Bridging the gap: Global transformation of the energy system

Mulugetta, Yacob; Carvajal, Pablo E. ; Haselip, James Arthur; Spencer, Thomas

Published in:
Emissions Gap Report 2019

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

UN environment programme

Emissions Gap Report 2019

ISBN: 978-92-807-3766-0
Job number: DEW/2263/NA

Suggested citation
United Nations Environment Programme (2019). *Emissions Gap Report 2019*. UNEP, Nairobi.

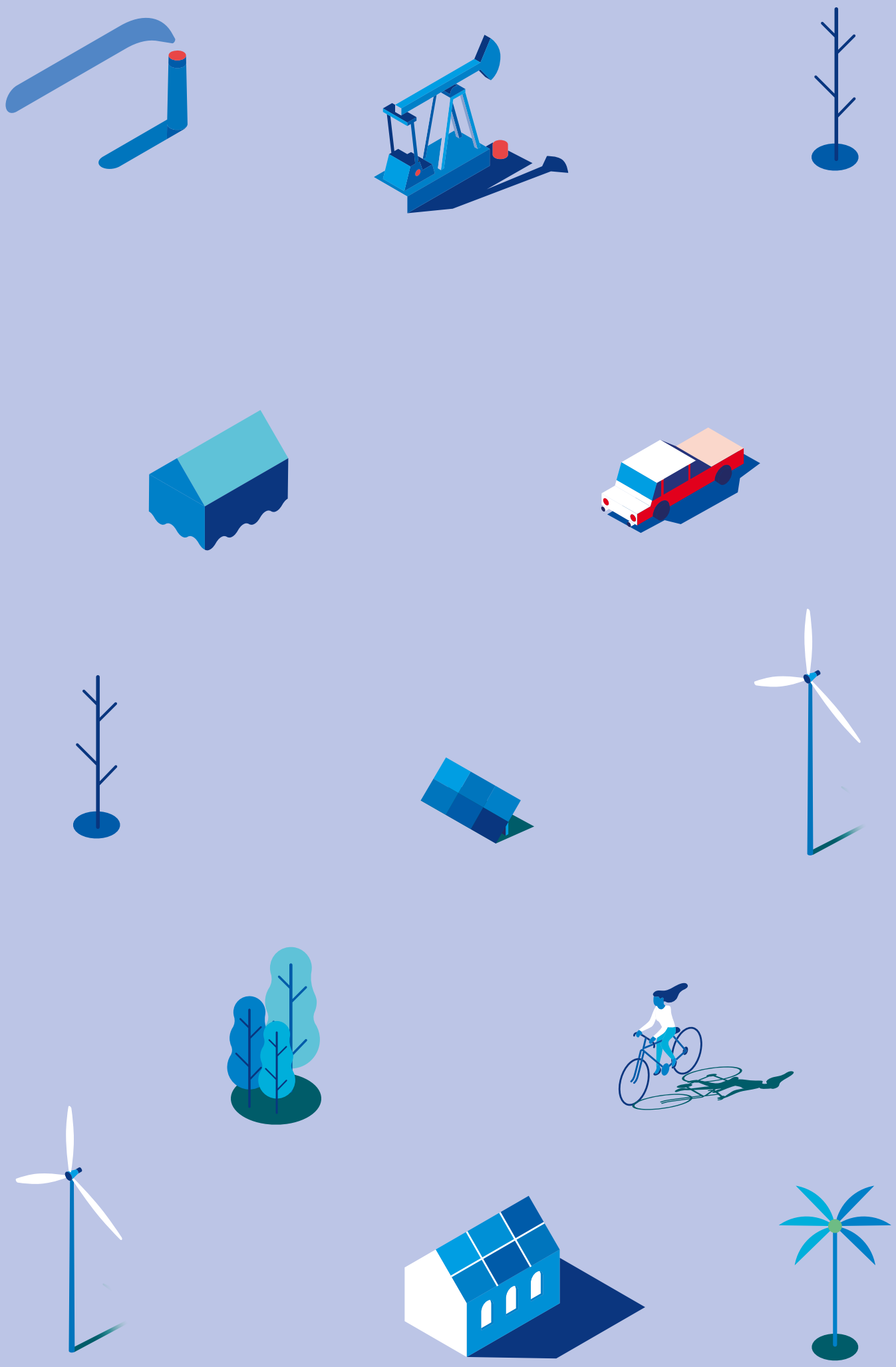
http://www.unenvironment.org/emissionsgap

