunities. Beyond a commitment to formally integrating CDR in existing climate policy frameworks, four important areas for political action can be identified: setting and signalling priorities; developing robust measurement, reporting and verification systems; harnessing synergies and co-benefits; and accelerating needed innovation.

7.1.1 CDR methods and characteristics differ

As a result of the continued increase in GHG emissions worldwide, CDR has gradually become an increasingly essential element of scenarios consistent with limiting global warming to 1.5°C or well below 2°C (Pathak *et al.* 2022; Riahi *et al.* 2022). Achieving these targets will still require the rapid decarbonization of industry, transport, heat and power systems, but will need to be combined with the scale-up of CDR technologies to address residual emissions from so-called hard-to-abate sectors, such as aviation, shipping, heavy industry and some agricultural activities.

When discussing CDR, it is vital to clearly differentiate between a set of related but different options for managing carbon emissions:

- CDR is only the direct removal of CO_2 from the atmosphere and its durable storage in geological, terrestrial or ocean reservoirs, or in products.

- While carbon capture and storage and carbon capture and utilization share components with some CDR methods, their application on CO_2 emissions from fossil fuels can never result in CO_2 removal from the atmosphere.

- Carbon capture and storage involves the capture of CO_2 from point-source emissions, industrial process streams or the atmosphere, which is then transferred into permanent CO_2 storage (e.g. long-term geological storage). Some CDR processes require carbon capture and storage technologies to be considered for CDR (e.g. bioenergy with carbon capture and storage or direct air carbon capture and storage).

- Carbon capture and utilization involves the capture of CO_2 from a point source or the atmosphere, which is then used to produce other products, such as fuels and chemicals. The key difference of this approach from CDR and carbon capture and storage is that most carbon capture and utilization products will eventually be combusted, resulting in the re-release of the CO_2 back into atmosphere.

Methods that can provide direct removal of CO_2 from the atmosphere and durably store it include afforestation, reforestation, coastal blue carbon management, enhanced weathering, biochar, soil carbon sequestration, direct air carbon capture and storage, bioenergy with carbon capture and storage, ocean alkalinity enhancement and ocean fertilization (Fuss *et al.* 2018; National Academies of Sciences, Engineering, and Medicine 2019; Babiker *et al.* 2022; Bui and Mac Dowell [eds.] 2022).[1] Figure 7.1 summarizes the main characteristics of CDR methods.

Conventional approaches such as afforestation and reforestation have been practised for centuries, but not at the scale assumed in IPCC-assessed mitigation scenarios, and will therefore need to be backed by improved inventory methods for credibility. Other so-called novel CDR methods are in the early stages of development, or have reached pilot, demonstration and even commercialization stages, for example bioenergy with carbon capture and storage, direct air carbon capture and storage, biochar or enhanced weathering (Smith *et al.* 2023).

CDR efficiency is the fraction of CO_2 captured that is permanently removed from the atmosphere, having also accounted for any GHG emissions arising along the supply chain. CDR potential and scalability of each CDR implementation pathway will depend on the method used. Specific CDR approaches will have different co-benefits (e.g. soil improvements), risks and adverse consequences (e.g. land competition for food production).

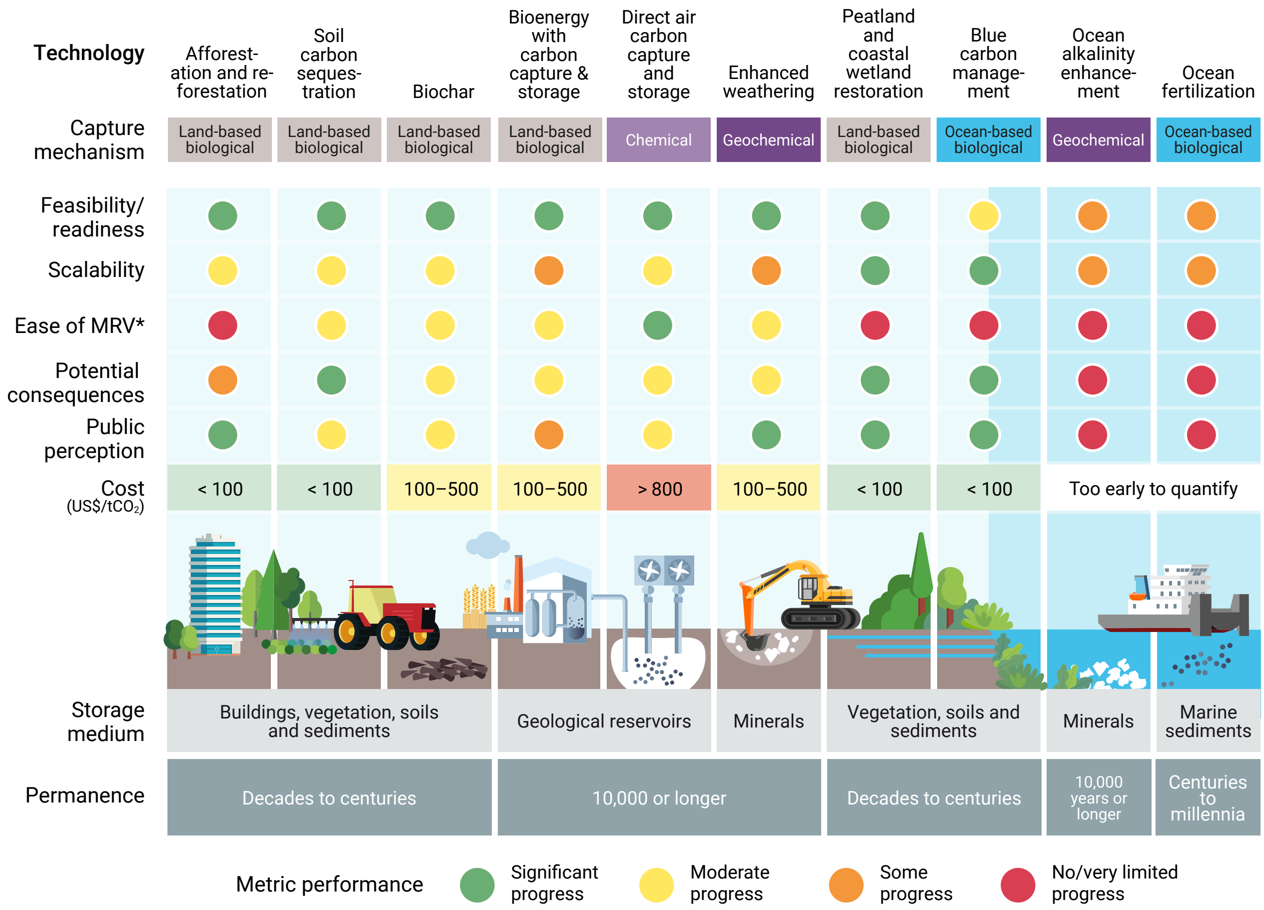
The timescale of CDR from different CDR approaches is an important factor to consider in terms of the possible speed at which global warming is reduced. For instance, forest carbon sinks can take decades to centuries to establish and saturate, while the mineral carbonation process of enhanced rock weathering can take months to years, or even decades to proceed to completion. In contrast, direct air capture removes CO_2 on much more immediate timescales (Chiquier *et al.* 2022).

CDR permanence is the duration of time for which the captured carbon is stored and is also referred to as carbon storage durability. Depending on the CDR method, this can vary from decades to thousands of years, or even longer (figure 7.1). Each carbon storage option will have some level of risk of reversal, which refers to the risk associated with the re-release of the stored carbon through an unintended event or activity.

To accurately measure net CDR, measurement, reporting and verification methodologies are being developed for different CDR options, which will provide standardized guidance on project eligibility criteria, required field measurements, best practice principles (e.g. to avoid the reversal of CDR) and life cycle assessment boundaries to quantify the carbon stored and emitted. The ease of measurement, reporting and verification will have an impact on the cost, feasibility and even the perception of CDR implementation options (Mercer and Burke 2023).

1 There is conceptual overlap between biological removal methods (such as reforestation, soil carbon sequestration or blue carbon management) and nature-based solutions, defined by the International Union for Conservation of Nature as actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges (e.g. climate change mitigation) effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits (Cohen-Shacham *et al.* 2016). Considering that nature-based solutions encompass both emission reductions/avoidance and removals, the term is not used in this chapter due to the focus on CDR.

Figure 7.1 Overview of CDR methods and their main characteristics



* Monitoring, reporting and verification. For example, ease of MRV indicates the level of development in practices for MRV of CO_2 for a given CDR option. Green suggests MRV is well developed, where the methodology and techniques are well-established and standardized due to comprehensive and demonstration trials providing valuable learnings. Red corresponds to either a lack of practical experience, or technical difficulties with the MRV development for a CDR approach.

Note: The coloured circles indicate the level of progress for different metrics based on current development of the technology. Green corresponds to progress being close to the target levels required for wider adoption, whereas red indicates no progress or limited progress towards the target.

Sources: Adapted from Geden *et al.* (2022) and Pisciotta, Davids and Wilcox (2022).

7.1.2 CDR plays different roles in current and future mitigation

Robust strategies for limiting a global temperature increase include both immediate and stringent emission reductions and the active removal of CO_2 from the atmosphere. Global mitigation scenarios assessed by the IPCC Working Group II Sixth Assessment Report (WGII AR6) show that the main mitigation focus until net-zero CO_2 emissions are reached is on reducing emissions, mainly by substantially reducing the use of all fossil fuels, electrifying energy end-use sectors (including mobility), reducing energy demand through energy efficiency measures and reducing deforestation and ecosystem degradation (Riahi *et al.* 2022).

CDR can support ambitious mitigation strategies in three ways. Firstly, it can contribute to the reduction of net emissions in the near term, primarily through sustainable land-use practices and the expansion of forested land. Secondly, in the medium term it can compensate for remaining emissions from challenging sectors, such as CO_2 from industrial activities (e.g. the production of chemicals, iron, steel and cement) and long-distance transport (e.g. aviation and shipping), as well as methane and nitrous oxide from agricultural activity (e.g. animal husbandry and fertilizer production), thereby supporting the achievement of net-zero CO_2 emissions and eventually net-zero GHG emissions later in the century. Lastly, in the long term, deploying CDR at levels surpassing annual residual gross GHG emissions would result in net-negative emissions that would then facilitate a decline in the global mean temperature, and a move towards the Paris Agreement long-term temperature goal after a temporary overshoot (Fuss *et al.* 2014; Minx *et al.* 2018; Rogelj *et al.* 2018).

7.2 The land sector dominates current CDR levels

CDR is already in use, with removals mostly taking place in the land sector. These carbon removals are largely carried out via conventional methods that have been used for decades (or even centuries), often for reasons other than climate change mitigation. Conventional methods include afforestation, reforestation, enhanced soil carbon sequestration, peatland and wetland restoration, agroforestry and forest management, including the transfer of biomass to durable harvested wood products, in which CO_2 is taken up by photosynthesis and is stored in terrestrial vegetation, soil or as wood products. Countries already report these carbon removals as standard practice under their land use, land-use change and forestry (LULUCF) activities. Bookkeeping methods estimate present-day direct removals through these conventional methods to be 2.0±0.9 gigatons (Gt) of CO_2 per year, primarily from afforestation and reforestation and the management of existing forests (Smith *et al.* 2023). The majority (about two thirds) of these removals occur on land in non-Annex I countries (Friedlingstein *et al.* 2022).

Total CO_2 uptake in the LULUCF sector is substantially larger than that estimated for CDR alone: gross removals in the LULUCF sector amount to 9.6±1.4 $GtCO_2$ per year averaged over 2012–2021, with a net (removal) flux on forested land of 3.5±1.0 $GtCO_2$ per year (Friedlingstein *et al.* 2022). However, these additional removals through forest regrowth are linked to land-use activities that also cause emissions, particularly from slash and burn practices, soil carbon and product decomposition in forestry and the clearing of forests by shifting cultivation. Only a transfer to durable storage, such as long-lived harvested wood products, is counted towards CDR (estimated to about 0.2 $GtCO_2$ in 2022) (Powis *et al.* 2023). Indirect anthropogenic effects, such as carbon fertilization, enhance the ability of the LULUCF sector to remove carbon from the atmosphere even further but are counted towards the natural terrestrial land sink and are not directly attributable to CDR activities in scientific assessments (Friedlingstein *et al.* 2022), although they are partly included in national GHG inventories (Grassi *et al.* 2023). Additional efforts to remove CO_2 through enhancing natural sinks include coastal wetland (blue carbon) management (Smith *et al.* 2023).

Other removal methods, including bioenergy with carbon capture and storage, biochar, direct air carbon capture and storage and enhanced weathering (collectively referred to here as novel CDR) are currently at lower levels of technological readiness and are at smaller pilot or experimental scales of implementation (Babiker *et al.* 2022). Estimates indicate that present-day removals from these approaches are small compared with removals from conventional methods, amounting to approximately 2.3 megatons (Mt) of CO_2 per year, primarily from a small number of bioenergy with carbon capture and storage facilities, which remove 1.8 $MtCO_2$ per year, with approximately 0.5 $MtCO_2$ of removals per year occurring from biochar production (Powis *et al.* 2023). Smaller contributions come from a range of other projects that use methods such as direct air carbon capture and storage and enhanced rock weathering. It is important to note that CO_2 captured by these methods is only considered CDR if the captured CO_2 is durably and permanently stored. Thus, captured CO_2 that is used in short-lived products (e.g. for sustainable aviation fuels) is not considered CDR. Similarly, captured CO_2 that is used for enhanced oil recovery raises serious carbon accounting concerns (Schenuit *et al.* 2023).

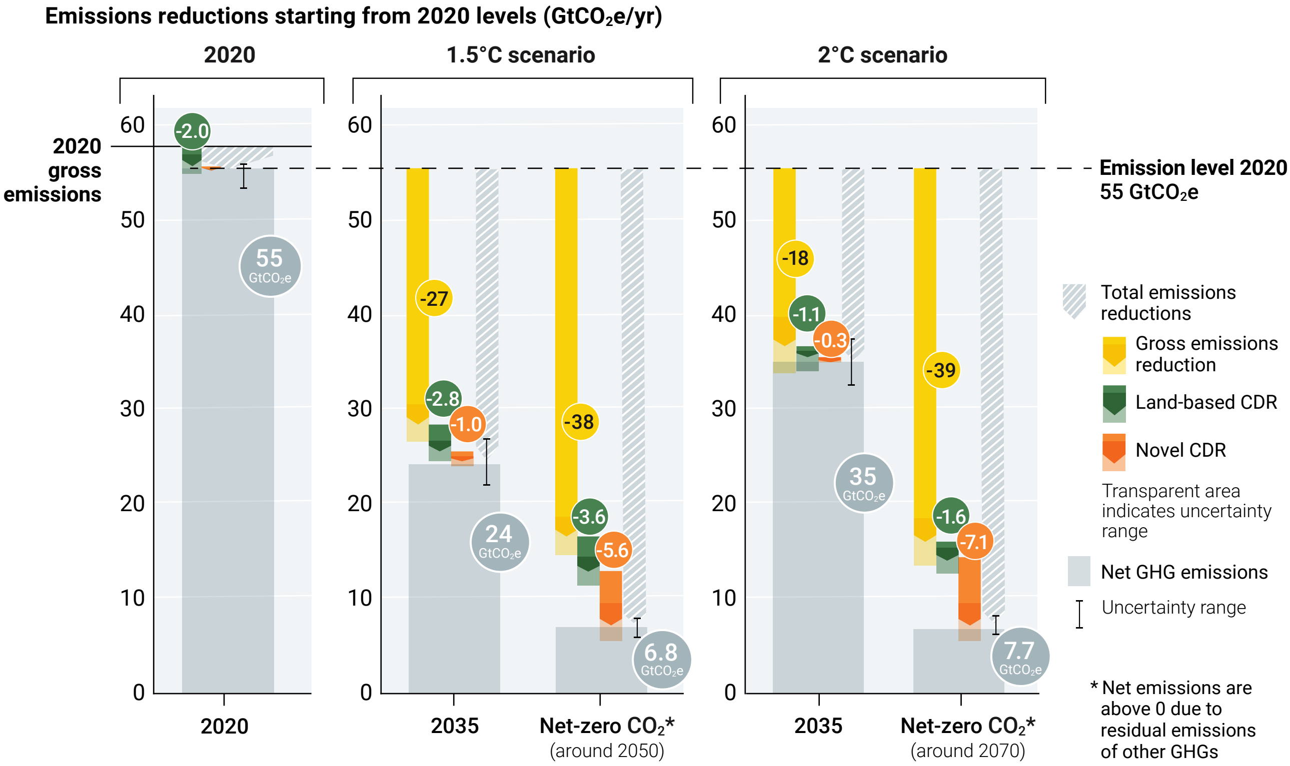
7.2.1 CDR contributes to global mitigation pathways

In least-cost mitigation pathways assessed in IPCC WII AR6 and considered in chapter 4, the amount of mitigation achieved by reducing gross emissions (e.g. switching from fossil fuels to renewable energy, increasing energy efficiency or reducing the demand for emission-intensive goods and services) compared with actively removing CO_2 from the atmosphere depends on various factors, most notably the magnitude and timing of the peak temperature achieved in a scenario as well as the degree of temperature reduced after the peak. Across all pathways assessed here, the primary mitigation activity both in the near and long term is reducing gross emissions (figure 7.2).

In the near term, 1.5°C and 1.8°C pathways both see rapid gross emission reductions, further highlighting the importance of reducing emissions this decade. However, these pathways differ, as the 1.5°C pathways tend to scale up land-based carbon removals more ambitiously, resulting in greater net emission reductions by 2035 compared with the 1.8°C pathways. In both cases, novel CDR plays a relatively minor role until at least 2035, as the various technologies begin to scale up to provide removals later in these scenarios. Less ambitious climate targets such as 2°C see slower gross emission reductions and lower levels of both land-based and novel CDR in comparison (figure 7.2).

Net-zero CO_2 emissions are achieved at different times depending on the temperature target, with 1.5°C pathways by mid-century and other pathways one or two decades thereafter. By the time net-zero CO_2 emissions are reached, most mitigation efforts across all scenarios continue to be in the form of gross emission reductions, through which roughly 80 per cent of total efforts occur (figure 7.2, panel c). The pathways mostly differ in the relative contribution of land-based CDR and novel CDR for the remaining 20 per cent of efforts. In 1.5°C pathways, land-based removals from afforestation and reforestation increase to 6.2 (4.5–6.8) $GtCO_2$ per year (median and interquartile range) by mid-century, while novel forms of CDR increase to around 4.2 (3.7–6.2) $GtCO_2$ per year, which is approximately 1,500 times more than present levels. Because net-zero CO_2 emissions are reached later in 1.8°C and 2.0°C pathways, larger relative contributions to total CDR come from novel methods. In all cases, novel CDR begins to overtake land-based CDR, on average, by around 2060, and is the main contributor to total CDR by the end of the century.

Figure 7.2 The role of emission reductions and CDR in least-cost pathways consistent with the Paris Agreement



Notes: The left panel shows global GHG emissions and levels of CDR in 2020. The centre panel shows snapshots of gross emission reductions, CDR and remaining GHG emissions in 2035 and at the time of net-zero CO_2 under a 1.5°C pathway. The right panel shows the same for a 2°C pathway.

Sources: Byers *et al.* (2022); Riahi *et al.* (2022); Smith *et al.* (2023).

Certain sectors are crucial in facilitating these levels of removals. The use of bioenergy with carbon capture and storage in scenarios provides a source of power and heat with net-negative emissions but uses less energy-efficient processes to produce electricity and synthetic fuels while drawing down CO_2 emissions (Bauer *et al.* 2018; Daioglou *et al.* 2020). Direct air carbon capture and storage is particularly dependent on the electricity sector, both from an operational perspective and for its net capture efficiency. When paired with zero-carbon or net-negative electricity systems, direct air carbon capture and storage can remove CO_2 without resulting in a substantive additional carbon footprint from its operation (Bistline and Blanford 2021; Fuhrman *et al.* 2021; Strefler *et al.* 2021). Other CDR methods, such as biochar, soil carbon sequestration and enhanced weathering, as well as bioenergy with carbon capture and storage, depend on agricultural and other environmental management practices and decarbonized supply chains to support their deployment (Strefler *et al.* 2018; Beerling *et al.* 2020). As highlighted in previous Emissions Gap Reports, the models' use of CDR options such as bioenergy with carbon capture and storage depend on several assumptions that may not be fully realistic in terms of the availability of required land areas and competition for water resources and food, among others (see section 7.3).

The level of CDR needed in 1.5°C and 2°C scenarios heavily relies on policy decisions and technological advancements. Further delays in near-term emission reductions are set to increase future reliance on CDR to achieve ambitious temperature goals or will otherwise make them unattainable this century (Babiker *et al.* 2022). Limiting reliance on CDR thus requires ambitious action to limit the total emissions left in the energy–economy system. The sectors that will end up contributing substantial residual emissions in a net-zero or net-negative future will depend on both sector and country-level mitigation strategies. Hard-to-abate sectors such as heavy industry (which includes iron, steel, cement, chemical and fertilizer production) have been identified as sectors with relatively more expensive mitigation options. For example, the agriculture sector contributes substantial amounts of short-lived non-CO_2 emissions mainly due to livestock husbandry and current agricultural practices, such as rice cultivation, and global transport sectors, including long-haul aviation and shipping, currently use high-emission fuels.

7.2.2 National climate strategies focus on land-based CDR

Many countries currently report net-negative LULUCF emissions in their national GHG inventories, and thus already include land-based CDR, which is part of the negative component of gross LULUCF fluxes (see section 7.2). At present, many nationally determined contributions (NDCs) for 2030 and net-zero pledges made by countries do not specify how much they will depend on CDR, nor the level of residual emissions they plan to maintain when achieving net-zero CO_2 and GHG emission targets (Buck *et al.* 2023b). Removals from the land sector form the bulk of current CDR estimates implied by existing NDCs, with 2030 levels estimated to be between 2.1 and 2.6 $GtCO_2$ of removals per year, depending on the conditionality of the NDC. Current literature estimates of the implied levels of land-based removals in long-term strategies and net-zero pledges are 2.1–2.9 $GtCO_2$ of removals per year by 2050, though this is based on an incomplete sample of 53 countries (updated from Smith *et al.* 2023). It is also important to note that the literature estimates vary based on whether they exclude indirect anthropogenic effects (see chapter 2). In general, very little information is available from country submissions to the United Nations Framework Convention on Climate Change (UNFCCC) in terms of the expected use of novel CDR to achieve net-zero targets, with aggregate estimates around 600–1,000 $MtCO_2$ per year by 2050 (Smith *et al.* 2023). As figure 7.2 illustrates, these levels implied by country pledges are substantially below the levels in least-cost pathways consistent with the Paris Agreement's long-term temperature goal.

At present, countries do not separate their planned gross emission reductions from their planned use of CDR in national target setting, and thus can in principle achieve their national climate targets by pursuing different mitigation strategies. Countries choose their mitigation strategies based on their capabilities, which in turn has significant impacts on the amount of CDR required to meet their climate targets. Countries with significant dependence on land-based removals may find their targets more difficult to achieve since these removals weaken with increasing climate action (Gidden, Gasser *et al.* 2023).

Large-scale CDR deployment may face significant ecological, environmental and social constraints (Fujimori *et al.* 2022). In many regions of the world, significant expansion of land-based CDR will require much stronger governance structures and will compete with agricultural production. CDR that involves energy use, such as direct air carbon capture and storage and enhanced weathering, will require net-zero energy supply to be truly carbon negative (Realmonte *et al.* 2019; Grant *et al.* 2021). Furthermore, these options may face opposition from citizens concerned with the impacts of new infrastructure, the cost of CDR, the ability of Governments to safely regulate geological CO_2 storage and unintended consequences, among others (Cox, Spence and Pidgeon 2020).

7.3 The risks of depending on large-scale CDR to meet climate goals

Relying on large-scale CDR has various risks. The main climate-related risks include the durability of conventional land-based CDR approaches and an inability to deliver novel CDR approaches at the envisaged scale, while the main sustainability-related risks include impacts on biodiversity, water resources, nutrient loading, food security and livelihoods.

7.3.1 Climate risks include issues with durability and acceptance

Currently, terrestrial ecosystems are responsible for absorbing a quarter of anthropogenic carbon emissions, with ecosystem restoration (including the expansion of forest cover through reforestation) the most cost-effective and scalable CDR option. The maintenance of the existing land carbon sink and its enhancement represent a substantial contribution to mitigation pledges and scenarios. However, the permanence of carbon stored in forests, peatlands, coastal wetlands and soils under both climate change and direct human intervention is uncertain (Windisch, Davin and Seneviratne 2021). Storing carbon in plant biomass and soils is limited to timescales of several decades to centuries, with the carbon storing ability saturating over time. Natural and managed ecosystems are also subject to natural and anthropogenic disturbances, such as fires, degradation and deforestation, which release the stored carbon back into the atmosphere.

The durability of carbon sequestered in the biosphere, including conventional CDR methods, is less than that of novel CDR measures that rely on geological storage (see figure 7.1) (Fuss *et al.* 2018; National Academies of Sciences, Engineering, and Medicine 2019; Bui and Mac Dowell [eds.] 2022; IPCC 2022a). However, the value of these options for climate policy (Fuss, Golub and Lubowski 2021; Kalkuhl *et al.* 2022) should not be underestimated as they are often associated with substantial ecosystem services and livelihood co-benefits (Smith *et al.* 2019; Ruseva *et al.* 2020).

For climate policy to be effective, it is crucial to understand the effects of CDR and emissions, potential interlinkages and the timing of effects. Due to the impact of natural disturbances on forests, the risk of such disturbances has been integrated into forest management with a focus on timber production rather than carbon benefits. A few risk-accounting methods have been introduced, specifically for hurricanes and wildfires at site, region or country-specific scales (Chiquier, Fajardy and Mac Dowell 2022).

While novel CDR approaches that store carbon in the geosphere have greater storage durability, there is a risk that the technical, economic and political requirements for large-scale deployment may not materialize in time. Controversies in the debate in many countries show that public acceptance is still uncertain for various CDR methods, particularly approaches involving carbon capture and storage or the open ocean (Cox, Spence and Pidgeon 2020; Merk *et al.* 2022; Nawaz, Peterson St-Laurent and Satterfield 2023; Satterfield, Nawaz and St-Laurent 2023), which can negatively affect the prospects for scale-up, despite the technical potential of the approach. Furthermore, transparent and robust measurement, reporting and verification is needed to build trust and support CDR scale-up (de Coninck *et al.* 2022).

At both the national and international levels, overly-optimistic dependence on future CDR could be used to design policies that divert the focus from stringent near-term emission reduction efforts (Lenzi *et al.* 2018; Markusson, McLaren and Tyfield 2018) or mask insufficient mitigation policies (Geden 2016; Carton 2019).

A broad CDR portfolio that balances these trade-offs and potential benefits will be important for mitigating the outlined risks. Furthermore, energy-intensive methods such as direct air carbon capture and storage or enhanced weathering in the near to medium term will only be an option in pathways with a quick and comprehensive phase-out of all fossil fuels (i.e. that involve a largely decarbonized energy mix and/or lower energy demand).[2] Carbon capture and storage will still be needed in this transition to capture and store industrial emissions (Bashmakov *et al.* 2022) that cannot easily be reduced to zero or at least not quickly enough (Lecocq *et al.* 2022). Carbon capture and storage thus has a dual role of addressing residual emissions from fossil fuel and industry in the medium term, and of removing CO_2 from the atmosphere in the longer term as part of direct air carbon capture and storage and bioenergy with carbon capture and storage.

Even if the risks described in this section could be mitigated, key uncertainties exist with respect to how much CDR will be needed, as scenario-based assessments do not currently account for the full range of uncertainties in Earth system responses. Asymmetries in the climate response to net-positive and net-negative emissions (Zickfeld *et al.* 2021), as well as the expected warming when CO_2 emissions cease (MacDougall *et al.* 2020; Koven, Sanderson and Swann 2023) can affect the levels of CDR needed to achieve a given climate outcome.

7.3.2 Addressing sustainability risks will be essential

Strategies underlying national net-zero pledges and NDCs generally tend to feature only conventional land-based CDR, most of which is centred around forestry and agriculture (Smith *et al.* 2023). Sustainability-related risks of conventional CDR (e.g. afforestation, reforestation, agroforestry, ecosystem restoration and soil carbon sequestration) are perceived to be less than those associated with novel biological CDR methods (e.g. bioenergy with carbon capture and storage) due to environmental concerns including land-use change, fertilizer use or irrigation. Co-benefits for biodiversity, ecosystem services and livelihoods, as well as co-delivery on other international and national commitments on biodiversity, land degradation and people, have also propelled the use of conventional CDR approaches. However, the risks and benefits of CDR depend on the method used and its implementation and management (e.g. reforestation with native species versus afforestation of non-forest biomes with non-native monocultures).

Competition for land is a pressing issue due to numerous global demands, including for food production, resource extraction, infrastructure development, biodiversity and ecosystem services conservation and climate change mitigation. Environmental changes, such as climate change, may exacerbate land-use competition, due to complex feedback processes between human and biophysical components in the land system (Haberl *et al.* 2014). Cropland and urban expansion therefore also compete with land-based CDR options. Modelling efforts show that cropland expansion to fulfil future food demand is the primary cause of such competition, with more severe impacts seen in the tropics due to their greater land-based mitigation potential (Zheng *et al.* 2022). Such findings highlight that careful spatial planning is essential for sustainable climate policies.

Various land-based CDR options have the potential to enhance biodiversity. An assessment of the biodiversity impacts of 20 land-based mitigation options showed that most options benefit biodiversity. However, a quarter of the assessed options, including bioenergy with carbon capture and storage, decreased mean species abundance, while afforestation and forest management either positively or negatively affected biodiversity depending on the local implementation method and forest conservation schemes adopted (Nunez, Verboom and Alkemade 2020). Recent studies explore how ambitious objectives and multiple targets of biodiversity and climate conventions can be operationalized spatially and pursued concurrently (e.g. Soto-Navarro *et al.* 2020; Jung *et al.* 2021; Duncanson *et al.* 2023). Given potential land competition, it is crucial to identify land areas where the greatest synergies can be achieved.

7.4 Equity and differentiated responsibilities associated with deploying CDR

Equity and the principle of "common but differentiated responsibilities and respective capabilities" are key normative pillars of the Paris Agreement. Scientists, analysts and policymakers have long debated how to operationalize

2 See Fasihi, Efimova and Breyer (2019) for an in-depth assessment of direct air carbon capture and storage energy requirements.

this principle, with a focus on how to set equitable emission reduction targets (Robiou du Pont *et al.* 2017; Holz *et al.* 2018; Kartha *et al.* 2018), regional carbon budgets (Raupach *et al.* 2014) and fair mitigation financial obligations (Pachauri *et al.* 2022; Semieniuk, Ghosh and Folbre 2023). Relatively little attention has been paid so far to extending this principle to equitable CDR targets, with some notable exceptions (Fyson *et al.* 2020; Mohan *et al.* 2021; Yuwono *et al.* 2023).

The global achievement of net-zero GHG emissions does not imply that all regions achieve net zero at the same time or contribute the same amount of carbon removal. The integrated assessment modelling pathways assessed in section 7.2.1 and in chapter 4, show specific regional patterns associated with cost-effective CDR deployment. When accounting for cumulative removals between 2020 and 2050, the highest shares of removals are in Asia and Latin America consistently across scenarios (table 7.1). Both regions tend to have higher removal levels than the Organisation for Economic Co-operation and Development (OECD) region when considering both land-based and novel removals, while other regions have consistently lower levels. Importantly, these results come from integrated assessment modelling approaches to achieve climate targets in a global cost-effective manner and are not necessarily oriented towards identifying an equitable distribution of efforts (Bauer *et al.* 2020).

Table 7.1 Shares of cumulative removals in different scenarios between 2020 and 2050 by IPCC WGIII modelling region

IPCC modelling regions Scenarios consistent with limiting global warming to specific temperature limits	Asia	Latin America	OECD	Reformed economies (R5REF)	Middle East and Africa (R5MAF)
1.5°C	34 (29–36)%	22 (20–26)%	20 (16–24)%	5 (5–6)%	16 (11–17)%
1.8°C	37 (34–43)%	20 (16–23)%	18 (17–25)%	7 (5–8)%	13 (9–17)%
2.0°C	38 (36–43)%	23 (19–25)%	19 (18–23)%	8 (6–9)%	12 (9–15)%

Note: The median value is shown with the interquartile range in brackets.

Equitable distributions can differ quite significantly from cost-effective deployment of mitigation options. Fyson *et al.* (2020) suggest one possible approach to allocating global CDR deployment fairly: allocating regional CDR in proportion to regional emissions that exceed a counterfactual equal per capita emission pathway. A slightly adapted version of this approach[3] is applied to the pathways assessed in section 7.2.1 to illustrate the difference of equitable distributions from cost-effective deployment. Under this approach, developed countries (taken as the OECD region from chapter 3 of IPCC WGIII AR6) have equitable allocations of around 80 per cent of the cumulative removals deployed between 2020 and 2050 across the three pathway categories (1.5°C, 1.8°C and 2°C) assessed in section 7.2. This illustrative calculation demonstrates the importance of extending considerations of equity under the Paris Agreement while deploying CDR.

Achieving more equitable outcomes in the 2020–2035 time frame will require two broad strategies, even when novel forms of CDR such as direct air carbon capture and storage are available (Gidden, Brutschin *et al.* 2023), models are increasing the technical representation of novel CDR: (1) deploying financial transfers at scale to facilitate emission reductions (Pachauri *et al.* 2022; Ganti *et al.* 2023); (2) investing in a broad range of CDR options both domestically and internationally to ensure a portfolio of approaches is available. The latter is significant as many novel CDR options are still in the early stages of innovation. Whether they will be used to help reduce temperatures and in turn long-term impacts will be decided by future generations.

CDR deployment decisions will also need to take into account domestic equity considerations. Countries will have to weigh the potential regressivity of payment schemes as well as concerns around land competition and food prices (for afforestation, reforestation and bioenergy with carbon capture and storage), water scarcity and nitrogen pollution (bioenergy with carbon capture and storage), additional energy demand (direct air carbon capture and storage) and health issues due to fine dust (enhanced weathering), among others (Strefler *et al.* 2021; Babiker *et al.* 2022). Land-based CDR deployment raises many of the same equity concerns as other land-based mitigation activities, including land tenure conflicts and dispossession, and mainly impacts poorer and more marginalized rural farmers and workers (McElwee 2023) and Indigenous Peoples, who manage a significant portion of the world's land area (Garnett *et al.* 2018). Unequal power relations and poor governance might further reduce confidence in and public acceptance of land-based CDR options (DeFries *et al.* 2022).

3 The approach is adapted from the original paper in the following ways: (1) the starting year for the calculation of excess emissions is 2005 as opposed to 1990, because the data set developed by Gidden, Brutschin *et al.* (2023) models are increasing the technical representation of novel CDR since 2005; and (2) the approach is applied to net CO_2 emissions (considering only the direct land component) as opposed to the aggregated six GHGs listed in Annex A of the Kyoto Protocol (the Kyoto "basket").

Frameworks to guide national priorities in balancing domestic equity considerations, intergenerational equity concerns and the possible contribution of CDR to meet NDCs through emerging carbon markets for removals are currently missing and will be important to advance policy discussions as a foundation for equitable future CDR deployment.

7.5 Scaling up CDR will require dedicated policies and innovation

Deliberate CDR policymaking is still scarce, apart from in the European Union, the United Kingdom and the United States of America. CDR has only just entered the climate policy debate in recent years, mainly as an unavoidable component of meeting net-zero CO_2 and GHG targets (IPCC 2022a). Only a few Governments have begun to specify the role of CDR in domestic climate policy explicitly through CDR strategies and policies. Overall, robust plans for CDR implementation are still scarce and policymaking remains largely incremental (Smith *et al.* 2023). While more than 100 countries have set net-zero emission targets, only a few countries include clear information on CDR in their NDCs and long-term low-emission development strategies. Most Governments have not yet expressed how large the contribution of CDR should be in reaching net-zero emissions and which CDR methods this might entail. Where this has been specified, removal via forests and soils is the most common approach, even in mid-century strategies (Smith, Vaughan and Forster 2022; Smith *et al.* 2023). Examples of dedicated CDR policy and governance exist mainly at the national level and primarily in developed countries (Schenuit *et al.* 2021). In multilateral initiatives, CDR only has a limited role at present (e.g. the Mission Innovation CDR). In the context of the UNFCCC, the Article 6.4 Supervisory Body has been mandated by the Parties to provide methodological guidance on CDR before the twenty-eighth session of the Conference of the Parties to the UNFCCC (COP 28).

This lack of concrete incentive frameworks is one of the reasons why there is currently almost no CDR deployment beyond the LULUCF sector. Comparing the current CDR level of 2 $GtCO_2$ to mid-century annual removals in scenarios compatible with reaching the Paris Agreement long-term temperature goal reveals a large discrepancy of several gigatons per year. In the absence of a more supportive policy environment than that indicated in existing NDCs and long-term low-emission development strategies, or the lack of CDR in national climate policy (Schenuit *et al.* 2021; Smith *et al.* 2023), this discrepancy is likely to persist and even grow, considering that the transition from first commercial deployment of a new technology to widespread adoption takes decades and not just a few years.

A large body of innovation research shows that new technologies must pass through a formative phase: the period between first commercial deployment to the beginning of widespread adoption (Jacobsson and Bergek 2004; Grubler and Wilson eds. 2013). Given the scale of removals at the time of net-zero CO_2 or GHG emissions described in scenarios, this platform for scaling up technologies is essential. The empirical literature on formative phases shows that the length of this period is highly variable, with an average estimate of around 20 years (Bento and Wilson 2016).

The highly successful technology of solar photovoltaics (PV) is a specific example of a technology in a formative phase and offers insight for the development of CDR approaches, such as small-scale direct air carbon capture and storage. In this case, the first commercial application of solar PV occurred in 1957, took 60 years to become cost-competitive and is now still a couple of decades away from widespread adoption. If small-scale direct air carbon capture and storage were to follow the path of solar PV, it would require a much faster progression through its formative phase to reach gigaton scale by mid-century. The development of expectations of large, reliable and growing markets is a repeated finding in innovation studies, as already emphasized in the Emissions Gap Report 2018, and will be crucial for CDR too. The research literature highlights the importance of local context and distinct factors, and the crucial but gradual progression in the period just before scale-up that takes decades rather than years. Two robust common implications are first, the need for strong policy support and second, urgency in delivering that support given the inherent lags in the innovation system.

There are already signs that CDR innovations are in motion. As Smith *et al.* (2023) show, the number of CDR-related patents have increased and are spread across a broader set of CDR technologies, indicating an acceleration in inventive activity and a healthy innovation system. Funding and entrepreneurial activity in CDR are also increasing. Furthermore, niche markets, such as voluntary purchase for removals, are providing the early support for novel CDR demand, with the possibility of initiating a positive feedback process of learning in which adoption begets cost reductions and performance improvements. Still, this is just the beginning. Stronger support is becoming an urgent priority if novel CDR is to play a gigaton-scale role in the longer term.