Supported by:

ClimateWorks Foundation
SITRA
Royal Norwegian Ministry of Climate and Environment
Udenrigsministeriet Ministry of Foreign Affairs of Denmark
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
Government of the Netherlands
Sweden Sverige

Emissions Gap Report 2019

November 2019



Acknowledgements

The United Nations Environment Programme (UNEP) would like to thank the members of the steering committee, the lead and contributing authors, 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.

Project steering committee

Juliane Berger (German Environment Agency), John Christensen (UNEP DTU Partnership), Navroz K. Dubash (Centre for Policy Research, India), Jian Liu (UNEP), Simon Maxwell (Independent), Surabi Menon (ClimateWorks Foundation), Bert Metz (European Climate Foundation), Katia Simeonova (UNFCCC), Priyadarshi Shukla (Ahmedabad University), Oksana Tarasova (World Meteorological Organization), Merlyn van Voore (UNEP)

Chapter 1

Lead authors: Anne Olhoff (UNEP DTU Partnership), John Christensen (UNEP DTU Partnership)

Chapter 2

Lead authors: Takeshi Kuramochi (NewClimate Institute, Germany), Michel den Elzen (PBL Netherlands Environmental Assessment Agency), Glen Peters (CICERO, Norway)

Contributing authors: Andrzej Ancyger (Climate Analytics, Germany), Ankit Bhardwaj (Centre for Policy Research, India), Gabriel Blanco (National University of the Center of the Buenos Aires Province, Argentina), Taryn Fransen (World Resources Institute, USA), Andreas Geiges (Climate Analytics, Germany), Frederic Hans (NewClimate Institute, Germany), Christopher Henderson (World Resources Institute, USA), Niklas Höhne (NewClimate Institute, Germany), Kejun Jiang (Energy Research Institute, China), Maria Jose de Villafranca (NewClimate Institute, Germany), Kimon Keramidas (Joint Research Centre/European Commissions), Joojin Kim (Solutions For Our Climate, Republic of Korea), Akihisa Kuriyama (Institute for Global Environmental Strategies, Japan), Leonardo Nascimento (NewClimate Institute, Germany), Jos Olivier (PBL Netherlands Environmental Assessment Agency), Deger Saygin (SHURA, Turkey), Ranping Song (World Resources Institute, China), Claire Stockwell (Climate Analytics, Germany), Kentaro Tamura (Institute for Global Environmental Strategies, Japan), Paola Tanguy (NewClimate Institute, Germany), Heleen van Soest (PBL Netherlands Environmental Assessment Agency), Jorge Villarreal Padilla (Iniciativa Climática de México), Ryan Wilson (Climate Analytics, Germany), William Wills (Centro Clima, Brazil), Paola Yanguas Parra (Climate Analytics, Germany)

Chapter 3

Lead authors: Joeri Rogelj (Grantham Institute, Imperial College London, UK; International Institute for Applied Systems Analysis, Austria), Michel den Elzen (PBL Netherlands Environmental Assessment Agency)

Contributing authors: Daniel Huppmann (International Institute for Applied Systems Analysis, Austria), Gunnar Luderer (Potsdam Institute for Climate Impact Research, Germany)

Chapter 4

Lead authors: Niklas Höhne (NewClimate Institute, Germany), Taryn Fransen (World Resources Institute, USA), Frederic Hans (NewClimate Institute, Germany)