7.6 Political priorities for action are needed

With the enhancement of carbon sinks forming part of climate change mitigation (Honegger, Burns and Morrow 2021), CDR governance challenges are in many respects similar to those related to emission reductions, and similar policy instruments, such as research, development and demonstration funding, carbon pricing, tax or investment credits, certification schemes and public procurement, will be relevant (Babiker *et al.* 2022). Effectively integrating CDR into Governments' climate policy portfolios should therefore build on pre-existing rules, procedures and instruments. Furthermore, there is a need to include learnings from shortcomings in the governance of land-based mitigation and to have a special focus on local conditions (Fridahl *et al.* 2020; Mace *et al.* 2021; Rickels *et al.* 2021; IPCC 2022b). Beyond a political commitment to formally integrate CDR into existing climate policy frameworks, four priority policy action areas can be identified for the short to medium term.

7.6.1 Political priorities need to be established and signalled

For countries with net-zero or net-negative emission targets, the core governance question is not whether CDR should be mobilized, but which CDR approaches Governments want to see deployed by whom, by when, at which volumes and in which ways (Babiker *et al.* 2022). The choice of CDR approaches and the scale and timing of their deployment will depend on the respective ambitions for gross emission reductions, feasibility and viability limitations, how their unintended impacts can be managed and how political preferences and social acceptability evolve (Bellamy 2018; Forster *et al.* 2020; Waller *et al.* 2020; Smith *et al.* 2023).

To avoid CDR being misperceived as a substitute for deep emission reductions, the prioritization of emission cuts can be signalled and achieved with differentiated target setting for reductions and removals (Geden, Peters and Scott 2019; McLaren *et al.* 2019).

This needs to include the LULUCF sector, for which only net fluxes tend to be highlighted in NDCs, long-term low-emission development strategies (Fyson and Jeffery 2019) and national strategies, whereas national inventory reports differentiate between land-based emissions and removals. Similarly, subtargets are conceivable for different types of CDR, to prioritize preferred methods according to characteristics such as removal processes or storage timescales (Smith 2021). Transparent information about expected levels and types of CDR (e.g. through mandatory inclusion in the 'information to facilitate clarity, transparency and understanding' tables in NDCs) will also enable policy debates about assumptions around the level of residual emissions in and beyond the first year of net-zero emissions (Buck *et al.* 2023a).

7.6.2 Robust measurement, reporting and verification systems are needed

To maintain credibility in the CDR sector while driving innovation and growth, measurement, reporting and verification frameworks for CDR methods will need to be developed and adapted to new CDR approaches (e.g. new measurement techniques or modelling tools).

Some measurement, reporting and verification methodologies already exist for project-based accounting of both LULUCF-related and novel CDR methods, but a lack of coordination and minimum standards, especially for voluntary carbon markets, leads to an inconsistent patchwork of measurement, reporting and verification approaches (Arcusa and Sprenkle-Hyppolite 2022; Mercer and Burke 2023). In contrast, accounting for national inventories under the UNFCCC has been established for conventional land-based CDR methods and some novel methods such as biochar and bioenergy with carbon capture and storage, but similar methods have yet to be developed and agreed upon for direct air carbon capture and storage or enhanced rock weathering, for example. Such agreed methodologies are crucial to make deployment eligible for consideration under national or supranational compliance regimes (Lebling, Schumer and Riedl 2023).

In the context of the UNFCCC, the priority must be to develop accounting rules for CDR and establish trusted measurement, reporting and verification frameworks, mainly based on methodological work carried out by the IPCC's Task Force on National Greenhouse Gas Inventories. This can be done, on the one hand, by strengthening rules for land-based biological removals (most importantly addressing pre-existing permanence and saturation challenges – see Mace *et al.* 2021), and on the other hand, by creating additional guidance for novel CDR methods, for which there is a need. For some methods, the measurement, reporting and verification of carbon flows will be relatively straightforward (e.g. direct air carbon capture and storage), whereas other methods still lack foundational science, particularly those operating in open-loop systems (e.g. enhanced weathering) (Mercer and Burke 2023).

Currently, measurement, reporting and verification and certification methodologies for novel CDR methods beyond LULUCF are being developed mainly in the European Union, the United Kingdom and the United States of America, with the latter already investigating measurement, reporting and verification for a wide range of marine methods (Cross *et al.* 2023). In the medium term, such methodologies will be relevant not only for national inventory reporting but also in the context of establishing international carbon trading under the Paris Agreement's article 6.4 mechanism. However, these methodologies need to be globally vetted and accepted as part of UNFCCC reporting standards as well as national inventory rules. The latter are currently based on IPCC guidelines from 2006 and 2019, which are unlikely to be expanded without the explicit request of national Governments.

7.6.3 The need to enhance synergies and co-benefits

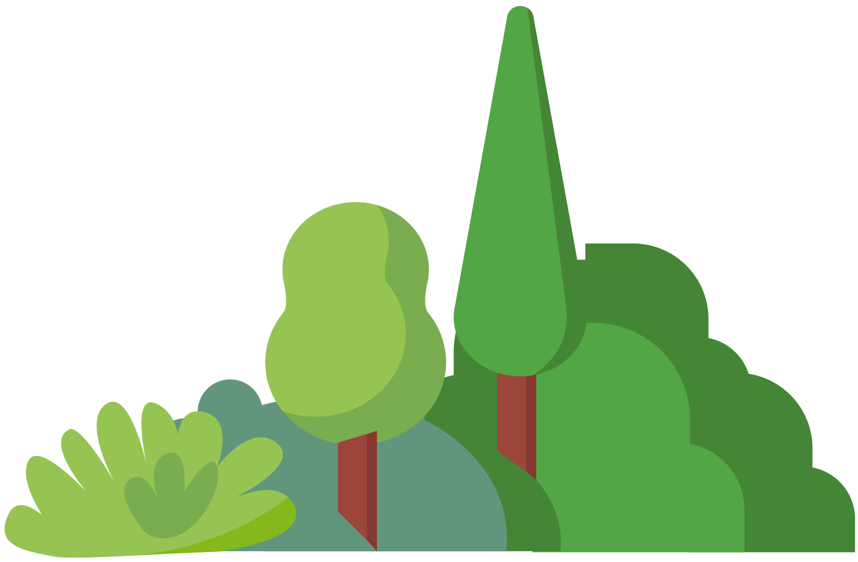
CDR approaches can have multiple benefits for adaptation, mitigation and other social and environmental goals. In some cases, these benefits may be a core motivator for adoption. For example, improved soil water retention is a key motivator for farmers to adopt practices that sequester soil carbon (Fleming *et al.* 2019; Gosnell, Gill and Voyer 2019; Buck and Palumbo-Compton 2022), and farm resilience, income diversification and food security can be important drivers of agroforestry adoption (Muthee *et al.* 2022). Co-benefits are not limited to land-based CDR. In fact, scientists are studying how forest biomass with carbon capture and storage can reduce the risk of wildfires when paired with forest thinning projects (Sanchez *et al.* 2021; Elias *et al.* 2023). Social co-benefits for industrial CDR with carbon capture and storage could include jobs or economic revenue in areas and fields affected by the energy transition (Romig 2021).

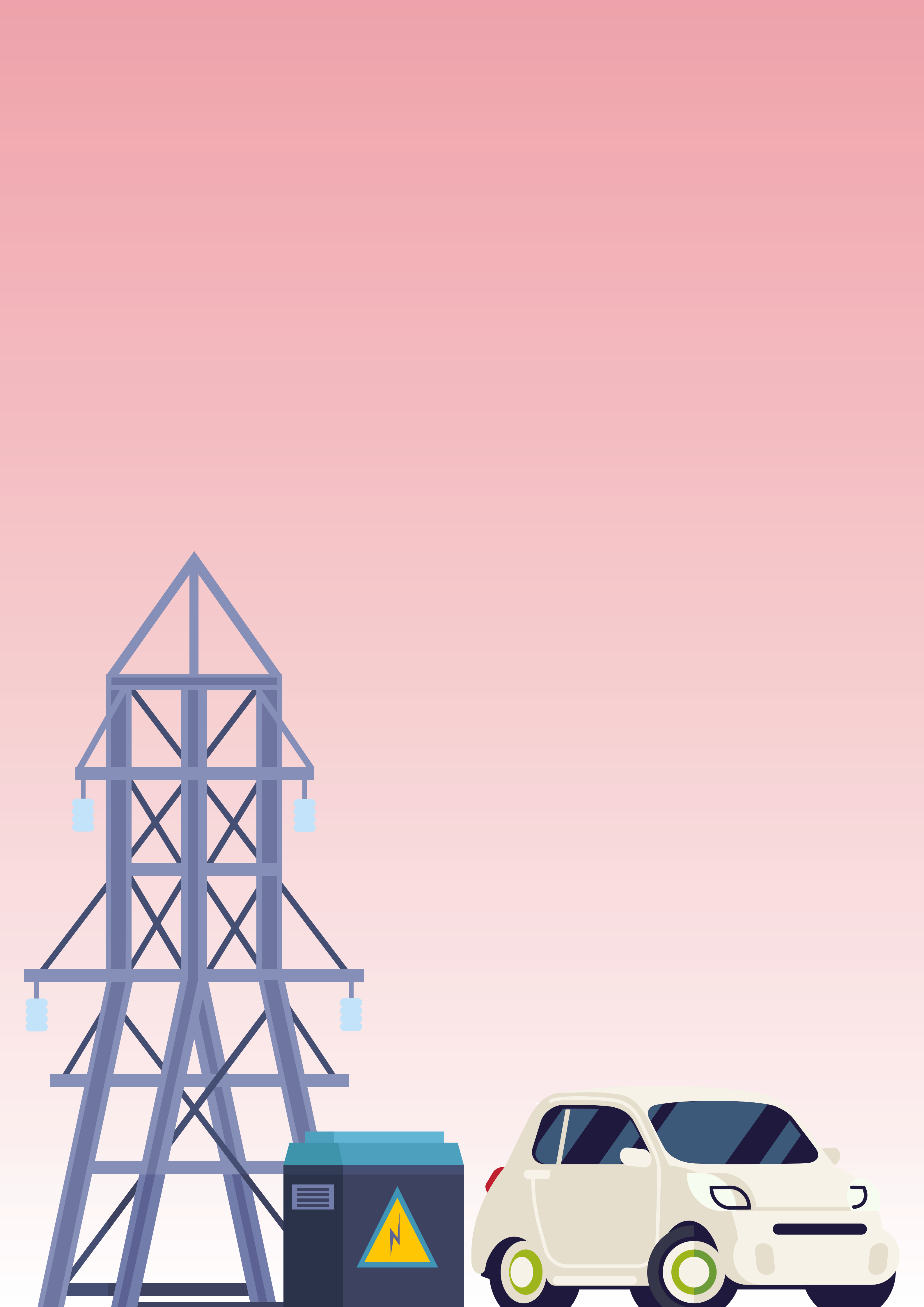
Dedicated policy design can enhance such synergies. For example, through government action to support improvements in CDR measurement, reporting and verification so that adaptation projects can have an additional revenue stream (Buck *et al.* 2020), or through planned actions that consider decarbonization and CDR together, and not just in terms of developing bioenergy via carbon capture and sequestration for hydrogen and electricity generation, but also considering how hydrogen or synthetic fuels may be co-products of direct ocean-based capture and sequestration (Digdaya *et al.* 2020). Considering CDR in mitigation and adaptation infrastructure planning can help ensure that potential co-benefits from CDR come to fruition.

7.6.4 Innovation and learning needs to be accelerated

Proceeding through the early years of CDR's formative phase will require various demonstration projects, for which a cost-reducing learning-by-doing process can be put in place (Lackner and Azarabadi 2021). For example, the Department of Energy of the United States of America will provide US$3.5 billion in federal support for four regional Direct Air Capture (DAC) hubs, with the United States Government also funding the feasibility and design studies of 19 other DAC projects at varying stages of technological readiness. Similarly, emerging programmes for bioenergy with carbon capture and storage in Sweden and the United Kingdom will provide valuable progress during the "middle" of the formative phase for CDR technologies.

Furthermore, the coming years of CDR development provide an opportunity for societal learning about the sustainability impacts of novel CDR (Honegger, Michaelowa and Roy 2021; Madhu *et al.* 2021; Fuhrman *et al.* 2023). Insight on a large set of issues can be gleaned from experiments, demonstrations and small-scale deployment. These issues include public acceptance, distributional effects, affordability, life cycle analysis, biodiversity, resource consumption, competition for land and interactions among CDR approaches (Buck 2016; Erans *et al.* 2022; Owen, Burke and Serin 2022), as well as future costs (Shayegh, Bosetti and Tavoni 2021).





References

Chapter 1

C

Copernicus Climate Change Services (2023a). Tracking breaches of the 1.5°C global warming threshold, 15 June. https://climate.copernicus.eu/tracking-breaches-150c-global-warming-threshold. Accessed 25 October 2023.

__________ (2023b). Copernicus: September 2023 – unprecedented temperature anomalies; 2023 on track to be the warmest year on record, 5 October. https://climate.copernicus.eu/copernicus-september-2023-unprecedented-temperature-anomalies. Accessed 25 October 2023.

I

International Energy Agency (2023). *World Energy Outlook*. Paris. https://iea.blob.core.windows.net/assets/26ca51d0-4a42-4649-a7c0-552d75ddf9b2/WorldEnergyOutlook2023.pdf.

L

Lee, H., Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. *et al.* (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf.

P

Pathak, M., Slade, R., Shukla, P.R., Skea, J., Pichs-Madruga, R., Ürge-Vorsatz, D. *et al.* (2022). Technical summary. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_TS.pdf.

U

United Nations (2023). *The Sustainable Development Goals Report 2023: Special Edition*. New York: United Nations Department Of Economic and Social Affairs. https://unstats.un.org/sdgs/report/2023/.

Chapter 2

B

Bruckner, B., Hubacek, K., Shan, Y., Zhong, H. and Feng, K. (2022). Impacts of poverty alleviation on national and global carbon emissions. *Nature Sustainability* 5, 311-320. https://doi.org/10.1038/s41893-021-00842-z.

C

Cerutti, N., Lamb, W.F., Crippa, M., Leip, A., Solazzo, E., Tubiello, F.N. *et al.* (2023). Food system emissions: A review of trends, drivers, and policy approaches, 1990–2018. *Environmental Research Letters* 18, 074030. https://doi.org/10.1088/1748-9326/acddfd.

Chancel, L. (2022). Global carbon inequality over 1990–2019. *Nature Sustainability* 5, 931-938. https://doi.org/10.1038/s41893-022-00955-z.

Chancel, L. and Piketty, T. (2015). *Carbon and Inequality: From Kyoto to Paris. Trends in the Global Inequality of Carbon Emissions (1998–2013) & Prospects for an Equitable Adaptation Fund*. Paris: World Inequality Lab. https://shs.hal.science/halshs-02655266.

Cheng, Y., Wang, Y., Chen, W., Wang, Q. and Zhao, G. (2021). Does income inequality affect direct and indirect household CO_2 emissions? A quantile regression approach. *Clean Technologies and Environmental Policy* 23, 1199-1213. https://doi.org/10.1007/s10098-020-01980-2.

Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf, E. *et al.* (2023). *GHG Emissions of All World Countries*. Luxembourg: Publications Office of the European Union. https://doi.org/10.2760/953322.

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F. and Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food* 2, 198-209. https://doi.org/10.1038/s43016-021-00225-9.

D

Dhakal, S., Minx, J.C., Toth, F.L., Abdel-Aziz, A., Meza, M.J.F., Hubacek, K. *et al.* (2022). Emissions trends and drivers. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press. Chapter 2. 214-294. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter02.pdf.

Duarte, R., Miranda-Buetas, S. and Sarasa, C. (2021). Household consumption patterns and income inequality in EU countries: Scenario analysis for a fair transition towards low-carbon economies. *Energy Economics* 104, 105614. https://doi.org/10.1016/j.eneco.2021.105614.

E

Energy Institute (2023). *Statistical Review of World Energy (72nd edition).* London. https://www.energyinst.org/statistical-review.

F

Feng, K., Hubacek, K. and Song, K. (2021). Household carbon inequality in the U.S. *Journal of Cleaner Production* 278, 123994. https://doi.org/10.1016/j.jclepro.2020.123994.

Forster, P.M., Smith, C.J., Walsh, T., Lamb, W.F., Lamboll, R., Hauser, M. *et al.* (2023). Indicators of Global Climate Change 2022: Annual update of large-scale indicators of the state of the climate system and human influence. *Earth System Science Data* 15, 2295-2327. https://doi.org/10.5194/essd-15-2295-2023.

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D. *et al.* (2021). The Earth's energy budget, climate feedbacks and climate sensitivity. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. *et al.* (eds.). Cambridge and New York: Cambridge University Press. Chapter 7. 923-1054. https://doi.org/10.1017/9781009157896.009.

Friedlingstein, P., Jones, M.W., O'Sullivan, M., Andrew, R.M., Bakker, D.C.E., Hauck, J. *et al.* (2022). Global Carbon Budget 2021. *Earth System Science Data* 14(4), 1917-2005. https://doi.org/10.5194/essd-14-1917-2022.

G

Gidden, M., Gasser, T., Grassi, G., Forsell, N., Janssens, I., Lamb, W.F. *et al.* (2022). Policy guidance and pitfalls aligning IPCC scenarios to national land emissions inventories. 24 October. https://essopenarchive.org/doi/full/10.1002/essoar.10512676.2.

Grassi, G., Conchedda, G., Federici, S., Abad Viñas, R., Korosuo, A., Melo, J. *et al.* (2022). Carbon fluxes from land 2000–2020: Bringing clarity to countries' reporting. *Earth System Science Data* 14(10), 4643-4666. https://doi.org/10.5194/essd-14-4643-2022.

Grassi, G., Schwingshackl, C., Gasser, T., Houghton, R.A., Sitch, S., Canadell, J.G. *et al.* (2023). Harmonising the land-use flux estimates of global models and national inventories for 2000–2020. *Earth System Science Data* 15(3), 1093-1114. https://doi.org/10.5194/essd-15-1093-2023.

Grassi, G., Stehfest, E., Rogelj, J., van Vuuren, D., Cescatti, A., House, J. *et al.* (2021). Critical adjustment of land mitigation pathways for assessing countries' climate progress. *Nature Climate Change* 11, 425-434. https://doi.org/10.1038/s41558-021-01033-6.

Guan, Y., Yan, J., Shan, Y., Zhou, Y., Hang, Y., Li, R. *et al.* (2023). Burden of the global energy price crisis on households. *Nature Energy* 8, 304-316. https://doi.org/10.1038/s41560-023-01209-8.

H

Hickel, J. and Slamersak, A. (2022). Existing climate mitigation scenarios perpetuate colonial inequalities. *The Lancet Planetary Health* 6(7), E628-E631. https://doi.org/10.1016/S2542-5196(22)00092-4.

Hubacek, K., Baiocchi, G., Feng, K., Castillo, R.-M., Sun, L. and Xue, J. (2017). Global carbon inequality. *Energy, Ecology and Environment* 2, 361-369. https://link.springer.com/article/10.1007/s40974-017-0072-9.

Hubacek, K., Chen, X., Feng, K., Wiedmann, T. and Shan, Y. (2021). Evidence of decoupling consumption-based CO_2 emissions from economic growth. *Advances in Applied Energy* 4, 100074. https://doi.org/10.1007/s40974-017-0072-9.

I

Indonesia, Ministry of Energy and Mineral Resources (2023). *Handbook of Energy & Economic Statistics of Indonesia 2022.* Jakarta.

International Air Transport Association (2023). *Air Passenger Market Analysis.* Montreal. https://www.iata.org/en/iata-repository/publications/economic-reports/air-passenger-market-analysis2/.

International Energy Agency (2022). *World Energy Outlook 2022*. Paris. https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf.

__________ (2023). *CO_2 Emissions in 2022*. Paris. https://iea.blob.core.windows.net/assets/3c8fa115-35c4-4474-b237-1b00424c8844/CO_2Emissionsin2022.pdf.

Intergovernmental Panel on Climate Change (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M. *et al.* (eds.). Cambridge and New York: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg3.

J

Jones, M.W., Peters, G.P., Gasser, T., Andrew, R.M., Schwingshackl, C., Gütschow, J. *et al.* (2023). National contributions to climate change due to historical emissions of carbon dioxide, methane, and nitrous oxide since 1850. *Scientific Data* 10, 155. https://doi.org/10.1038/s41597-023-02041-1.

K

Kartha, S., Kemp-Benedict, E., Ghosh, E., Nazareth, A. and Gore, T. (2020). *The Carbon Inequality Era: An Assessment of the Global Distribution of Consumption Emissions Among Individuals from 1990 to 2015 and Beyond.* Oxford: Oxfam and Stockholm Environment Institute. https://oxfamilibrary.openrepository.com/handle/10546/621049.

L

Lamb, W.F. (2023). UNEP Gap Report 2023 Chapter 2. https://github.com/lambwf/UNEP-Gap-Report-2023-Chapter-2. Accessed 25 October 2023.

Lamb, W.F., Grubb, M., Diluiso, F. and Minx, J.C. (2021a). Countries with sustained greenhouse gas emissions reductions: An analysis of trends and progress by sector. *Climate Policy* 22(1), 1-17. https://doi.org/10.1080/14693062.2021.1990831.

Lamb, W.F., Wiedmann, T., Pongratz, J., Andrew, R., Crippa, M., Olivier, J.G.J. *et al.* (2021b). A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environmental Research Letters* 16(7), 073005. https://doi.org/10.1088/1748-9326/abee4e/meta.

Le Quéré, C., Korsbakken, J.I., Wilson, C., Tosun, J., Andrew, R., Andres, R.J. *et al.* (2019). Drivers of declining CO_2 emissions in 18 developed economies. *Nature Climate Change* 9, 213–217. https://doi.org/10.1038/s41558-019-0419-7.

Liu, X., Wang, X., Song, J., Wang, H. and Wang, S. (2019). Indirect carbon emissions of urban households in China: Patterns, determinants and inequality. *Journal of Cleaner Production* 241, 118335. https://doi.org/10.1016/j.jclepro.2019.118335.

Liu, Z., Deng, Z., Davis, S. and Ciais, P. (2023). Monitoring global carbon emissions in 2022. *Nature Reviews Earth & Environment* 4, 205-206. https://doi.org/10.1038/s43017-023-00406-z.

M

Mi, Z., Zheng, J., Meng, J., Ou, J., Hubacek, K., Liu, Z. *et al.* (2020). Economic development and converging household carbon footprints in China. *Nature Sustainability* 3, 529-537. https://doi.org/10.1038/s41893-020-0504-y.

O

Oswald, Y., Owen, A. and Steinberger, J.K. (2020). Large inequality in international and intranational energy footprints between income groups and across consumption categories. *Nature Energy* 5, 231-239. https://doi.org/10.1038/s41560-020-0579-8.

P

Pachauri, S. (2014). Household electricity access a trivial contributor to CO_2 emissions growth in India. *Nature Climate Change* 4, 1073-1076. https://doi.org/10.1038/nclimate2414.

Pan, X., Wang, H., Lu, X., Zheng, X., Wang, L. and Chen, W. (2022). Implications of the consumption-based accounting for future national emissions budgets. *Climate Policy* 22(9/10), 1306-1318. https://doi.org/10.1080/14693062.2022.2067113.

Q

Qin, X., Wu, H., Zhang, X. and Wang, W. (2022). The widening wealth inequality as a contributor to increasing household carbon emissions. *Frontiers Earth Science* 10, 872806. https://www.doi.org/10.3389/feart.2022.872806/full.

R

Rajaeifar, M.A., Belcher, O., Parkinson, S., Neimark, B., Weir, D., Ashworth, K. *et al.* (2022). Decarbonize the military — mandate emissions reporting. *Nature* 611, 29-32. https://doi.org/10.1038/d41586-022-03444-7.

Rao, N.D., Min, J. and Mastrucci, A. (2019). Energy requirements for decent living in India, Brazil and South Africa. *Nature Energy* 4, 1025-1032. https://doi.org/10.1038/s41560-019-0497-9.

S

Santillán Vera, M. and de la Vega Navarro, A. (2020). Do the rich pollute more? Mexican household consumption by income level and CO emissions. *International Journal of Energy Sector Management* 13(3), 694-712. https://doi.org/10.1108/IJESM-07-2018-0016.

Seriño, M.N.V. (2020). Rising carbon footprint inequality in the Philippines. *Environmental Economics and Policy Studies* 22, 173-195. https://doi.org/10.1007/s10018-019-00253-7.

Sri, P. and Banerjee, R. (2023). Characteristics, temporal trends, and driving factors of household carbon inequality in India. *Sustainable Production and Consumption* 35, 668-683. https://doi.org/10.1016/j.spc.2022.11.017.

Starr, J., Nicolson, C., Ash, M., Markowitz, E.M. and Moran, D. (2023) Income-based U.S. household carbon footprints (1990–2019) offer new insights on emissions inequality and climate finance. *PLOS Climate* 2(8), e0000190. https://doi.org/10.1371/journal.pclm.0000190.

Steffen, B. and Patt, A. (2022). A historical turning point? Early evidence on how the Russia-Ukraine war changes public support for clean energy policies. *Energy Research & Social Science* 91, 102758. https://doi.org/10.1016/j.erss.2022.102758.

T

Tollefson, J. (2022). What the war in Ukraine means for energy, climate and food. *Nature* 604, 232-233. https://doi.org/10.1038/d41586-022-00969-9.

U

United Kingdom (2022). *UK Government takes next steps to boost domestic energy production.* 22 September. https://www.gov.uk/government/news/uk-government-takes-next-steps-to-boost-domestic-energy-production.

United Nations Environment Programme (2021). *Emissions Gap Report 2021: The Heat Is On – A world of climate promises not yet delivered.* Nairobi. https://www.unep.org/resources/emissions-gap-report-2021.

__________ (2022). *Emissions Gap Report 2022: The Closing Window – Climate crisis calls for rapid transformation of societies.* Nairobi. https://www.unep.org/emissions-gap-report-2022.

V

Vélez-Henao, J.A. and Pauliuk, S. (2023). Material requirements of decent living standards. *Environmental Science & Technology* 57, 14206-14217. https://doi.org/10.1021/acs.est.3c03957.

Vogel, J. and Hickel, J. (2023). Is green growth happening? An empirical analysis of achieved versus Paris-compliant CO_2–GDP decoupling in high-income countries. *The Lancet Planetary Health* 7(9), E759-E769. https://doi.org/10.1016/S2542-5196(23)00174-2.

W

Wiedmann, T., Lenzen, M., Keyßer, L.T. and Steinberger, J.K. (2020). Scientists' warning on affluence. *Nature Communications* 11, 3107, 1-10. https://doi.org/10.1038/s41467-020-16941-y.

W

World Bank (2023). World Development Indicators. https://datacatalog.worldbank.org/search/dataset/0037712/World-Development-Indicators. Accessed 25 October 2023.

World Inequality Database (2023). World Inequality Database. https://wid.world/. Accessed 25 October 2023.

World Meteorological Organization (2023). *WMO Greenhouse Gas Bulletin*. Geneva. https://public.wmo.int/en/greenhouse-gas-bulletin.

Z

Zheng, H., Wood, R., Moran, D., Feng, K., Tisserant, A., Jiang, M. *et al.* (2023). Rising carbon inequality and its driving factors from 2005 to 2015. *Global Environmental Change* 82, 102704. https://doi.org/10.1016/j.gloenvcha.2023.102704.

Chapter 3

A

Argentina, Ministry of Environment and Sustainable Development (2022). *Plan Nacional de Adaptación y Mitigación al Cambio Climático*. https://www.argentina.gob.ar/ambiente/cambio-climatico/plan-nacional.

Bistline, J., Blanford, G., Brown, M., Burtraw, D., Domeshek, M., Farbes, J. *et al.* (2023). Emissions and energy impacts of the Inflation Reduction Act. *Science* 380(6652), 1324-1327. https://doi.org/10.1126/science.adg3781.

B

Black, S., Liu, A.A., Parry, I. and Vernon, N. (2023). IMF fossil fuel subsidies data: 2023 update. IMF Working Paper No. 2023/169. Washington, August. https://www.imf.org/en/Publications/WP/Issues/2023/08/22/IMF-Fossil-Fuel-Subsidies-Data-2023-Update-537281.

Buck, H.J., Carton, W., Lund, J.F. and Markusson, N. (2023). Why residual emissions matter right now. *Nature Climate Change* 13, 351-358. https://doi.org/10.1038/s41558-022-01592-2.

Byers, E., Krey, V., Kriegler, E., Riahi, K., Schaeffer, R., Kikstra, J. *et al.* (2022). AR6 Scenarios Database. https://pure.iiasa.ac.at/id/eprint/18399/. Accessed 6 November 2023.

C

Canada (2022). Clean Fuel Regulations: SOR/2022-140. *Canada Gazette* part II, 156(14). https://www.canadagazette.gc.ca/rp-pr/p2/2022/2022-07-06/html/sor-dors140-eng.html. Accessed 6 November.

Canada, Environment and Climate Change Canada (2022). *2030 Emissions Reduction Plan: Canada's Next Steps for Clean Air and a Strong Economy.* Gatineau: Minister of Environment and Climate Change Canada. https://publications.gc.ca/collections/collection_2022/eccc/En4-460-2022-eng.pdf.

China Electricity Council (2023). Analysis and forecast of China power demand-supply situation in the first quarter of 2023, 28 April. https://english.cec.org.cn/#/newsdetails?id=1658663989908951042. Accessed 6 November 2023.

China, National Energy Administration (2023). Transcript of the National Energy Administration's online press conference for the third quarter of 2023, 31 July. https://www.nea.gov.cn/2023-07/31/c_1310734825.htm. Accessed 6 November 2023.

Climate Action Tracker (2022a). Canada (Update of 20 December 2022). https://climateactiontracker.org/countries/canada/. Accessed 6 November 2023.

Climate Action Tracker (2022b). CAT net zero target evaluations, 10 November. https://climateactiontracker.org/global/cat-net-zero-target-evaluations/.

Climate Action Tracker (2023a). CAT Climate Target Update Tracker. https://climateactiontracker.org/climate-target-update-tracker-2022/. Accessed 6 November 2023.

Climate Action Tracker (2023b). Countries, 30 August. https://climateactiontracker.org/countries/. Accessed 27 October 2023.

Climate Action Tracker (2023c). European Union (Update of June 2023). https://climateactiontracker.org/countries/eu/. Accessed 6 November 2023.

Climate Analytics and NewClimate Institute (2022). *Climate Action Tracker: Warming Projections Global Update – November 2022*. Berlin. https://climateactiontracker.org/documents/1094/CAT_2022-11-10_GlobalUpdate_COP27.pdf.

Climate Change Committee (2023). *Progress in Reducing Emissions: 2023 Report to Parliament*. London. https://www.theccc.org.uk/wp-content/uploads/2023/06/Progress-in-reducing-UK-emissions-2023-Report-to-Parliament.pdf.

Climate Resource (2022). NDC factsheets. https://www.climate-resource.com/tools/ndcs. Accessed 27 October 2023.

Climate Watch (2023). NDC Enhancement Tracker. https://www.climatewatchdata.org/2020-ndc-tracker. Accessed 27 October 2023.

Conan, R. (2023). Sonora Plan to boost Mexico nearshoring: Fitch, 12 April. https://www.argusmedia.com/en/news/2438614-sonora-plan-to-boost-mexico-nearshoring-fitch. Accessed 27 October 2023.

D

Dafnomilis, I., den Elzen, M. and van Vuuren, D.P. (2023). Achieving net-zero emissions targets: An analysis of long-term scenarios using an integrated assessment model. *Annals of the New York Academy of Sciences* 1522(1), 98- 108. https://doi.org/10.1111/nyas.14970.

den Elzen, M., Kuramochi, T., Höhne, N., Cantzler, J., Esmeijer, K., Fekete, H. *et al.* (2019). Are the G20 economies making enough progress to meet their NDC targets? *Energy Policy* 126, 238-250. https://doi.org/10.1016/j.enpol.2018.11.027.

den Elzen, M.G.J., Dafnomilis, I., Hof, A.F., Olsson, M., Beusen, A., Botzen, W.J.W. *et al.* (2023). The impact of policy and model uncertainties on emissions projections of the Paris Agreement pledges. *Environmental Research Letters* 18(5), 054026. https://dx.doi.org/10.1088/1748-9326/acceb7.

Dooks, T. (2023). CCC assessment of recent announcements and developments on Net Zero, 12 October. https://www.theccc.org.uk/2023/10/12/ccc-assessment-of-recent-announcements-and-developments-on-net-zero/. Accessed 27 October 2023.

E

Edianto, A.S. (2023). JETP: A reflection of Indonesia's commitment to transform its power sector, 26 January. https://ember-climate.org/insights/commentary/jetp-indonesia/. Accessed 27 October 2023.

Eskom, South African Photovoltaic Industry Association and South African Wind Energy Association (2023). *2023 South African Renewable Energy Grid Survey*. https://www.eskom.co.za/wp-content/uploads/2023/06/RE_Survey_202304rev0_Pub.pdf.

European Commission (2021). 'Fit for 55': Delivering the EU's 2030 Climate Target on the Way to Climate Neutrality. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of The Regions Empty. Brussels, July. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX%3A52021DC0550.

European Commission (2022). *REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition**. 18 May. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_3131.

European Commission, Directorate-General for Energy, Directorate-General for Climate Action, Directorate-Generate for Mobility and Transport (2021). *EU Reference Scenario 2020: Energy, transport and GHG emissions – Trends to 2050*. Luxembourg: Publications Office of the European Union. https://op.europa.eu/en/publication-detail/-/publication/96c2ca82-e85e-11eb-93a8-01aa75ed71a1/language-en.

European Environment Agency (2023). Member States' greenhouse gas (GHG) emission projections, 24 October. https://www.eea.europa.eu/en/datahub/datahubitem-view/4b8d94a4-aed7-4e67-a54c-0623a50f48e8. Accessed 27 October 2023.

F

Fransen, T., Henderson, C., O'Connor, R., Alayza, N., Caldwell, M., Chakrabarty, S. *et al.* (2022). *The State of Nationally Determined Contributions: 2022*. Washington: World Resources Institute. https://files.wri.org/d8/s3fs-public/2022-10/state-of-ndcs-2022.pdf?VersionId=VqrCpyQHmf5utPcHCScbqeTgU2p2SOam.

G

Garaffa, R., Weitzel, M., Vandyck, T., Keramidas, K., Dowling, P., Fosse, F. *et al.* (2022). Global and regional energy and employment transition implied by climate policy pledges. 21 June. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4141955.

Global Energy Monitor, Centre for Research on Energy and Clean Air, E3G, Reclaim Finance, Sierra Club, Solutions for Our Climate *et al.* (2023). *Boom and Bust Coal: Tracking the global coal plant pipeline*. https://globalenergymonitor.org/wp-content/uploads/2023/03/Boom-Bust-Coal-2023.pdf.

Gütschow, J. and Pflüger, M. (2023). The PRIMAP-Hist National Historical Emissions Time Series (1750–2021). Zenodo. https://zenodo.org/records/7727475. Accessed 27 October 2023.

H

Hans, F., Woollands, S., Nascimento, L., Höhne, N. and Kuramochi, T. (2022). Unpacking the COVID-19 rescue and recovery spending: An assessment of implications on greenhouse gas emissions towards 2030 for key emitters. *Climate Action* 1, 3. https://doi.org/10.1007/s44168-022-00002-9.

I

Independent Power Producers Office (2023). Publications, 2 May. IPP Projects. https://www.ipp-projects.co.za/Publications. Accessed 6 November 2023.

Indonesia, Presidential Regulation No. 112 of 2022 concerning the Acceleration of Development of Renewable Energy for Electric Power Supply.

Iniciativa Climática de México (2022). *Una Propuesta Desde La Sociedad Civil Para Aumentar La Ambición Mediante Un Enfoque De Justicia Climática*. Mexico City. https://iniciativaclimatica.org/ndc/wp-content/uploads/2022/11/Una-propuesta-desde-la-sociedad-civil-091122.pdf.

International Energy Agency (IEA) (2023). *World Energy Investment 2023*. Paris. https://iea.blob.core.windows.net/assets/8834d3af-af60-4df0-9643-72e2684f7221/WorldEnergyInvestment2023.pdf.

__________ (2022). *An Energy Sector Roadmap to Net Zero Emissions in Indonesia*. Paris. https://iea.blob.core.windows.net/assets/b496b141-8c3b-47fc-adb2-90740eb0b3b8/AnEnergySectorRoadmaptoNetZeroEmissionsinIndonesia.pdf.

__________ (2023). World Energy Statistics and Balances (2022 edition). https://doi.org/10.1787/enestats-data-en. Accessed 27 October 2023.

J

Japan (2021). Act on Promotion of Smooth Transition to a Decarbonized Growth Economic Structure. Law No. 32 of 2021. https://elaws.e-gov.go.jp/document?lawid=505AC0000000032_20230630_000000000000000. Accessed 6 November 2023.

Japan, Cabinet Secretariat (2023). *Hydrogen Basic Strategy*. Tokyo. https://www.cas.go.jp/jp/seisaku/saisei_energy/pdf/hydrogen_basic_strategy_kaitei.pdf.

Japan, Ministry of Economy, Trade and Industry (2023). *The Basic Policy for the Realization of GX: A Roadmap for the Next 10 Years*. Tokyo. https://www.meti.go.jp/english/press/2023/pdf/0210_003a.pdf.

Jiménez, C. and Pineda, L. (2022). Proyecto de modificación de la norma mexicana de rendimiento de combustible para vehículos ligeros – NOM-163-SEMARNAT-ENER-SCFI-2013, 7 November. https://theicct.org/publication/mexico-lvs-nom163-update-nov22/. Accessed 27 October 2023.

K

Keramidas, K., Fosse, F., Diaz Rincon, A., Dowling, P., Garaffa, R., Ordonez, J. *et al.* (2022). *Global Energy and Climate Outlook 2022: Energy Trade in a Decarbonised World*. Luxembourg: Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC131864.

L

Lebling, K., Schumer, C. and Riedl, D. (2023). International governance of technological carbon removal: Surfacing questions, exploring solutions. Washington, D.C.: World Resources Institute. https://doi.org/10.46830/wriwp.23.00013.

M

Meinshausen, M., Lewis, J., McGlade, C., Gütschow, J., Nicholls, Z., Burdon, R. *et al.* (2022). Realization of Paris Agreement pledges may limit warming just below 2 °C. *Nature* 604, 304-309. https://doi.org/10.1038/s41586-022-04553-z.

Meinshausen, M., Lewis, J., Nicholls, Z.R.J. and Guetschow, J. (2023). NDC factsheets. Zenodo. https://doi.org/10.5281/zenodo.8010081. Accessed 6 November 2023.

Mexico, Secretariat of the Government (2023). Agreement No. A/018/2023 of the Energy Regulatory Commission which updates the reference values of the methodologies for calculating the efficiency of electrical energy cogeneration systems and the criteria for determining efficient cogeneration, as well as the efficiency criteria and calculation methodology to determine the percentage of fuel-free energy established in resolutions RES/003/2011, RES/2016/2014, RES 291/2012 and RES/1838/2016, respectively. https://www.dof.gob.mx/nota_detalle.php?codigo=5690142&fecha=26/05/2023#gsc.tab=0.