Contributing authors: Ankit Bhardwaj (Centre for Policy Research, India), Gabriel Blanco (National University of the Center of the Buenos Aires Province, Argentina), Jesse Burton (University of Cape Town, South Africa), Michel den Elzen (PBL Netherlands Environmental Assessment Agency), Markus Hagemann (NewClimate Institute, Germany), Christopher Henderson (World Resources Institute, USA), Maria Daniela Keesler (National University of the Center of the Buenos Aires Province, Argentina), Jiang Kejun (Energy Research Institute, China), Akihisa Kuriyama (Institute for Global Environmental Strategies (IGES), Japan), Fu Sha (National Centre for Climate Change Strategy, China), Ranping Song (World Resources Institute, China), Kentaro Tamura (Institute for Global Environmental Strategies, Japan), Jorge Villarreal (Iniciativa Climática de México), William Wills (Centro Clima, Brazil)

Chapter 5

Lead authors: Nebojsa Nakićenović (International Institute for Applied Systems Analysis and Vienna University of Technology, Austria), Charlie Wilson (Tyndall Centre for Climate Change Research, UK)

Contributing authors: Bill Colglazier (American Association for Advancement of Science), Owen Gaffney (Potsdam Institute for Climate Impact Research, Germany), Dirk Messner (United Nations University), Narasimha Rao (Yale School of Forestry & Environmental Studies, USA), Caroline Zimm (International Institute for Applied Systems Analysis, Austria)

Chapter 6

Lead Authors: Yacob Mulugetta (Department of Science, Technology, Engineering & Public Policy, University College London, UK), Pablo E. Carvajal (International Renewable

Energy Agency, Germany), James Haselip (UNEP DTU Partnership), Thomas Spencer (The Energy and Resources Institute, India)

Contributing Authors: Edo Abraham (Delft University of Technology, the Netherlands), Simon Batchelor (Gamos Ltd, UK), Brigitte Knopf (Mercator Research Institute on Global Commons and Climate Change, Germany)

Chapter 7

Lead authors: Edgar Hertwich (Norwegian University of Science and Technology), Reid Lifset (Yale School of Forestry & Environmental Studies, USA), Stefan Pauliuk (Faculty of Environment and Natural Resources, University of Freiburg, Germany), Niko Heeren (Yale School of Forestry & Environmental Studies, USA)

Contributing Authors: Saleem Ali (University of Delaware, USA), Peter Berrill (Yale School of Forestry & Environmental Studies USA), Tomer Fishman (Interdisciplinary Center Herzliya, Israel), Qingshi Tu (Yale School of Forestry & Environmental Studies USA), Paul Wolfram (Yale School of Forestry & Environmental Studies, USA)

Reviewers

Lawrence Agbemabiese (University of Delaware), Juan Carlos Altamirano (World Resources Institute /New Climate Economy), Birgit Aru (European Commission DG CLIMA), Mohammed Awojobi (University of Delaware), Christoph Bertram (Potsdam Institute for Climate Impact Research), Kathryn Jennifer Bowen (Australian National University), Sylvain Cail (Enerdata), Rachel Chi Kiu Mok (World Bank), Filippo Civitelli (UK Department for Business, Energy and Industrial Strategy), Robert Ddamulira (University of Delaware), Maya De Souza (Resource Efficiency, DEFRA), Riyanti Djalante (United Nations University – Institute for the Advanced Study of Sustainability), Eric Fee (German Environment Agency), Steve Forden (UK Department for Business, Energy and Industrial Strategy), James Foster (UK Department for Business, Energy and Industrial Strategy), Sabine Fuß (Mercator Research Institute on Global Commons and Climate Change), Harikumar Gadde (World Bank), Manuela Galan (UK Department for Business, Energy and Industrial Strategy), Mengpin Ge (World Resources Institute), Olivia Grippner (European Commission DG CLIMA), Christoph Helbig (Augsburg University), Fintan Hurley (Institute of Occupational Medicine), Yasuko Kameyama (National Institute for Environmental Studies, Japan), Rakhyun E. Kim (Utrecht University), Peter King (Institute for Global Environmental Strategies), Almbana Kona (European Commission DG CLIMA), Xavier Labandeira (University of Vigo), Gerd Leipold (Humboldt-Viadrina Governance Platform), Kelly Levin (World Resources Institute), Shannon McDaniel (Global Covenant of Mayors), Apurba Mitra (World Resources Institute), Miles Perry (European Commission DG CLIMA), John Quinn (UK Department for Business, Energy and Industrial Strategy), Chandra Shekhar Sinha (World Bank), Leena Srivastava (The Energy Resource Institute), Joel N. Swisher (Western Washington University), Saara Tamminen (SITRA), Oras Tynkkynen (SITRA), Tom Van-Ierland (European Commission DG CLIMA), Marion Vieweg (Current Future), Kenichi Wada (Research Institute of Innovative Technology for the Earth), Jim Watson (UK Energy Research Centre), Zhao Xiusheng (Tsinghua University)