N

Nahm, J.M., Miller, S.M. and Urpelainen, J. (2022). G20's US$14-trillion economic stimulus reneges on emissions pledges. *Nature* 603, 28-31. https://doi.org/10.1038/d41586-022-00540-6.

Nascimento, L., Kuramochi, T., Woollands, S., Moiso, M., de Villafranca Casas, M.J., Hans, F. *et al.* (2022). *Greenhouse Gas Mitigation Scenarios For Major Emitting Countries: Analysis of Current Climate Policies and Mitigation Commitments – 2022 Update*. Cologne and Berlin: NewClimate Institute for Climate Policy and Global Sustainability. https://newclimate.org/sites/default/files/2022-10/EC-PBL2022_CurrentPolicies_Oct22.pdf.

Net Zero Tracker (2023). Data Explorer. https://zerotracker.net/. Accessed 27 October 2023.

NewClimate Institute and Climate Analytics (2023). *Countdown to COP28: Time for World to Focus on Oil and Gas Phase-out, Renewables Target – Not Distractions Like CCS – June 2023*. https://climateactiontracker.org/documents/1144/CAT_2023-06-08_Briefing_PhaseOutOilGas.pdf.

R

Republic of Korea, Climate Change Strategy Division (2023). *The Yoon administration's blueprint for achieving carbon neutrality and green growth revealed*. 30 March. https://m.me.go.kr/eng/file/readDownloadFile.do?fileId=255266&fileSeq=1.

Riahi, K., Schaeffer, R., Arango, J., Calvin, K., Jiang, K., Kriegler, E. *et al.* (2022). Mitigation pathways compatible with long-term goals. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M. *et al.* (eds.). Cambridge and New York: Cambridge University Press. Chapter 3. 295-408. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter03.pdf.

Roelfsema, M., van Soest, H.L., Harmsen, M., van Vuuren, D.P., Bertram, C., den Elzen, M. *et al.* (2020). Taking stock of national climate policies to evaluate implementation of the Paris Agreement. *Nature Communications* 11, 2096. https://doi.org/10.1038/s41467-020-15414-6.

Rogelj, J., Fransen, T., den Elzen, M.G.J., Lamboll, R.D., Schumer, C., Kuramochi, T. *et al.* (2023). Credibility gap in net-zero climate targets leaves world at high risk. *Science* 380(6649), 1014-1016. https://www.science.org/doi/10.1126/science.adg6248.

S

Sawyer, D., Griffin, B., Beugin, D., Förg, F. and Smith, R. (2022). *Independent Assessment: 2030 Emissions Reduction Plan*. Canadian Climate Institute. https://climateinstitute.ca/wp-content/uploads/2022/04/ERP-Volume-2-FINAL.pdf.

South Africa, Presidency (2022). *South Africa's Just Energy Transition Investment Plan (JET IP): For the Initial Period 2023–2027*. Pretoria: Presidency, Republic of South Africa. https://pccommissionflo.imgix.net/uploads/images/South-Africas-Just-Energy-Transition-Investment-Plan-JET-IP-2023-2027-FINAL.pdf.

Stockholm Environment Institute, Climate Analytics, E3G, International Institute for Sustainable Development and United Nations Environment Programme (2023). *The Production Gap: Phasing Down or Phasing Up?*

Top Fossil Fuel Producers Plan Even More Extraction Despite Climate Promises. Stockholm: Stockholm Environment Institute. https://doi.org/10.51414/sei2023.050.

U

United Kingdom (2023). Carbon Budget Delivery Plan. Policy paper. March. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1147369/carbon-budget-delivery-plan.pdf.

United Nations (2022). World Population Prospects 2022. https://population.un.org/wpp/. Accessed 27 October 2023.

United Nations Environment Programme (UNEP) (2015). *The Emissions Gap Report 2015*. Nairobi: UNEP. https://www.un-ilibrary.org/content/books/9789210479677.

United Nations, Framework Convention on Climate Change (2011). *Report of the Conference of the Parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010, Addendum, Part Two: Action taken by the Conference of the Parties at its sixteenth session*. 15 March. FCCC/CP/2010/7/Add.1. http://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf.

__________ (2015). *Paris Agreement*. https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

__________ (2023). Fifth Biennial Reports – Annex I. https://unfccc.int/BR5. Accessed 27 October 2023.

__________ (2023). Technical dialogue of the first global stocktake. Synthesis report by the co-facilitators on the technical dialogue, 8 September. https://unfccc.int/documents/631600. Accessed 27 October 2023.

United States of America, Department of the Interior, Bureau of Land Management (2023). Final draft of the proposed Onshore Oil and Gas Leasing Rule. https://www.blm.gov/sites/default/files/docs/2023-07/Final-Draft-Proposed-Onshore-Oil-and-Gas-Leasing-Rule-07-18-2023.pdf.

United States of America, Department of the Interior, Bureau of Ocean Energy Management (2023). Lease Sale 259. https://www.boem.gov/oil-gas-energy/leasing/lease-sale-259.

United States of America, Energy Information Administration (2023). International. https://www.eia.gov/international/data/world. Accessed 27 October 2023.

United States of America, Environmental Protection Agency (2023). Methane Emissions Reduction Program, 23 October. https://www.epa.gov/inflation-reduction-act/methane-emissions-reduction-program. Accessed 27 October 2023.

United States of America, Internal Revenue Service (2023). Inflation Reduction Act of 2022, 20 October. https://www.irs.gov/inflation-reduction-act-of-2022. Accessed 27 October 2023.

X

Xinhua (2023). Xi stresses higher-standard open economy, energy transition, 12 July. The State Council Information Office of the People's Republic of China. http://english.scio.gov.cn/m/topnews/2023-07/12/content_91999967.htm. Accessed 6 November 2023.

Xinhuanet (2023). Non-fossil energy power generation installed capacity accounts for more than 50%, 11 June. http://www.news.cn/2023-06/11/c_1129686294.htm. Accessed 6 November 2023.

Chapter 4

B

Byers, E., Krey, V., Kriegler, E., Riahi, K., Schaeffer, R., Kikstra, J. *et al.* (2022). AR6 Scenarios Database. https://pure.iiasa.ac.at/id/eprint/18399/. Accessed 1 November 2023.

C

Canadell, J.G., Monteiro, P.M.S., Costa, M.H., da Cunha, L.C., Cox, P.M., Eliseev, A.V. *et al.* (2021). Global carbon and other biogeochemical cycles and feedbacks. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. *et al.* (eds.). Cambridge and New York: Cambridge University Press. Chapter 5. 673-816. https://doi.org/10.1017/9781009157896.007.

Climate Action Tracker (2022). *Warming Projections Global Update – November 2022*. https://climateactiontracker.org/documents/1094/CAT_2022-11-10_GlobalUpdate_COP27.pdf.

D

Dafnomilis, I., den Elzen, M. and van Vuuren, D.P. (2023). Achieving net-zero emissions targets: An analysis of long-term scenarios using an integrated assessment model. *Annals of the New York Academy of Sciences* 1522(1), 98-108. https://doi.org/10.1111/nyas.14970.

den Elzen, M.G.J., Dafnomilis, I., Forsell, N., Fragkos, P., Fragkiadakis, K., Höhne, N. *et al.* (2022). Updated nationally determined contributions collectively raise ambition levels but need strengthening further to keep Paris goals within reach. *Mitigation and Adaptation Strategies for Global Change* 27, 33. https://doi.org/10.1007/s11027-022-10008-7.

den Elzen, M.G.J., Dafnomilis, I., Hof, A.F., Olsson, M., Beusen, A., Botzen, W.J.W. *et al.* (2023). The impact of policy and model uncertainties on emissions projections of the Paris Agreement pledges. *Environmental Research Letters* 18(5), 054026. https://doi.org/10.1088/1748-9326/acceb7.

F

Forster, P.M., Smith, C.J., Walsh, T., Lamb, W.F., Lamboll, R., Hauser, M. *et al.* (2023). Indicators of Global Climate Change 2022: Annual update of large-scale indicators of the state of the climate system and human influence. *Earth System Science Data* 15(6), 2295-2327. https://doi.org/10.5194/essd-15-2295-2023.

H

Höhne, N., den Elzen, M., Rogelj, J., Metz, B., Fransen, T., Kuramochi, T. *et al.* (2020). Emissions: World has four times the work or one-third of the time. *Nature* 579(7797), 25-28. https://doi.org/10.1038/d41586-020-00571-x.

I

Intergovernmental Panel on Climate Change (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. *et al.* (eds.). Cambridge and New York: Cambridge University Press. https://doi.org/10.1017/9781009157896.

K

Keramidas, K., Fosse, F., Diaz Rincon, A., Dowling, P., Garaffa, R., Ordonez, J. *et al.* (2022). *Global Energy and Climate Outlook 2022: Energy Trade in a Decarbonised World*. Luxembourg: Publications Office of the European Union. https://doi.org/10.2760/863694.

Kikstra, J.S., Nicholls, Z.R.J., Smith, C.J., Lewis, J., Lamboll, R.D., Byers, E. *et al.* (2022). The IPCC *Sixth Assessment Report* WGIII climate assessment of mitigation pathways: From emissions to global temperatures. *Geoscientific Model Development* 15(24), 9075-9109. https://doi.org/10.5194/gmd-15-9075-2022.

L

Lecocq, F., Winkler, H., Daka, J.P., Fu, S., Gerber, J., Kartha, S. *et al.* (2022). Mitigation and development pathways in the near- to mid-term. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M. *et al.* (eds.). Cambridge and New York: Cambridge University Press. Chapter 4. 409-502. https://doi.org/10.1017/9781009157926.006.

M

Meinshausen, M., Lewis, J., Nicholls, Z.R.J. and Guetschow, J. (2023). NDC factsheets. Zenodo. https://doi.org/10.5281/zenodo.8010081. Accessed 6 November 2023.

N

Nascimento, L., Kuramochi, T., Woollands, S., Moiso, M., de Villafranca Casas, M.J., Hans, F. *et al.* (2022). *Greenhouse Gas Mitigation Scenarios for Major Emitting Countries: Analysis of Current Climate Policies and Mitigation Commitments – 2022 Update*. Cologne and Berlin: NewClimate Institute for Climate Policy and Global Sustainability. https://newclimate.org/sites/default/files/2022-10/EC-PBL2022_CurrentPolicies_Oct22.pdf.

NewClimate Institute (2023). Climate Policy Database. https://climatepolicydatabase.org/. Accessed 1 November 2023.

Nicholls, Z.R.J., Meinshausen, M., Forster, P., Armour, K., Berntsen, T., Collins, W. *et al.* (2021). Cross-chapter box 7.1: Physical emulation of Earth System Models for scenario classification and knowledge integration in AR6. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. *et al.* (eds.). Cambridge and New York: Cambridge University Press. 962-967. https://doi.org/10.1017/9781009157896.009.

R

Riahi, K., Bertram, C., Huppmann, D., Rogelj, J., Bosetti, V., Cabardos, A.-M. *et al.* (2021). Cost and attainability of meeting stringent climate targets without overshoot. *Nature Climate Change* 11, 1063-1069. https://doi.org/10.21203/rs.3.rs-127847/v1.

Riahi, K., Schaeffer, R., Arango, J., Calvin, K., Guivarch, C., Hasegawa, T. *et al.* (2022). Mitigation pathways compatible with long-term goals. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M. *et al.* (eds.). Cambridge and New York: Cambridge University Press. Chapter 3. 295-408. https://doi.org/10.1017/9781009157926.005.

Roelfsema, M., van Soest, H.L., Harmsen, M., van Vuuren, D.P., Bertram, C., den Elzen, M. *et al.* (2020). Taking stock of national climate policies to evaluate implementation of the Paris Agreement. *Nature Communications* 11(1), 2096. https://doi.org/10.1038/s41467-020-15414-6.

Roelfsema, M., van Soest, H.L., den Elzen, M., de Coninck, H., Kuramochi, T., Harmsen, M. *et al.* (2022). Developing scenarios in the context of the Paris Agreement and application in the integrated assessment model IMAGE: A framework for bridging the policy-modelling divide. *Environmental Science & Policy* 135, 104-116. https://doi.org/10.1016/j.envsci.2022.05.001.

Rogelj, J., Fransen, T., den Elzen, M., Lamboll, R.D., Schumer, C., Kuramochi, T. *et al.* (2023). Credibility gap in net-zero climate targets leaves world at high risk. *Science* 380(6649), 1014-1016. https://doi.org/10.1126/science.adg6248.

S

Smith, C. (2023). FaIR calibration data (FaIR v2.1.0). https://doi.org/10.5281/zenodo.7740606. Accessed 1 November 2023.

Schmidt Tagomori, I., Hooijschuur, E. and Muyasyaroh, A. (2023). Promising climate progress. IIASA Policy Brief No. 34. Laxenburg: International Institute for Applied Systems Analysis. http://www.engage-climate.org/wp-content/uploads/2023/10/PB34_Engage-policy-briefweb_0.pdf.

U

United Nations Environment Programme (2015). *The Emissions Gap Report 2015*. Nairobi. https://www.unep.org/resources/emissions-gap-report-2015.

__________ (2019). *Emissions Gap Report 2019*. Nairobi. https://www.unep.org/resources/emissions-gap-report-2019.

__________ (2022). The Closing Window: Climate Crisis Calls for Rapid Transformation of Societies. Emissions Gap Report 2022. Nairobi. https://www.unep.org/resources/emissions-gap-report-2022.

V

van Ruijven, B., Jäger, J., Riahi, K., Battersby, S., Bertram, C., Bosetti, V. *et al.* (2023). Plausible pathways that meet the Paris and Glasgow targets. In *ENGAGE Summary for Policymakers*. Laxenburg, Austria: International Institute for Applied Systems Analysis. 23-26. https://pure.iiasa.ac.at/id/eprint/19116/.

Chapter 5

A

Ameli, N., Dessens, O., Winning, M., Cronin, J., Chenet, H., Drummond, P. *et al.* (2021). Higher cost of finance exacerbates a climate investment trap in developing economies. *Nature Communications* 12, 4046. https://doi.org/10.1038/s41467-021-24305-3.

B

Bustamente, M. *et al.* Ten new insights in climate science 2023. *Global Sustainability.* In review.

C

Clarke, L., Wei, Y.M., de la Vega Navarro, A., Garg, A., Hahmann, A.N., Khennas, S. *et al.* (2022). Energy systems. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M. *et al.* (eds.). Cambridge and New York: Cambridge University Press. Chapter 6. 613-746. https://doi.org/10.1017/9781009157926.008.

Cozzi, L., Wetzel, D., Tonolo, G. and Hyppolite II, J. (2022). For the first time in decades, the number of people without access to electricity is set to increase in 2022, 3 November. https://www.iea.org/commentaries/for-the-first-time-in-decades-the-number-of-people-without-access-to-electricity-is-set-to-increase-in-2022. Accessed 26 October 2023.

D

Deep Decarbonization Pathways (2021). *Policy Lessons on Deep Decarbonization in Large Emerging Economies: Brazil, India, Indonesia and South Africa*. Paris: IDDRI. https://www.ddpinitiative.org/wp-content/pdf/DDP_BIICS_CountryReport.pdf.

Dubash, N.K. (2023). The G20 should forge a pact to support nations' shifts to a low-carbon future. *Nature* 619(9). https://doi.org/10.1038/d41586-023-02208-1.

F

Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Gregor, L., Hauck, J. *et al.* (2022). Global carbon budget 2022. *Earth System Science Data* 14(11), 4811-4900. https://doi.org/10.5194/essd-14-4811-2022.

G

Garg, A. (2020) Synchronizing carbon mitigation and the Sustainable Development Goals. *Carbon Management* 11(3), 203-204. https://doi.org/10.1080/17583004.2020.1757338.

Gunfaus, M.T. and Waisman, H. (2021). Assessing the adequacy of the global response to the Paris Agreement: Toward a full appraisal of climate ambition and action. *Earth System Governance* 8, 100102. https://doi.org/10.1016/j.esg.2021.100102.

H

Holz, C., Cunliffe, G., Mbeva, K., Pauw, P.W. and Winkler, H. (2023). Tempering and enabling ambition: How equity is considered in domestic processes preparing NDCs. *International Environmental Agreements: Politics, Law and Economics* 23, 271-292. https://doi.org/10.1007/s10784-023-09599-6.

I

Intergovernmental Panel on Climate Change (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M. *et al.* (eds.). Cambridge and New York: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg3/.

International Energy Agency (2021). *Net Zero by 2050: A Roadmap for the Global Energy Sector.* Paris: International Energy Agency. Paris. https://www.iea.org/reports/net-zero-by-2050.

__________ (2023). *Net Zero Roadmap: A Global Pathway to Keep the 1.5°C Goal in Reach. 2023 Update*. Paris. https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach.

International Energy Agency and International Finance Corporation (2023). *Scaling up Private Finance for Clean Energy in Emerging and Developing Economies*. Paris. https://www.iea.org/reports/scaling-up-private-finance-for-clean-energy-in-emerging-and-developing-economies.

International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, World Bank and World Health Organization (2023). *Tracking SDG 7: The Energy Progress Report 2023*. Washington, D.C.: World Bank. https://trackingsdg7.esmap.org/data/files/download-documents/sdg7-report2023-full_report.pdf.

International Labour Organization (2015). *Guidelines for a Just Transition Towards Environmentally Sustainable Economies and Societies for All*. Geneva. https://www.ilo.org/wcmsp5/groups/public/@ed_emp/@emp_ent/documents/publication/wcms_432859.pdf.

K

Kikstra, J., Mastrucci, A., Min, J., Riahi, K. and Rao, N. (2021). Decent living gaps and energy needs around the world. *Environmental Research Letters* 16, 095006. https://doi.org/10.1088/1748-9326/ac1c27.

L

La Rovere, E.L., Grottera, C. and Wills, W. (2018) Overcoming the financial barrier to a low emission development strategy in Brazil. *International Economics* 155, 61-68. https://doi.org/10.1016/j.inteco.2017.12.004.

M

McCauley, D. and Heffron, R. (2018). Just transition: Integrating climate, energy and environmental justice. *Energy Policy* 119, 1-7. https://doi.org/10.1016/j.enpol.2018.04.014.

Millward-Hopkins, J., Steinberger, J.K., Rao, N.D. and Oswald, Y. (2020). Providing decent living with minimum energy: A global scenario. *Global Environmental Change* 65, 102168. https://doi.org/10.1016/j.gloenvcha.2020.102168.

Mulugetta, Y., Sokona, Y., Trotter, P.A., Fankhauser, S., Omukuti, J., Croxatto, L.S. *et al.* (2022). Africa needs context-relevant evidence to shape its clean energy future. *Nature Energy* 7, 1015-1022. https://doi.org/10.1038/s41560-022-01152-0.

Muttitt, G. and Kartha, S. (2020). Equity, climate justice and fossil fuel extraction: Principles for a managed phase out. *Climate Policy* 20(8), 1024-1042. https://doi.org/10.1080/14693062.2020.1763900.

Muttitt, G., Price, J., Pye, S. and Welsby, D. (2023). Socio-political feasibility of coal power phase-out and its role in mitigation pathways. *Nature Climate Change* 13, 140-147. https://doi.org/10.1038/s41558-022-01576-2.

O

Organisation for Economic Co-operation and Development (2020). *Global Outlook on Financing for Sustainable Development 2021: A New Way to Invest for People and Planet*. Paris. https://doi.org/10.1787/e3c30a9a-en.

P

Pachauri, S., Pelz, S., Bertram, C., Kriebiehl, S., Rao, N.D., Sokona, Y. *et al.* (2022). Fairness considerations in global mitigation investments. *Science* 378(6624), 1057-1059. https://doi.org/10.1126/science.adf0067.

R

Rao, N.D., Min, J. and Mastrucci, A. (2019). Energy requirements for decent living in India, Brazil and South Africa. *Nature Energy* 4, 1025-1032. https://doi.org/10.1038/s41560-019-0497-9.

S

Smith, S. (2017). *Just Transition: A Report for the OECD*. Brussels: International Trade Union Confederation. https://www.oecd.org/environment/cc/g20-climate/collapsecontents/Just-Transition-Centre-report-just-transition.pdf.

Sokona, Y., Mulugetta, Y., Tesfamichael, M., Kaboub, F., Hällström, N., Stilwell, M. *et al.* (2023). *Just Transition: A Climate, Energy and Development Vision for Africa.* Power Shift Africa. https://www.powershiftafrica.org/publications/just-transition-a-climate-energy-and-development-vision-for-africa.

Stockholm Environment Institute, Climate Analytics, E3G, International Institute for Sustainable Development and United Nations Environment Programme (2023). *The Production Gap Report 2023.* Stockholm: Stockholm Environment Institute. http://productiongap.org/2023report.

Svensson, J. (2023). IDDRI submission to the GST on behalf of the IMAGINE project: Using the Global Stocktake to identify and design opportunities for enhanced global collaboration that accelerates national climate and development action: The case of international finance. March. https://unfccc.int/sites/default/files/resource/202303101031---GST_submission_finance_final.pdf.

T

Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C. *et al.* (2019). Committed emissions from existing energy infrastructure jeopardize 1.5°C climate target. *Nature* 572, 373-377. https://doi.org/10.1038/s41586-019-1364-3.

Trout, K., Muttitt, G., Lafleur, D., Van de Graaf, T., Mendelevitch, R. Mei, L. *et al.* (2022). Existing fossil fuel extraction would warm the world beyond 1.5°C. *Environmental Research Letters* 17(6), 064010. https://doi.org/10.1088/1748-9326/ac6228.

U

United Nations (2015). Paris Agreement. https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.

United Nations Department of Economic and Social Affairs (2022). *Addressing Energy's Interlinkages with Other SDGs: Policy Briefs in Support of the High-level Political Forum 2022*. New York: United Nations. https://sdgs.un.org/sites/default/files/2022-06/Policy%20Briefs%20-2022%20Energy%27s%20Interlinkages%20With%20Other%20SDGs.pdf.

United Nations Environment Programme (2019). *Emissions Gap Report 2019*. Nairobi. https://www.unep.org/resources/emissions-gap-report-2019.

__________ (2020). *Emissions Gap Report 2020*. Nairobi. https://www.unep.org/emissions-gap-report-2020.

__________ (2022). *The Closing Window: Climate Crisis Calls for Rapid Transformation of Societies. Emissions Gap Report 2022*. Nairobi. https://www.unep.org/resources/emissions-gap-report-2022.

United Nations Framework Convention on Climate Change Standing Committee on Finance (2022). *First Report on the Determination of the Needs of Developing Country Parties Related to Implementing the Convention and the Paris Agreement*. Bonn: United Nations Framework Convention on Climate Change. https://unfccc.int/topics/climate-finance/workstreams/determination-of-the-needs-of-developing-country-parties/first-report-on-the-determination-of-the-needs-of-developing-country-parties-related-to-implementing.

United Nations Secretary-General (2023). Secretary-General calls on States to tackle climate change 'time bomb' through new solidarity pact, acceleration agenda, at launch of Intergovernmental Panel report, 20 March. https://press.un.org/en/2023/sgsm21730.doc.htm. Accessed 26 October 2023.

United Nations University Institute for Natural Resources in Africa (2019). *Africa's Development in the Age of Stranded Assets: Discussion Paper 2019*. Accra. https://i.unu.edu/media/inra.unu.edu/publication/5247/DIscussion-paper-Africas-Development-in-the-age-of-stranded-Assets_INRAReport2019-.pdf.

V

Vinichenko, V., Cherp, A. and Jewell, J. (2021). Historical precedents and feasibility of rapid coal and gas decline required for the 1.5°C target. *One Earth* 4(10), 1477-1490. https://doi.org/10.1016/j.oneear.2021.09.012.

W

Waisman, H., Bataille, C., Winkler, H., Jotzo, F., Shukla, P., Colombier, M. *et al.* (2019). A pathway design framework for national low greenhouse gas emission development strategies. *Nature Climate Change* 9(4), 261-268. https://doi.org/10.1038/s41558-019-0442-8.

Wollburg, P., Hallegatte, S. and Mahler, D. (2023). *The Climate Implications of Ending Global Poverty*. Policy Research Working Paper 10318. Washington, D.C.: World Bank Group. https://documents1.worldbank.org/curated/en/099557002242323911/pdf/IDU0bbf17510061a9045530b57a0ccaba7a1dc79.pdf.

Chapter 6

A

Akinola, O., Olawade, D.B. and David-Olawade, A.C. (2022) What lessons can African nations learn from the COVID-19 pandemic? *Tropical Medicine and Health* 50, 89. https://doi.org/10.1186/s41182-022-00480-x.

Allan, R.P., Arias, P.A., Berger, S. Canadell, J.G., Cassou, C., Chen, D. *et al.* (2021). Summary for policymakers. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. *et al.* (eds.). Cambridge and New York: Cambridge University Press. https://doi.org/10.1017/9781009157896.001.

Ameli, N., Dessens, O., Winning, M., Cronin, J., Chenet, H., Drummond, P. *et al.* (2021). Higher cost of finance exacerbates a climate investment trap in developing economies. *Nature Communications*, 12(1), 4046. https://doi.org/10.1038/s41467-021-24305-3.

Anwar, M., Neary, P. and Huixham, M. (2022). *Natural Gas in Africa Amid a Global Low Carbon Energy Transition*. Cape Town: African Climate Foundation. https://africanclimatefoundation.org/wp-content/uploads/2022/10/ACF-GAS-REPORT-2.0-African-Landscape-Final-Web.pdf.

Assunção, J., Gandour, C. and Rocha, R. (2015). Deforestation slowdown in the Brazilian Amazon: Prices or policies? *Environment and Development Economics* 20(6), 697-722. https://doi.org/10.1017/S1355770X15000078.

Ayaburi, J., Bazilian, M., Kincer, J. and Moss, T. (2020). Measuring "reasonably reliable" access to electricity services. *The Electricity Journal* 33(7), 106828. https://doi.org/10.1016/j.tej.2020.106828.

B

Behuria, P. (2020). The politics of late late development in renewable energy sectors: Dependency and contradictory tensions in India's National Solar Mission. *World Development* 126, 104726. https://doi.org/10.1016/j.worlddev.2019.104726.

Bhatia, P., Chandra, M., Dubash, N.K. and Srivastava, A. (2023). Keeping development at the forefront of India's long-term climate strategy, 5 June. https://www.ideasforindia.in/topics/environment/keeping-development-at-the-forefront-of-india-s-long-term-climate-strategy.html. Accessed 31 October 2023.

BloombergNEF (2021). *The Cost of Producing Battery Precursors in the DRC*. New York: Bloomberg. https://assets.bbhub.io/professional/sites/24/BNEF-The-Cost-of-Producing-Battery-Precursors-in-the-DRC_FINAL.pdf.

Bridle, R., Bellmann, C., Loyola, V., Mostafa, M., Moerenhout, T. *et al.* (2021). *Driving Demand: Assessing the Impacts and Opportunities of the Electric Vehicle Revolution on Cobalt and Lithium Raw Material Production and Trade*. Manitoba: International Institute for Sustainable Development. https://www.iisd.org/system/files/2021-07/electric-vehicle-cobalt-lithium-production-trade.pdf.

Brito, B., Barreto, P., Brandão Jr., A., Baimaa, S. and Gomes, P.H. (2019). Stimulus for land grabbing and deforestation in the Brazilian Amazon. *Environmental Research Letters* 14(6), 064018. https://doi.org/10.1088/1748-9326/ab1e24.

C

Chen, P., Wu, Y., Meng, J., He, P., Li, D., Coffman, D. *et al.* (2022). The heterogeneous role of energy policies in the energy transition of Asia-Pacific emerging economies. *Nature Energy* 7, 588-596. https://doi.org/10.1038/s41560-022-01029-2.

Cozzi, L., Wetzel, D., Tonolo, G. and Hyppolite II, J. (2022). For the first time in decades, the number of people without access to electricity is set to increase in 2022, 3 November. https://www.iea.org/commentaries/for-the-first-time-in-decades-the-number-of-people-without-access-to-electricity-is-set-to-increase-in-2022. Accessed 26 October 2023.

Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M., Bruine de Bruin, W., Dalkmann, H. 2018. Towards demand-side solutions for mitigating climate change. *Nature Climate Change* 8(4), 260-263. https://doi.org/10.1038/s41558-018-0121-1.

Cui, R.Y., Hultman, N., Cui, D., McJeon, H., Yu, S., Edwards, M.R. *et al.* (2021). A plant-by-plant strategy for high-ambition coal power phaseout in China. *Nature Communications* 12(1), 1468. https://doi.org/10.1038/s41467-021-21786-0.

Cui, R.Y., Hultman, N., Edwards, M.R., He, L., Sen, A., Surana, K. *et al.* (2019). Quantifying operational lifetimes for coal power plants under the Paris goals. *Nature Communications* 10, 4759. https://doi.org/10.1038/s41467-019-12618-3.

Davis, K.F., Chhatre, A., Rao, N.D., Singh, D., Ghosh-Jerath, S., Mridul, A. *et al.* (2019). Assessing the sustainability of post-Green Revolution cereals in India. *Proceedings of the National Academy of Sciences* 116(50), 25034-25041. https://doi.org/10.1073/pnas.1910935116.

D

de Hoog, N., Bodnar, D. and Smid, T. (2023). Energy transition not a panacea for fuel importers, 4 April. https://group.atradius.com/publications/economic-research/energy-transition-not-a-panacea-for-fuel-importers.html. Accessed 31 October 2023.

Doblas-Reyes, F.J., Sörensson, A.A., Almazroui, M., Dosio, A. Gutowski, W.J., Haarsma, R. *et al.* (2021). Linking global to regional climate change. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. *et al.* (eds.). Cambridge and New York: Cambridge University Press. Chapter 10. 1363-1512. https://doi.org/10.1017/9781009157896.012.

Dubash, N.K., Pillai, A.V., Flachsland, C., Harrison, K., Hochstetler, K., Lockwood, M. *et al.* (2021). National climate institutions complement targets and policies. *Science* 374(6568), 690-693. https://doi.org/10.1126/science.abm1157.

Dumas, P., Wirsenius, S., Searchinger, T., Andrieu, N. and Vogt-Schilb, A. (2022). *Options to Achieve Net-zero Emissions from Agriculture and Land Use Changes in Latin America and the Caribbean*. IDB Working Paper Series No. IDB-WP-01377. Washington, D.C.: Inter-American Development Bank. https://doi.org/10.18235/0004427.

F

Fazekas, A., Bataille, C. and Vogt-Schilb, A. (2022). *Achieving Net-Zero Prosperity: How Governments Can Unlock 15 Essential Transformations*. Washington, D.C.: Inter-American Development Bank. http://dx.doi.org/10.18235/0004364.

G

Gerval, A. and Hansen, J. (2022). *COVID-19 Working Paper: Single Commodity Export Dependence and the Impacts of COVID-19 in Sub-Saharan Africa*. Washington, D.C.: United States Department of Agriculture Economic Research Service. https://ageconsearch.umn.edu/record/323866.

Groenewoudt, A.C. and Romijn, H.A. (2022). Limits of the corporate-led market approach to off-grid energy access: A review. *Environmental Innovation and Societal Transitions*, 42: 27-43. https://doi.org/10.1016/j.eist.2021.10.027.

H

Hamadeh, N., van Rompaey, C., Metreau, E. and Eapen, S.G. (2022). New World Bank country classifications by income level: 2022–2023, 1 July. https://blogs.worldbank.org/opendata/new-world-bank-country-classifications-income-level-2022-2023. Accessed 30 October 2023.

He, J., Li, Z., Zhang, X., Wang, H. Dong, W., Du, E. *et al.* (2022). Towards carbon neutrality: A study on China's long-term low-carbon transition pathways and strategies. *Environmental Science and Ecotechnology* 9, 100134. https://doi.org/10.1016/j.ese.2021.100134.

Hiep, D.V., Tran, N.H., Tuan, N.A., Hung, T.M., Duc, N.V. and Tung, H. (2023). Assessment of electric two-wheelers development in establishing a national e-mobility roadmap to promote sustainable transport in Vietnam. *Sustainability* 15(9), 7411. https://doi.org/10.3390/su15097411.

Hochstetler, K. (2020). *Political Economies of Energy Transition in Brazil and South Africa*. Cambridge: Cambridge University Press.

Huang, P., Negro, S.O., Hekkert, M.P. and Bi, K. (2016). How China became a leader in solar PV: An innovation system analysis. *Renewable and Sustainable Energy Reviews* 64, 777-789. https://doi.org/10.1016/j.rser.2016.06.061.

I

India, Ministry of Environment, Forest and Climate Change (2022). *India's Long-term Low-carbon Development Strategy: Submission to the United Nations Framework Convention on Climate Change*. New Delhi. https://unfccc.int/documents/623511.

India, Ministry of New and Renewable Energy (2023). *National Green Hydrogen Mission*. New Delhi. https://mnre.gov.in/img/documents/uploads/file_f-1673581748609.pdf.

India, Ministry of Power, Central Electrical Authority (2023). *Report on Optimal Generation Capacity Mix for 2029–30, Version 2.0*. New Delhi. https://cea.nic.in/wp-content/uploads/irp/2023/05/Optimal_mix_report__2029_30_Version_2.0__For_Uploading.pdf.

International Energy Agency (2021a). *Mineral Requirements for Clean Energy Transitions*. Paris. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/mineral-requirements-for-clean-energy-transitions.

__________ (2021b). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. Paris. https://www.iea.org/reports/net-zero-by-2050.

__________ (2021c). *Financing Clean Energy Transitions in Emerging and Developing Countries*. Paris. https://www.iea.org/reports/financing-clean-energy-transitions-in-emerging-and-developing-economies.

__________ (undated). Policies Database. https://www.iea.org/policies. Accessed 30 October 2023.

International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, World Bank and World Health Organization (2021). *Tracking SDG7: The Energy Progress Report*. Washington, D.C.: World Bank. https://www.iea.org/reports/tracking-sdg7-the-energy-progress-report-2021.

__________ (2023). *Tracking SDG 7: The Energy Progress Report 2023*. Washington, D.C.: World Bank. https://trackingsdg7.esmap.org/data/files/download-documents/sdg7-report2023-full_report.pdf.

International Monetary Fund (2022). *Angola: Selected Issues*. IMF Country Report No. 22/12. Washington, D.C. https://www.elibrary.imf.org/view/journals/002/2022/012/article-A001-en.xml.

__________ (2023). *Republic of South Sudan*. IMF Country Report No. 23/108. Washington, D.C. https://www.imf.org/-/media/Files/Publications/CR/2023/English/1SSDEA2023001.ashx.

International Renewable Energy Agency (2022). *Renewable Power Generation Costs in 2021*. Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Power_Generation_Costs_2021.pdf.

International Renewable Energy Agency and Food and Agriculture Organization of the United Nations (2021). *Renewable Energy for Agri-food Systems: Towards the Sustainable Development Goals and the Paris Agreement*. Abu Dhabi and Rome: International Renewable Energy Agency and Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/cb7433en.

J

Jaramillo, M., Quirs-Torts, J., Vogt-Schilb, A., Money, A. and Howells, M. (2023). Data-to-deal (D2D): Open data and modelling of long term strategies to financial resource mobilization – the case of Costa Rica, 19 March. https://doi.org/10.33774/coe-2023-sqbfm-v5. Accessed 31 October 2023.

K

Kikstra, J.S., Mastrucci, A., Min, J., Riahi, K. and Rao, N.D. (2021). Decent living gaps and energy needs around the world. *Environmental Research Letters*, 16(9), 095006. https://doi.org/10.1088/1748-9326/ac1c27.

Klinsky, S. and Sagar, A.D. (2022). The why, what and how of capacity building: Some exploration. *Climate Policy* 22(5), 549-556. https://doi.org/10.1080/14693062.2022.2065059.

Klinsky, S., Waskow, D., Northrop, E. and Bevins, W. (2017). Operationalizing equity and supporting ambition: Identifying a more robust approach to 'respective capabilities'. *Climate and Development* 9(4), 287-297. https://www.tandfonline.com/doi/abs/10.1080/17565529.2016.1146121.

L

Le, H., Posada, F. and Yang, Z. (2022). *Electric Two-Wheeler Market Growth in Vietnam: An Overview*. San Francisco: International Council on Clean Transportation. https://theicct.org/wp-content/uploads/2022/10/asia-pacific-lvs-NDC-TIA-E2W-mkt-growth-Vietnam-nov22.pdf.

Lema, R., Andersen, M.H., Hanlin, R. and Nzila, C. (2021). Renewable electrification pathways and sustainable industrialisation: Lessons learned and their implications. In *Building Innovation Capabilities for Sustainable Industrialisation*. Lema, R., Andersen, M.H., Hanlin, R. and Nzila, C. (eds.). London: Routledge. 249-269. https://www.taylorfrancis.com/chapters/oa-edit/10.4324/9781003054665-12/renewable-electrification-pathways-sustainable-industrialisation-rasmus-lema-margrethe-holm-andersen-rebecca-hanlin-charles-nzila.

Lwasa, S., Seto, K.C., Bai, X., Blanco, H., Gurney, K.R., Kılkış, Ş. *Et al.* (2022). Urban systems and other settlements. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M. *et al.* (eds.). Cambridge and New York: Cambridge University Press. Chapter 8. 861-952. https://doi.org/10.1017/9781009157926.010.

M

Maji, P., Mehrabi, Z. and Kandlikar, M. (2021). Incomplete transitions to clean household energy reinforce gender inequality by lowering women's respiratory health and household labour productivity. *World Development* 139: 105309. https://doi.org/10.1016/j.worlddev.2020.105309.

McCollum, D.L., Echeverri, L.G., Busch, S., Pachauri, S., Parkinson, S., Rogelj, J. *et al.* (2018). Connecting the sustainable development goals by their energy inter-linkages. *Environmental Research Letters*, 13(3), 033006. https://doi.org/10.1088/1748-9326/aaafe3.

Mihalyi, D. and Scurfield, T. (2020). *How Did Africa's Prospective Petroleum Producers Fall Victim to the Presource Curse?* Policy Research Working Paper 9384. Washington, D.C.: World Bank Group. https://openknowledge.worldbank.org/server/api/core/bitstreams/5856f832-cb86-5417-bd72-39c2471c51a2/content.

Millward-Hopkins, J. and Oswald, Y. (2023). Reducing global inequality to secure human wellbeing and climate safety: A modelling study. *The Lancet Planetary Health* 7(2), e147-e154. https://doi.org/10.1016/S2542-5196(23)00004-9.

Mithatcan A., Toledano, P., Brauch, M.D., Mehranvar, L., Iliopoulos, T. And Sasmal, S. (2022). *Scaling Investment in Renewable Energy Generation to Achieve Sustainable Development Goals 7 (Affordable and Clean Energy)* *and 13 (Climate Action) and the Paris Agreement: Roadblocks and Drivers*. New York: Columbia Center on Sustainable Investment. https://ccsi.columbia.edu/sites/default/files/content/docs/publications/ccsi-renewable-energy-investment-roadblocks-drivers.pdf.