Chief scientific editors

Anne Olhoff (UNEP DTU Partnership), John Christensen (UNEP DTU Partnership)

Editorial support

Olivier Bois von Kursk (UNEP DTU Partnership)

Secretariat and project coordination

Ivana Audia (UNEP DTU Partnership), Olivier Bois von Kursk (UNEP DTU Partnership), Anne Olhoff (UNEP DTU Partnership), John Christensen (UNEP DTU Partnership), Pinya Sarasas (UNEP), Maarten Kappelle (UNEP)

Media and launch support

Keishamaza Rukikaire, Nancy Groves, Michael Logan, Josie Raine, Sajni Shah, Moses Osani, Despina Kannaourou, David Cole, Pooja Munshi, Gregory Mwaura, Richard Waiguchu, Salome Mbeyu Chamanje, Florian Fussstetter, Joyce Sang, Viola Kup, Alejandro Laguna, Mark Grassi, Charlotte De kruijk (UNEP), Mette Annelie Rasmussen, Lasse Hemmingsen (UNEP DTU Partnership)

Design, layout and printing

Joseph & Sebastian (Layout and cover), Caren Weeks (Figures), Cuartalinea (Printing), Despina Kannaourou (UNEP)

Language editing and translation of the executive summary

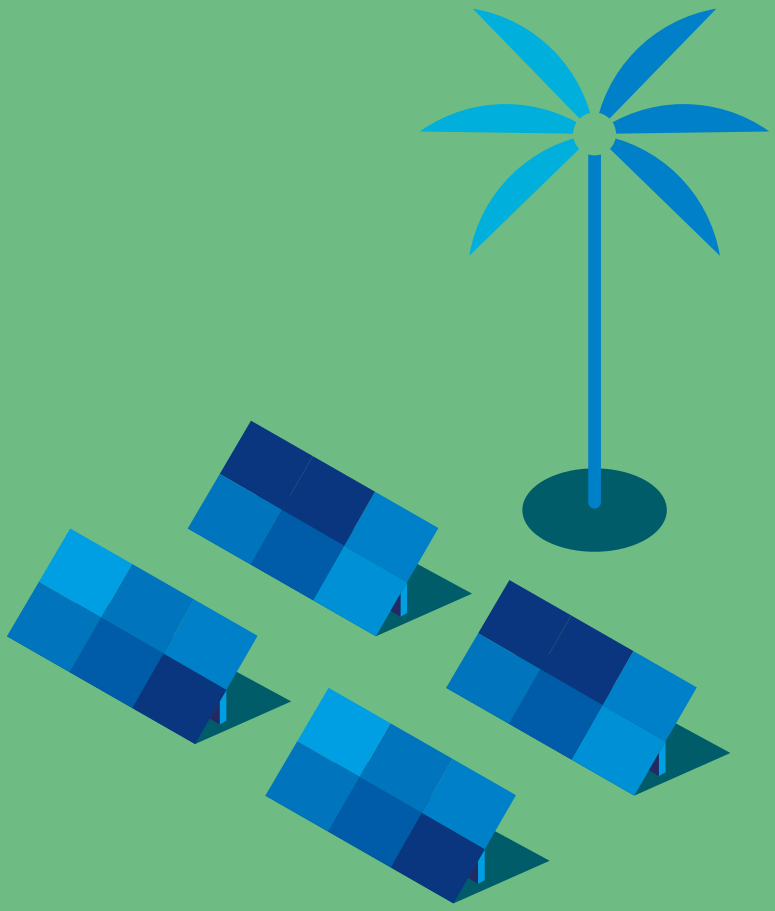
Strategic Agenda

Thanks also to:

Climate Transparency, Oras Tynkkynen (Sitra), Sandra Aparcana, Jacob Ipsen Hansen, Pia Riis Kofoed-Hansen, Susanne Konrad, Thomas Kragh Laursen, Daniel Puig, Fatima-Zahra Taibi, Xianli Zhu (UNEP DTU Partnership), David Berman, Yunting Duan, Angeline Djampou, Lu Liu, Daria Vasilevskaia, Ying Wang and Edoardo Zandri (UNEP)

Finally, the United Nations Environment Programme would like to thank the ClimateWorks Foundation, the Danish Ministry of Foreign Affairs, the Dutch Ministry of Economic Affairs and Climate Policy, the Finnish Innovation Fund (Sitra), the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), the Norwegian Ministry of Climate and Environment, and the Swedish International Development Authority (SIDA) for their support to the work of the Emissions Gap Report.

Contents



Glossary

This glossary is compiled according to the Lead Authors of the Report drawing on glossaries and other resources available on the websites of the following organizations, networks and projects: Intergovernmental Panel on Climate Change, Non-State Actor Zone for Climate Action, United Nations Environment Programme, United Nations Framework Convention on Climate Change and World Resources Institute.

Baseline/reference: The state against which change is measured. In the context of transformation pathways, the term 'baseline scenarios' refers to scenarios that are based on the assumption that no mitigation policies or measures will be implemented beyond those that are already in force and/or are 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 effort. Typically, baseline scenarios are then compared to mitigation scenarios that are constructed to meet different goals for greenhouse gas emissions, atmospheric concentrations or temperature change. The term 'baseline scenario' is used interchangeably with 'reference scenario' and 'no policy scenario'. In much of the literature the term is also synonymous with the term 'business as usual (BAU) scenario', although the term 'BAU' has fallen out of favour because the idea of 'business as usual' in century-long socioeconomic projections is hard to fathom.

Bioenergy: Energy derived from any form of biomass such as recently living organisms or their metabolic by-products

Cancun pledge: During 2010, many countries submitted their existing plans for controlling greenhouse gas emissions to the Climate Change Secretariat and these proposals were formally acknowledged under the United Nations Framework Convention on Climate Change (UNFCCC). Developed countries presented their plans in the shape of economy-wide targets to reduce emissions, mainly up to 2020, while developing countries proposed ways to limit their growth of emissions in the shape of plans of action.

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 the 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 climate. It describes, for a given mixture and amount of greenhouse gases, 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, greenhouse gas emissions (unless otherwise specified) are the sum of the basket of greenhouse gases listed in Annex A to the Kyoto Protocol, expressed as CO_2e assuming a 100-year global warming potential.

Carbon intensity: The amount of emissions of CO_2 released per unit of another variable such as gross domestic product, output energy use, transport or agricultural/forestry products.

Carbon offset: See Offset.

Carbon price: The price for avoided 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 that are used to assess the economic costs of mitigation, carbon prices are used as a proxy to represent the level of effort in mitigation policies.

Carbon tax: A levy on the carbon content of fossil fuels. Because virtually all of the carbon in fossil fuels is ultimately emitted as CO_2, a carbon tax is equivalent to an emission tax on CO_2 emissions.

Co-benefits: The positive effects that a policy or measure aimed at one objective might have on other objectives, without yet evaluating the net effect on overall social welfare. Co-benefits are often subject to uncertainty and depend on, among others, local circumstances and implementation practices. Co-benefits are often referred to as ancillary benefits.

Conditional NDC: NDC proposed by some countries that are 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 (COP): The supreme body of the United Nations Framework Convention on Climate Change. It currently meets once a year to review the Convention's progress.