Mulugetta, Y., Sokona, Y., Trotter, P.A., Fankhauser, S., Omukuti, J., Croxatto, L.S. *et al.* (2022). Africa needs context-relevant evidence to shape its clean energy future. *Nature Energy* 7, 1015-1022. https://doi.org/10.1038/s41560-022-01152-0.

Muttitt, G. and Kartha, S. (2020). Equity, climate justice and fossil fuel extraction: Principles for a managed phase out. *Climate Policy* 20(8), 1024-1042. https://doi.org/10.1080/14693062.2020.1763900.

Muttitt, G., Price, J., Pye, S. and Welsby, D. (2023). Socio-political feasibility of coal power phase-out and its role in mitigation pathways. *Nature Climate Change* 13, 140-147. https://doi.org/10.1038/s41558-022-01576-2.

N

Nago, M. and Krott, M. (2022). Systemic failures in north–south climate change knowledge transfer: A case study of the Congo basin. *Climate Policy* 22(5), 623-636. https://doi.org/10.1080/14693062.2020.1820850.

Ouedraogo, S.N.D. and Gasser, T.S. (2022). *Renewable Energy Development for Industrialization and Economic Diversification in Central Africa*. ECA Policy Brief. Addis Ababa: United Nations Economic Commission for Africa. https://repository.uneca.org/bitstream/handle/10855/49371/b12024235.pdf.

O

Oxford Analytica (2023). *Algerian Efforts to Diversify the Economy Will Be Slow*. Expert Briefing. Oxford: Oxford Analytica. https://doi.org/10.1108/OXAN-DB280723.

P

Pachauri, S., Pelz, S., Bertram, C., Kreibiehl, S., Rao, N.D., Sokona, Y. *et al.* (2022). Fairness considerations in global mitigation investments. *Science* 378(6624), 1057-1059. https://doi.org/10.1126/science.adf0067.

Pachauri, S., Poblete-Cazenave, M., Aktas, A. and Gidden, M.J. (2021). Access to clean cooking services in energy and emission scenarios after COVID-19. *Nature Energy* 6(11), 1067-1076. https://doi.org/10.1038/s41560-021-00911-9.

Pauw, W.P., Klein, R.J.T., Mbeva, K., Dzebo, A., Cassanmagnago, D. and Rudloff, A. (2018). Beyond headline mitigation numbers: We need more transparent and comparable NDCs to achieve the Paris Agreement on climate change. *Climatic Change* 147, 23-29. https://doi.org/10.1007/s10584-017-2122-x.

Rao, N.D., Min, J. and Mastrucci, A. (2019). Energy requirements for decent living in India, Brazil and South Africa. *Nature Energy* 4, 1025-1032. https://doi.org/10.1038/s41560-019-0497-9.

R

Ruppert Bulmer, E., Pela, K., Eberhard-Ruiz, A. and Montoya, J. (2021). *Global Perspective on Coal Jobs and Managing Labor Transition out of Coal: Key Issues and Policy Responses*. Washington, D.C.: World Bank. http://hdl.handle.net/10986/37118.

S

Shawoo, Z., Maltais, A., Dzebo, A. and Pickering, J. (2022). Political drivers of policy coherence for sustainable development: An analytical framework. *Environmental Policy and Governance* 33(4), 339-350. https://doi.org/10.1002/eet.2039.

Sokona Y. (2021): Building capacity for 'energy for development' in Africa: Four decades and counting. *Climate Policy* 22(5), 671-679. https://doi.org/10.1080/14693062.2020.1870915.

Sokona Y., Mulugetta, Y., Tesfamichael, M., Kaboub, F., Hällström, N., Stilwell, M. *et al.* (2023). *Just Transition: A Climate, Energy and Development Vision for Africa*. Independent Expert Group on Just Transition and Development. https://justtransitionafrica.org/wp-content/uploads/2023/05/Just-Transition-Africa-report-ENG_single-pages.pdf.

Solano-Rodríguez, B., Pye, S., Li, P., Ekins, P., Manzano, O. and Vogt-Schilb, A. (2021). Implications of climate targets on oil production and fiscal revenues in Latin America and the Caribbean. *Energy and Climate Change* 2, 100037. https://doi.org/10.1016/j.egycc.2021.100037.

South Africa, Department of Mineral Resources and Energy (2019). *Integrated Resource Plan 2019*. Pretoria. https://www.energy.gov.za/irp/2019/IRP-2019.pdf.

South Africa, Presidency (2022). *South Africa's Just Energy Transition Investment Plan (JET IP) for the Initial Period 2023–2027*. Pretoria. https://pccommissionflo.imgix.net/uploads/images/South-Africas-Just-Energy-Transition-Investment-Plan-JET-IP-2023-2027-FINAL.pdf.

South African Photovoltaic Industry Association (2023). SA Renewable Energy Grid Survey results presentation – PV only, 7 June. https://sapvia.co.za/sa-renewable-energy-grid-survey-results-presentation-pv-only/. Accessed 31 October 2023.

Southeast Asia Energy Transition Partnership (2022). *2022 Annual Report*. Bangkok: United Nations Office for Project Services. https://www.energytransitionpartnership.org/uploads/2023/03/2022-ETP-Annual-Report-Final-1.pdf.

Sovacool, B.K. (2016). How long will it take? Conceptualizing the temporal dynamics of energy transitions. *Energy Research & Social Science* 13: 202-215. https://doi.org/10.1016/j.erss.2015.12.020.

T

Tongia, R., Sehgal, A. and Kamboj, P. (eds.) (2020). *Future of Coal in India: Smooth Transition or Bumpy Road Ahead?* Chennai and New Delhi: Notion Press and Brookings India.

U

United Nations (2023). *With clock ticking for the SDGs, UN Chief and Barbados Prime Minister call for urgent action to transform broken global financial system*. 26 April. https://www.un.org/sustainabledevelopment/

blog/2023/04/press-release-with-clock-ticking-for-the-sdgs-un-chief-and-barbados-prime-minister-call-for-urgent-action-to-transform-broken-global-financial-system/.
United Nations Conference on Trade and Development (2023). *Formulating Strategic Policy Responses to Open Green Windows of Opportunity*. Policy Brief No. 108. Geneva: United Nations Conference on Trade and Development. https://unctad.org/system/files/official-document/presspb2023d2_en.pdf.
United Nations Economic Commission for Africa (2020). *Economic Report on Africa 2020: Innovative Finance for Private Sector Development in Africa*. Addis Ababa. https://uneca.org/era2020.
United Nations Environment Programme (2019). *Emissions Gap Report 2019*. Nairobi. https://www.unep.org/resources/emissions-gap-report-2019.
Ürge-Vorsatz, D., Herrero, S.T., Dubash, N.K. and Lecocq, F. (2014). Measuring the co-benefits of climate change mitigation. *Annual Review of Environment and Resources* 39, 549-582. https://doi.org/10.1146/annurev-environ-031312-125456.

W

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S. *et al.* (2019). Food in the Anthropocene: The EAT-Lancet Commission on healthy diets from sustainable food systems. *The Lancet* 393(10170), 447-492. https://doi.org/10.1016/S0140-6736(18)31788-4.
World Bank (2022). *International Debt Report 2022: Updated International Debt Statistics*. Washington, D.C. http://hdl.handle.net/10986/38045.
World Bank Group (2022). *South Africa: Country Climate and Development Report*. Washington, D.C. http://hdl.handle.net/10986/38216.
World Bank, Office of the Chief Economist for the Africa Region (2023). *Africa's Pulse. April 2023, Volume 27: Leveraging Resource Wealth During the Low Carbon Transition*. Washington, D.C.: World Bank. http://hdl.handle.net/10986/39615.
World Health Organization (2014). WHO Guidelines for Indoor Air Quality: Household Fuel Combustion. Geneva. https://iris.who.int/bitstream/handle/10665/141496/9789241548885_eng.pdf.
__________ (2022). Household air pollution, 28 November. https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health. Accessed 31 October 2023.
Winkler, H., Lecocq, F., Lofgren, H., Vilariño, M.V., Kartha, S. and Portugal-Pereira, J. (2022). Examples of shifting development pathways: lessons on how to enable broader, deeper, and faster climate action. *Climate Action* 1, 27 (2022). https://doi.org/10.1007/s44168-022-00026-1.

X

Xing, X., Wang, R., Bauer, N., Ciais, P., Cao, J., Chen, J. *et al.* (2021). Spatially explicit analysis identifies significant potential for bioenergy with carbon capture and storage in China. *Nature Communications* 12(1), 3159. https://doi.org/10.1038/s41467-021-23282-x.
Yangka, D., Rauland, V. and Newman, P. (2019) Carbon neutral policy in action: The case of Bhutan. *Climate Policy* 19(6), 672-687. https://doi.org/10.1080/14693062.2018.1551187.

Z

Zhang, F. and Gallagher, K. (2016). Innovation and technology transfer through global value chains: Evidence from China's PV industry. *Energy Policy* 94, 191-203. https://doi.org/10.1016/j.enpol.2016.04.014.

Chapter 7

A

Arcusa, S. and Sprenkle-Hyppolite, S. (2022). Snapshot of the carbon dioxide removal certification and standards ecosystem (2021–2022). *Climate Policy* 22(9-10), 1319-1332. https://doi.org/10.1080/14693062.2022.2094308.

B

Babiker, M., Berndes, G., Blok, K., Cohen, B., Cowie, A., Geden, O. *et al.* (2022). Cross-sectoral perspectives. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M. *et al.* (eds.). Cambridge and New York: Cambridge University Press. Chapter 12. 1245-1354. https://doi.org/10.1017/9781009157926.014.
Bashmakov, I.A., Nilsson, L.J., Acquaye, A., Bataille, C., Cullen, J.M., de la Rue du Can, S. *et al.* (2022). Industry. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M. *et al.* (eds.). Cambridge and New York: Cambridge University Press. Chapter 11. 1161-1243. https://doi.org/10.1017/9781009157926.013.
Bauer, N., Rose, S.K., Fujimori, S., van Vuuren, D.P., Weyant, J., Wise, M. *et al.* (2018). Global energy sector emission reductions and bioenergy use: Overview of the bioenergy demand phase of the EMF-33 model comparison. *Climatic Change* 163, 1553-1568. https://doi.org/10.1007/s10584-018-2226-y.
Bauer, N., Bertram, C., Schultes, A., Klein, D., Luderer, G., Kriegler, E. *et al.* (2020). Quantification of an efficiency–sovereignty trade-off in climate policy. *Nature* 588(7837), 261-266. https://doi.org/10.1038/s41586-020-2982-5.

Beerling, D.J., Kantzas, E.P., Lomas, M.R., Wade, P., Eufrasio, R.M., Renforth, P. *et al.* (2020). Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. *Nature* 583(7815), 242-248. https://doi.org/10.1038/s41586-020-2448-9.

Bellamy, R. (2018). Incentivize negative emissions responsibly. *Nature Energy* 3(7), 532-534. https://doi.org/10.1038/s41560-018-0156-6.

Bento, N. and Wilson, C. (2016). Measuring the duration of formative phases for energy technologies. *Environmental Innovation and Societal Transitions* 21, 95-112. https://doi.org/10.1016/j.eist.2016.04.004.

Bistline, J.E.T. and Blanford, G.J. (2021). Impact of carbon dioxide removal technologies on deep decarbonization of the electric power sector. *Nature Communications* 12(1), 3732. https://doi.org/10.1038/s41467-021-23554-6.

Buck, H.J. (2016). Rapid scale-up of negative emissions technologies: Social barriers and social implications. *Climatic Change* 139(2), 155-167. https://doi.org/10.1007/s10584-016-1770-6.

Buck, H.J., Furhman, J., Morrow, D.R., Sanchez, D.L. and Wang, F.M. (2020). Adaptation and carbon removal. *One Earth* 3(4), 425-435. https://doi.org/10.1016/j.oneear.2020.09.008.

Buck, H.J. and Palumbo-Compton, A. (2022). Soil carbon sequestration as a climate strategy: What do farmers think? *Biogeochemistry* 161(1), 59-70. https://doi.org/10.1007/s10533-022-00948-2.

Buck, H.J., Carton, W., Lund, J.F. and Markusson, N. (2023a). Why residual emissions matter right now. *Nature Climate Change* 13(4), 351-358. https://doi.org/10.1038/s41558-022-01592-2.

__________ (2023b). Countries' long-term climate strategies fail to define residual emissions. *Nature Climate Change* 13(4), 317-319. https://doi.org/10.1038/s41558-023-01614-7.

Bui, M. and Mac Dowell, N. (eds.) (2022). *Greenhouse Gas Removal Technologies*. London: Royal Society of Chemistry. https://doi.org/10.1039/9781839165245.

Byers, E., Krey, V., Kriegler, E., Riahi, K., Schaeffer, R., Kikstra, J. *et al.* (2022). AR6 Scenarios Database. https://pure.iiasa.ac.at/id/eprint/18399/. Accessed 27 October 2023.

C

Carton, W. (2019). 'Fixing' climate change by mortgaging the future: Negative emissions, spatiotemporal fixes, and the political economy of delay. *Antipode* 51(3), 750-769. https://doi.org/10.1111/anti.12532.

Chiquier, S., Fajardy, M. and Mac Dowell, N. (2022). CO_2 removal and 1.5°C: What, when, where, and how? *Energy Advances* 1(8), 524-561. https://doi.org/10.1039/D2YA00108J.

Chiquier, S., Patrizio, P., Bui, M., Sunny, N. and Mac Dowell, N. (2022). A comparative analysis of the efficiency, timing, and permanence of CO_2 removal pathways. *Energy & Environmental Science* 15(10), 4389-4403. https://doi.org/10.1039/D2EE01021F.

Cohen-Shacham, E., Walters, G., Janzen, C. and Maginnis, S. (2016). Nature-based solutions: From theory to practice. In *Nature-based Solutions to Address Global Societal Challenges. Part A.* Gland: International Union for Conservation of Nature. Chapter 1. 2-32. https://portals.iucn.org/library/node/46191.

Cox, E., Spence, E. and Pidgeon, N. (2020). Public perceptions of carbon dioxide removal in the United States and the United Kingdom. *Nature Climate Change* 10(8), 744-749. https://doi.org/10.1038/s41558-020-0823-z.

Cross, J.N., Sweeney, C., Jewett, E.B., Feely, R.A., McElhany, P., Carter, B. *et al.* (2023). *Strategy for NOAA Carbon Dioxide Removal (CDR) Research: A White Paper Documenting a Potential NOAA CDR Science Strategy as an Element of NOAA's Climate Intervention Portfolio.* Washington, D.C.: NOAA. https://doi.org/10.25923/GZKE-8730.

D

Daioglou, V., Rose, S.K., Bauer, N., Kitous, A., Muratori, M., Sano, F. *et al.* (2020). Bioenergy technologies in long-run climate change mitigation: Results from the EMF-33 study. *Climatic Change* 163(3), 1603-1620. https://doi.org/10.1007/s10584-020-02799-y.

de Coninck, H., Revi, A., Babiker, M., Bakker, S., Bazaz, A., Belfer, E. *et al.* (2022). Strengthening and implementing the global response. In *Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-Industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Masson-Delmotte, V., Pörtner, H.-O., Skea, J., Zhai, P., Roberts, D., Shukla, P.R. *et al.* (eds.). Cambridge and New York: Cambridge University Press. Chapter 4. 313-444. https://doi.org/10.1017/9781009157940.006.

DeFries, R., Ahuja, R., Friedman, J., Gordon, D.R., Hamburg, S.P., Kerr, S. *et al.* (2022). Land management can contribute to net zero. *Science* 376(6598), 1163-1165. https://doi.org/10.1126/science.abo0613.

Digdaya, I.A., Sullivan, I., Lin, M., Han, L., Cheng, W.-H., Atwater, H.A. *et al.* (2020). A direct coupled electrochemical system for capture and conversion of CO_2 from oceanwater. *Nature Communications* 11(1), 4412. https://doi.org/10.1038/s41467-020-18232-y.

Duncanson, L., Liang, M., Leitold, V., Armston, J., Krishna Moorthy S.M., Dubayah, R. *et al.* (2023). The effectiveness of global protected areas for climate change mitigation. *Nature Communications* 14(1), 2908. https://doi.org/10.1038/s41467-023-38073-9.

E

Elias, M., Dees, J., Cabiyo, B., Saksa, P. and Sanchez, D.L. (2023). Financial analysis of innovative wood products and carbon finance to support forest restoration in California. *Forest Products Journal* 73(1), 31-42. https://doi.org/10.13073/FPJ-D-22-00049.

Erans, M., Sanz-Pérez, E.S., Hanak, D.P., Clulow, Z., Reiner, D.M. and Mutch, G.A. (2022). Direct air capture: Process technology, techno-economic and socio-political challenges. *Energy & Environmental Science* 15(4), 1360-1405. https://doi.org/10.1039/D1EE03523A.

F

Fasihi, M., Efimova, O. and Breyer, C. (2019). Techno-economic assessment of CO_2 direct air capture plants. *Journal of Cleaner Production* 224, 957-980. https://doi.org/10.1016/j.jclepro.2019.03.086.

Fleming, A., Stitzlein, C., Jakku, E. and Fielke, S. (2019). Missed opportunity? Framing actions around co-benefits for carbon mitigation in Australian agriculture. *Land Use Policy* 85, 230-238. https://doi.org/10.1016/j.landusepol.2019.03.050.

Forster, J., Vaughan, N.E., Gough, C., Lorenzoni, I. and Chilvers, J. (2020). Mapping feasibilities of greenhouse gas removal: Key issues, gaps and opening up assessments. *Global Environmental Change* 63, 102073. https://doi.org/10.1016/j.gloenvcha.2020.102073.

Fridahl, M., Bellamy, R., Hansson, A. and Haikola, S. (2020). Mapping multi-level policy incentives for bioenergy with carbon capture and storage in Sweden. *Frontiers in Climate* 2, 604787. https://doi.org/10.3389/fclim.2020.604787.

Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Gregor, L., Hauck, J. *et al.* (2022). Global carbon budget 2022. *Earth System Science Data* 14(11), 4811-4900. https://doi.org/10.5194/essd-14-4811-2022.

Fuhrman, J., Clarens, A., Calvin, K., Doney, S.C., Edmonds, J.A., O'Rourke, P. *et al.* (2021). The role of direct air capture and negative emissions technologies in the shared socioeconomic pathways towards +1.5 °C and +2 °C futures. *Environmental Research Letters* 16(11), 114012. https://doi.org/10.1088/1748-9326/ac2db0.

Fuhrman, J., Bergero, C., Weber, M., Monteith, S., Wang, F.M., Clarens, A.F. *et al.* (2023). Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system. *Nature Climate Change* 13, 341-350. https://doi.org/10.1038/s41558-023-01604-9.

Fujimori, S., Wu, W., Doelman, J., Frank, S., Hristov, J., Kyle, P., Sands, R. *et al.* (2022). Land-based climate change mitigation measures can affect agricultural markets and food security. *Nature Food* 3(2), 110-121. https://doi.org/10.1038/s43016-022-00464-4.

Fuss, S., Canadell, J.G., Peters, G.P., Tavoni, M., Andrew, R.M., Ciais, P. *et al.* (2014). Betting on negative emissions. *Nature Climate Change* 4, 850-853. https://doi.org/10.1038/nclimate2392.

Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T. *et al.* (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters* 13(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f.

Fuss, S., Golub, A. and Lubowski, R. (2021). The economic value of tropical forests in meeting global climate stabilization goals. *Global Sustainability* 4, e1. https://doi.org/10.1017/sus.2020.34.

Fyson, C.L. and Jeffery, M.L. (2019). Ambiguity in the land use component of mitigation contributions toward the Paris Agreement goals. *Earth's Future* 7(8), 873-891. https://doi.org/10.1029/2019EF001190.