Current policy trajectory: This trajectory is based on estimates of 2020 emissions considering projected economic trends and current policy approaches including policies at least through 2015. Estimates may be based on either official data or independent analysis.

Deforestation: Conversion of forest to non-forest.

Economic mitigation potential: The mitigation potential, which takes into account social costs and benefits and social discount rates, assuming that market efficiency is improved by policies and measures and barriers are removed.

Downcycling: A form of recycling that involves reusing materials in less demanding applications, accepting reduced performance of the material in terms of specifications such as hardness, tensile strength, or ductility. In its new application, the downcycled material replaces a material of lower economic value than the original application.

Emissions gap: The difference between the greenhouse gas emission levels consistent with a specific probability of limiting the mean global temperature rise to below 2°C or 1.5°C in 2100 above pre-industrial levels and the GHG emission levels consistent with the global effect of the NDCs, assuming full implementation from 2020.

Emission pathway: The trajectory of annual greenhouse gas emissions over time.

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

Greenhouse gases: The atmospheric gases responsible for causing global warming and climatic change. The major greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Less prevalent, but very powerful, GHGs are 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 production of greenhouse gases to atmospheric responses. This necessarily includes relevant links and feedbacks between socio-economic and biophysical processes.

Intended Nationally Determined Contribution (INDC): INDCs 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 INDC is automatically converted to its NDC (see below), unless it chooses to further update it. INDCs are thus only used in this publication in reference to countries that have not yet ratified the Paris Agreement.

Kigali Amendment: The Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer aims for the phase-down of hydrofluorocarbons (HFCs) by cutting their production and consumption.

Kyoto Protocol: An international agreement, 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 greenhouse gas emissions by industrialized countries.

Land Use, Land-Use Change and Forestry (LULUCF): A greenhouse gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use, land use change and forestry activities.

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

Last-mile solution: A solution designed for the movement of people and goods to the final destination of a multi-staged journey. In a public transportation system, this refers to the last leg of the journey.

Lock-in: Lock-in occurs when a market is stuck with a standard even though participants would be better off with an alternative.

Mitigation: In the context of climate change, a human intervention to reduce the sources, or enhance the sinks of greenhouse gases. 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.

Monitoring, reporting and verification: A process/concept that potentially supports greater transparency in the climate change regime.

Nationally Determined Contribution (NDC): Submissions by countries that have ratified the Paris Agreement which presents 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/target for reducing emissions nationally.

Non-state and subnational actors: 'Non-state and subnational actors' includes companies, cities, subnational regions and investors that take or commit to climate action.

Offset (in climate policy): A unit of CO_2e emissions that is reduced, avoided, or sequestered to compensate for emissions occurring elsewhere.

Product lightweighting: A process of creating lighter products through designs that require less material or substitute heavier material with lighter and/or less energy-intensive materials. Lighter material alternatives, both in weight or volume, can generate substantial energy savings in the transport and building sectors.

Ride sharing/car sharing: Two forms of arrangements in which two or more people share a vehicle for transportation. In ride sharing, also known as carpooling, the driver takes a passenger along for a ride that the driver gains utility from as well, often for commutes or long distance trips. This arrangement is distinguishable from ride hailing or ride sourcing, both of which are a form of taxi service. In car sharing, a person hires a car from another for a limited duration of time without the owner to undertake the desired trip.

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

Shared Socioeconomic Pathways (SSP): Scenarios of projected socioeconomic global changes up to 2100. They are used to derive greenhouse gas emissions scenarios associated with different climate policies scenarios.

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

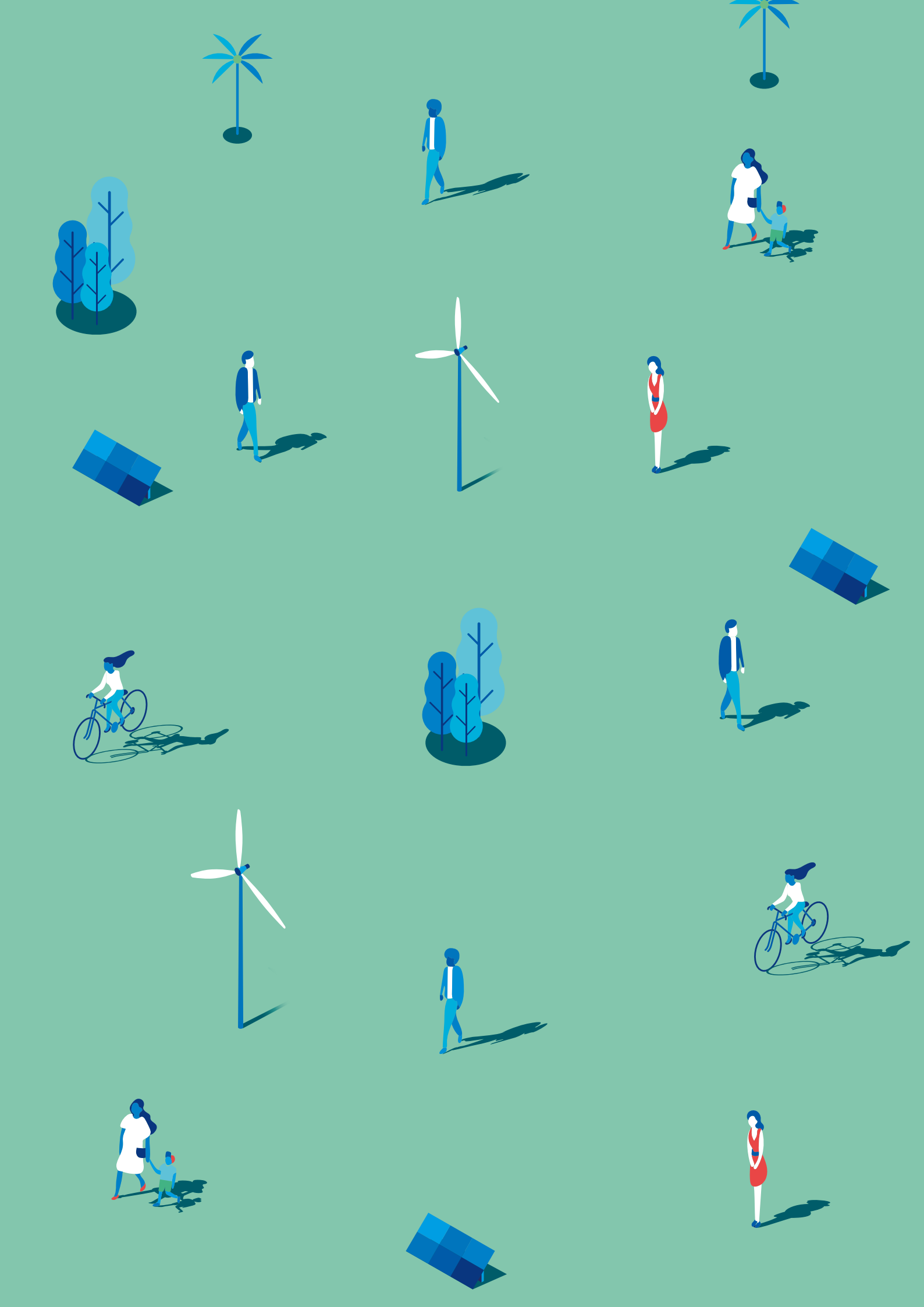
Sustainable development: Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Technical mitigation potential: Such potential is estimated for given scenarios assuming full implementation of the best available pollutant reduction technology, as it exists today, by 2030 independent of their costs but considering the technical lifetime of technologies and other key constraints (e.g., cultural acceptance) that could limit applicability of certain measures in specific regions.

Uncertainty: A cognitive state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (for example a probability density function) or by qualitative statements (for example reflecting the judgement of a team of experts).

Unconditional NDCs: NDCs proposed by countries without conditions attached.

2020 pledge: See Cancun pledge.