Fyson, C.L., Baur, S. Gidden, M. and Schleussner, C.-F. (2020). Fair-share carbon dioxide removal increases major emitter responsibility. *Nature Climate Change* 10(9), 836-841. https://doi.org/10.1038/s41558-020-0857-2.

G

Ganti, G., Gidden, M.J., Smith, C.J., Fyson, C., Nauels, A., Riahi, K. *et al.* (2023). Uncompensated claims to fair emission space risk putting Paris Agreement goals out of reach. *Environmental Research Letters* 18(2), 024040. https://doi.org/10.1088/1748-9326/acb502.

Garnett, S.T., Burgess, N.D., Fa, J.E., Fernández-Llamazares, Á., Molnár, Z., Robinson, C.J. *et al.* (2018). A spatial overview of the global importance of Indigenous lands for conservation. *Nature Sustainability* 1(7), 369-374. https://doi.org/10.1038/s41893-018-0100-6.

Geden, O. (2016). The Paris Agreement and the inherent inconsistency of climate policymaking. *WIREs Climate Change* 7(6), 790-797. https://doi.org/10.1002/wcc.427.

Geden, O., Peters, G.P. and Scott, V. (2019). Targeting carbon dioxide removal in the European Union. *Climate Policy* 19(4), 487-494. https://doi.org/10.1080/14693062.2018.1536600.

Geden, O., Khourdajie, A.A., Bataille, C., Berndes, G., Buck, H.J., Calvin, K. *et al.* Cross-chapter box 8: Carbon dioxide removal – key characteristics and multiple roles in mitigation strategies. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M. *et al.* (eds.). Cambridge and New York: Cambridge University Press. 1261-1263. https://www.ipcc.ch/report/ar6/wg3/.

Gidden, M.J., Brutschin, E., Ganti, G., Unlu, G., Zakeri, B., Fricko, O. *et al.* (2023). Fairness and feasibility in deep mitigation pathways with novel carbon dioxide removal considering institutional capacity to mitigate. *Environmental Research Letters* 18(7), 074006. https://doi.org/10.1088/1748-9326/acd8d5.

Gidden, M.J., Gasser, T., Grassi, G., Forsell, N., Janssens, I., Lamb, W.F. *et al.* (2023). Aligning IPCC scenarios to national land emissions inventories shifts global mitigation benchmarks. https://d197for5662m48.cloudfront.net/documents/publicationstatus/125532/preprint_pdf/86adfe1dcbe096720eb2f2156377e00a.pdf.

Gosnell, H., Gill, N. and Voyer, M. (2019). Transformational adaptation on the farm: Processes of change and persistence in transitions to 'climate-smart' regenerative agriculture. *Global Environmental Change* 59, 101965. https://doi.org/10.1016/j.gloenvcha.2019.101965.

Grant, N., Hawkes, A., Mittal, S. and Gambhir, A. (2021). The policy implications of an uncertain carbon dioxide removal potential. *Joule* 5(10), 2593-2605. https://doi.org/10.1016/j.joule.2021.09.004.

Grassi, G., Schwingshackl, C., Gasser, T., Houghton, R.A., Sitch, S., Canadell, J.G. *et al.* (2023). Harmonising the land-use flux estimates of global models and national inventories for 2000–2020. *Earth System Science Data* 15(3), 1093-1114. https://doi.org/10.5194/essd-15-1093-2023.

Grubler, A. and Wilson, C. (eds.) (2013). *Energy Technology Innovation: Learning from Historical Successes and Failures*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781139150880.

H

Haberl, H., Mbow, C., Deng, X., Irwin, E.G., Kerr, S., Kuemmerle, T. *et al.* (2014). Finite land resources and competition. In *Rethinking Global Land Use in an Urban Era*. Seto, K.C. and Reenberg, A. (eds.). Cambridge, MA: MIT Press. Chapter 4. 35-69. https://doi.org/10.7551/mitpress/9780262026901.003.0004.

Holz, C., Siegel, L.S., Johnston, E., Jones, A.P. and Sterman, J. (2018). Ratcheting ambition to limit warming to 1.5 °C–trade-offs between emission reductions and carbon dioxide removal. *Environmental Research Letters* 13(6), 064028. https://doi.org/10.1088/1748-9326/aac0c1.

Honegger, M., Burns, W. and Morrow, D.R. (2021). Is carbon dioxide removal 'mitigation of climate change'? *Review of European, Comparative & International Environmental Law* 30(3), 327-335. https://doi.org/10.1111/reel.12401.

Honegger, M., Michaelowa, A. and Roy, J. (2021). Potential implications of carbon dioxide removal for the Sustainable Development Goals. *Climate Policy* 21(5), 678-698. https://doi.org/10.1080/14693062.2020.1843388.

I

Intergovernmental Panel on Climate Change (2022a). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M. *et al.* (eds.). Cambridge and New York: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg3/.

__________ (2022b). *Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R. *et al.* (eds.). Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157988.

J

Jacobsson, S. and Bergek, A. (2004). Transforming the energy sector: The evolution of technological systems in renewable energy technology. *Industrial and Corporate Change* 13(5), 815-849. https://doi.org/10.1093/icc/dth032.

Jung, M., Arnell, A., De Lamo, X., García-Rangel, S., Lewis, M., Mark, J. *et al.* (2021). Areas of global importance for conserving terrestrial biodiversity, carbon and water. *Nature Ecology & Evolution* 5(11), 1499-1509. https://doi.org/10.1038/s41559-021-01528-7.

K

Kalkuhl, M., Franks, M., Gruner, F., Lessmann, K. and Edenhofer, O. (2022). Pigou's advice and Sisyphus' warning: Carbon pricing with non-permanent carbon-dioxide removal. CESifo Working Paper No. 10169. Munich: CESifo. https://doi.org/10.2139/ssrn.4315996.

Kartha, S., Caney, S., Dubash, N.K. and Muttitt, G. (2018). Whose carbon is burnable? Equity considerations in the allocation of a 'right to extract'. *Climatic Change* 150(1), 117-129. https://doi.org.10.1007/s10584-018-2209-z.

Koven, C.D., Sanderson, B.M. and Swann, A.L.S. (2023). Much of zero emissions commitment occurs before reaching net zero emissions. *Environmental Research Letters* 18(1), 014017. https://doi.org/10.1088/1748-9326/acab1a.

L

Lebling, K., Schumer, C. and Riedl, D. (2023). International governance of technological carbon removal: Surfacing questions, exploring solutions. Washington, D.C.: World Resources Institute. https://doi.org/10.46830/wriwp.23.00013.

Lackner, K.S. and Azarabadi, H. (2021). Buying down the cost of direct air capture. *Industrial & Engineering Chemistry Research* 60(22), 8196-8208. https://doi.org/10.1021/acs.iecr.0c04839.

Lecocq, F., Winkler, H., Daka, J.P., Fu, S., Gerber, J.S., Kartha, S. *et al.* (2022). Mitigation and development pathways in the near- to mid-term. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M. *et al.* (eds.). Cambridge and New York: Cambridge University Press. Chapter 4. 409-502. https://doi.org/10.1017/9781009157926.006.

Lenzi, D., Lamb, W.F., Hilaire, J., Kowarsch, M. and Minx, J.C. (2018). Don't deploy negative emissions technologies without ethical analysis. *Nature* 561, 303-305. https://doi.org/10.1038/d41586-018-06695-5.

M

MacDougall, A.H., Frölicher, T.L., Jones, C.D., Rogelj, J., Matthews, H.D., Zickfeld, K., Arora, V.K. *et al.* (2020). Is there warming in the pipeline? A multi-model analysis of the zero emissions commitment from CO_2. *Biogeosciences* 17(11), 2987-3016. https://doi.org/10.5194/bg-17-2987-2020.

Mace, M.J., Fyson, C.L., Schaeffer, M. and Hare, W.L. (2021). Large-scale carbon dioxide removal to meet the 1.5°C limit: Key governance gaps, challenges and priority responses. *Global Policy* 12(S1), 67-81. https://doi.org/10.1111/1758-5899.12921.

Madhu, K., Pauliuk, S., Dhathri, S. and Creutzig, F. (2021). Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment. *Nature Energy* 6(11), 1035-1044. https://doi.org/10.1038/s41560-021-00922-6.

Markusson, N., McLaren, D. and Tyfield, D. (2018). Towards a cultural political economy of mitigation deterrence by negative emissions technologies (NETs). *Global Sustainability* 1, e10. https://doi.org/10.1017/sus.2018.10.

McElwee, P. (2023). Advocating afforestation, betting on BECCS: Land-based negative emissions technologies (NETs) and agrarian livelihoods in the Global South. *The Journal of Peasant Studies* 50(1), 185-214. https://doi.org/10.1080/03066150.2022.2117032.

McLaren, D.P., Tyfield, D.P., Willis, R., Szerszynski, B. and Markusson, N.O. (2019). Beyond 'net-zero': A case for separate targets for emissions reduction and negative emissions. *Frontiers in Climate* 1, 4. https://doi.org/10.3389/fclim.2019.00004.

Mercer, L. and Burke, J. (2023). *Strengthening MRV Standards for Greenhouse Gas Removals to Improve Climate Governance*. London: Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London School of Economics and Political Science. https://www.cccep.ac.uk/wp-content/uploads/2023/05/Strengthening-MRV-standards-for-greenhouse-gas-removals.pdf.

Merk, C., Dyrnes Nordø, Å., Andersen, G., Lægreid, O.M. and Tvinnereim, E. (2022). Don't send us your waste gases: Public attitudes toward international carbon dioxide transportation and storage in Europe. *Energy Research & Social Science* 87, 102450. https://doi.org/10.1016/j.erss.2021.102450.

Minx, J.C., Lamb, W.F., Callaghan, M.W., Fuss, S., Hilaire, J., Creutzig, F. *et al.* (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters* 13(6), 063001. https://doi.org/10.1088/1748-9326/aabf9b.

Mohan, A., Geden, O., Fridahl, M., Buck, H.J. and Peters, G.P. (2021). UNFCCC must confront the political economy of net-negative emissions. *One Earth* 4(10), 1348-1051. https://doi.org/10.1016/j.oneear.2021.10.001.

Muthee, K., Duguma, L., Majale, C., Mucheru-Muna, M., Wainaina, P. and Minang, P. (2022). A quantitative appraisal of selected agroforestry studies in the sub-Saharan Africa. *Heliyon* 8(9), e10670. https://doi.org/10.1016/j.heliyon.2022.e10670.

N

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

Nawaz, S., Peterson St-Laurent, G. and Satterfield, T. (2023). Public evaluations of four approaches to ocean-based carbon dioxide removal. *Climate Policy* 23(3), 379-394. https://doi.org/10.1080/14693062.2023.2179589.

Nunez, S., Verboom, J. and Alkemade, R. (2020). Assessing land-based mitigation implications for biodiversity. *Environmental Science & Policy* 106, 68-76. https://doi.org/10.1016/j.envsci.2020.01.006.

O

Owen, A., Burke, J. and Serin, E. (2022). Who pays for BECCS and DACCS in the UK: Designing equitable climate policy. *Climate Policy* 22(8), 1050-1068. https://doi.org/10.1080/14693062.2022.2104793.

P

Pachauri, S., Pelz, S., Bertram, C., Kreibiehl, S., Rao, N.D., Sokona, Y. *et al.* (2022). Fairness considerations in global mitigation investments. *Science* 378(6624), 1057-1059. https://doi.org/10.1126/science.adf0067.

Pathak, M., Slade, R., Shukla, P.R., Skea, J., Pichs-Madruga, R. and Ürge-Vorsatz, D. (2022). Technical summary. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M. *et al.* (eds.). Cambridge and New York: Cambridge University Press. 51-147. https://doi.org/10.1017/9781009157926.

Pisciotta, M., Davids, J. and Wilcox, J. (2022). Greenhouse gas removal: Overview and current status of deployment. In *Greenhouse Gas Removal Technologies*. Bui, M. and Mac Dowell, N. (eds.) London: Royal Society of Chemistry. https://doi.org/10.1039/9781839165245-00006.

Powis, C.M., Smith, S.M., Minx, J.C. and Gasser, T. (2023). Quantifying global carbon dioxide removal deployment. *Environmental Research Letters* 18(2), 024022. https://doi.org/10.1088/1748-9326/acb450.

R

Raupach, M.R., Davis, S.J., Peters, G.P., Andrew, R.M., Canadell, J.G., Ciais, P. *et al.* (2014). Sharing a quota on cumulative carbon emissions. *Nature Climate Change* 4(10), 873-879. https://doi.org/10.1038/nclimate2384.

Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A.C. *et al.* (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature Communications* 10(1), 3277. https://doi.org/10.1038/s41467-019-10842-5.

Riahi, K., Schaeffer, R., Arango, J., Calvin, K., Guivarch, C., Hasegawa, T. *et al.* (2022). Mitigation pathways compatible with long-term goals. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M. *et al.* (eds.). Cambridge and New York: Cambridge University Press. Chapter 3. 295-408. https://doi.org/10.1017/9781009157926.005.

Rickels, W., Proelß, A., Geden, O., Burhenne, J. and Fridahl, M. (2021). Integrating carbon dioxide removal into European emissions trading. *Frontiers in Climate* 3, 690023. https://doi.org/10.3389/fclim.2021.690023.

Robiou du Pont, Y., Jeffery, M.L., Gütschow, J., Rogelj, J., Christoff, P. and Meinshausen, M. (2017). Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change* 7(1), 38-43. https://doi.org/10.1038/nclimate3186.

Rogelj, J., Popp, A., Calvin, K.V., Luderer, G., Emmerling, J., Gernaat, D. *et al.* (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change* 8, 325-332. https://doi.org/10.1038/s41558-018-0091-3.

Romig, K.D. (2021). Workers have a stake in CCUS. *The Electricity Journal* 34(7), 107001. https://doi.org/10.1016/j.tej.2021.107001.

Ruseva, T., Hedrick, J., Marland, G., Tovar, H., Sabou, C. and Besombes, E. (2020). Rethinking standards of permanence for terrestrial and coastal carbon: Implications for governance and sustainability. *Current Opinion in Environmental Sustainability* 45, 69-77. https://doi.org/10.1016/j.cosust.2020.09.009.

S

Sanchez, D.L., Fingerman, K., Herbert, C. and Uden, S. (2021). Policy options for deep decarbonization and wood utilization in California's Low Carbon Fuel Standard. *Frontiers in Climate* 3, 665778. https://doi.org/10.3389/fclim.2021.665778.

Satterfield, T., Nawaz, S. and Peterson St-Laurent, G. (2023). Exploring public acceptability of direct air carbon capture with storage: Climate urgency, moral hazards and perceptions of the 'whole versus the parts'. *Climatic Change* 176, 14. https://doi.org/10.1007/s10584-023-03483-7.

Schenuit, F., Colvin, R., Fridahl, M., McMullin, B., Reisinger, A., Sanchez, D.L. *et al.* (2021). Carbon dioxide removal policy in the making: Assessing developments in 9 OECD cases. *Frontiers in Climate* 3, 638805. https://doi.org/10.3389/fclim.2021.638805.

Schenuit, F., Gidden, M.J., Boettcher, M., Brutschin, E., Fyson, C., Gasser, T. *et al.* (2023). Secure robust carbon dioxide removal policy through credible certification. *Communications Earth & Environment* 4, 349. https://doi.org/10.1038/s43247-023-01014-x.

Semieniuk, G., Ghosh, J. and Folbre, N. (2023). Technical comment on 'Fairness considerations in global mitigation investments.' *Science* 380(6646), eadg5893. https://doi.org/10.1126/science.adg5893.

Shayegh, S., Bosetti, V. and Tavoni, M. (2021). Future prospects of direct air capture technologies: Insights from an expert elicitation survey. *Frontiers in Climate* 3, 630893. https://doi.org/10.3389/fclim.2021.630893.

Smith, P., Adams, J., Beerling, D.J., Beringer, T., Calvin, K.V., Fuss, S. *et al.* (2019). Land-management options for greenhouse gas removal and their impacts on ecosystem services and the Sustainable Development Goals. *Annual Review of Environment and Resources* 44(1), 255-286. https://doi.org/10.1146/annurev-environ-101718-033129.

Smith, S.M. (2021). A case for transparent net-zero carbon targets. *Communications Earth & Environment* 2(1), 24. https://doi.org/10.1038/s43247-021-00095-w.

Smith, H.B., Vaughan, N.E. and Forster, J. (2022). Long-term national climate strategies bet on forests and soils to reach net-zero. *Communications Earth & Environment* 3(1), 305. https://doi.org/10.1038/s43247-022-00636-x.

Smith, S.M., Geden, O., Nemet, G.F., Gidden, M.J., Lamb, W.F., Powis, C. *et al.* (2023). *The State of Carbon Dioxide Removal - First Edition*. The State of Carbon Dioxide Removal. https://www.stateofcdr.org.

Soto-Navarro, C., Ravilious, C., Arnell, A., De Lamo, X., Harfoot, M., Hill, S.L.L. *et al.* (2020). Mapping Co-Benefits for carbon storage and biodiversity to inform conservation policy and action. *Philosophical Transactions of the Royal Society B* 375(1794), 20190128. https://doi.org/10.1098/rstb.2019.0128.

Strefler, J., Amann, T., Bauer, N., Kriegler, E. and Hartmann, J. (2018). Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters* 13(3), 034010. https://doi.org/10.1088/1748-9326/aaa9c4.

Strefler, J., Bauer, N., Humpenöder, F., Klein, D., Popp, A. and Kriegler, E. (2021). Carbon dioxide removal technologies are not born equal. *Environmental Research Letters* 16(7), 074021. https://doi.org/10.1088/1748-9326/ac0a11.

W

Waller, L., Rayner, T., Chilvers, J., Gough, C.A., Lorenzoni, I., Jordan, A. *et al.* (2020). Contested framings of greenhouse gas removal and its feasibility: Social and political dimensions. *WIREs Climate Change* 11(4), e649. https://doi.org/10.1002/wcc.649.

Windisch, M.G., Davin, E.L. and Seneviratne, S.I. (2021). Prioritizing forestation based on biogeochemical and local biogeophysical impacts. *Nature Climate Change* 11(10), 867-871. https://doi.org/10.1038/s41558-021-01161-z.

Y

Yuwono, B., Yowargana, P., Fuss, S., Griscom, B.W., Smith, P. and Kraxner, F. (2023). Doing burden-sharing right to deliver natural climate solutions for carbon dioxide removal. *Nature-Based Solutions* 3, 100048. https://doi.org/10.1016/j.nbsj.2022.100048.

Z

Zheng, Q., Siman, K., Zeng, Y., Teo, H.C., Sarira, T.V., Sreekar, R. and Koh, L.P. (2022). Future land-use competition constrains natural climate solutions. *Science of The Total Environment* 838, 156409. https://doi.org/10.1016/j.scitotenv.2022.156409.

Zickfeld, K., Azevedo, D., Mathesius, S. and Matthews, H.D. (2021). Asymmetry in the climate–carbon cycle response to positive and negative CO_2 emissions. *Nature Climate Change* 11(7), 613-617. https://doi.org/10.1038/s41558-021-01061-2.

This publication is supported by the Environment Fund – UNEP's core financial fund. The Fund is used to provide scientific evidence on the state of the global environment, identify emerging environmental issues and innovative solutions, raise awareness and advocacy, bring together stakeholders to agree on action, and for building capacity of partners. Core funding gives UNEP the strength and flexibility to implement the programme of work (in support of the 2030 Agenda) as approved by its Member States, and to strategically respond to emerging challenges. UNEP is grateful to all the Member States that contribute to the Environment Fund.

For more information: unep.org/environment-fund

UN environment programme

For more information:
United Nations Avenue, Gigiri
P O Box 30552, 00100
Nairobi, Kenya
unep-communication-director@un.org

unep.org