Foreword

Each year for the last decade, the UN Environment Programme's Emissions Gap Report has compared where greenhouse gas emissions are headed, against where they should be to avoid the worst impacts of climate change. Each year, the report has found that the world is not doing enough. Emissions have only risen, hitting a new high of 55.3 gigatonnes of CO_2 equivalent in 2018. The UNEP Emissions Gap Report 2019 finds that even if all unconditional Nationally Determined Contributions (NDCs) under the Paris Agreement are implemented, we are still on course for a 3.2°C temperature rise.

Our collective failure to act strongly and early means that we must now implement deep and urgent cuts. This report tells us that to get in line with the Paris Agreement, emissions must drop 7.6 per cent per year from 2020 to 2030 for the 1.5°C goal and 2.7 per cent per year for the 2°C goal. The size of these annual cuts may seem shocking, particularly for 1.5°C. They may also seem impossible, at least for next year. But we have to try.

We have to learn from our procrastination. Any further delay brings the need for larger, more expensive and unlikely cuts. We need quick wins, or the 1.5°C goal of the Paris Agreement will slip out of reach. The Intergovernmental Panel on Climate Change (IPCC) has warned us that going beyond 1.5°C will increase the frequency and intensity of climate impacts, such as the heatwaves and storms witnessed across the globe in the last few years. We cannot afford to fail.

The Climate Action Summit has increased momentum to address this global challenge. Now, in this critical period, the world must deliver concrete, stepped-up action. To deliver the cuts we need, nations have to raise the ambition of their current pledges over fivefold for the 1.5°C goal when they revise their NDCs in 2020. To reach the 2°C goal, they must triple ambition. They must then immediately follow up with policies and strategies to implement their promises.

The report tells us that the major transformation of our societies and economies we need can still happen. Political and societal focus on the climate crisis is at an all-time high, with youth movements holding us to account. There are many ambitious efforts from governments, cities, businesses and investors. There are plentiful options for rapid and cost-effective emission reductions. A shift to renewable energy and energy efficiency in the power, buildings and transport sectors, for example, could deliver reductions of over 16 gigatonnes of CO_2 equivalent each year by 2050. Using materials such as iron, steel and cement more efficiently also offers opportunities.

This report gives us a stark choice: set in motion the radical transformations we need now, or face the consequences of a planet radically altered by climate change. I hope that its findings inspire governments to step forward with the increased climate ambition the world so desperately needs.

Inger Andersen

Executive Director
United Nations Environment Programme

Executive summary – Emissions Gap Report 2019

Introduction

This is the tenth edition of the United Nations Environment Programme (UNEP) Emissions Gap Report. It provides the latest assessment of scientific studies on current and estimated future greenhouse gas (GHG) emissions and compares these with the emission levels permissible for the world to progress on a least-cost pathway to achieve the goals of the Paris Agreement. This difference between "where we are likely to be and where we need to be" has become known as the 'emissions gap'.

Reflecting on the ten-year anniversary, a summary report, entitled Lessons from a decade of emissions gap assessments, was published in September for the Secretary-General's Climate Action Summit.

The summary findings are bleak. Countries collectively failed to stop the growth in global GHG emissions, meaning that deeper and faster cuts are now required. However, behind the grim headlines, a more differentiated message emerges from the ten-year summary. A number of encouraging developments have taken place and the political focus on the climate crisis is growing in several countries, with voters and protestors, particularly youth, making it clear that it is their number one issue. In addition, the technologies for rapid and cost-effective emission reductions have improved significantly.

As in previous years, this report explores some of the most promising and applicable options available for countries to bridge the gap, with a focus on how to create transformational change and just transitions. Reflecting on the report's overall conclusions, it is evident that incremental changes will not be enough and there is a need for rapid and transformational action.

The political context in 2019 has been dominated by the United Nations Secretary-General's Global Climate Action Summit, which was held in September and brought together governments, the private sector, civil society, local authorities and international organizations.

The aim of the Summit was to stimulate action and in particular to secure countries' commitment to enhance their nationally determined contributions (NDCs) by 2020 and aim for net zero emissions by 2050.

According to the press release at the end of the Summit, around 70 countries announced their intention to submit enhanced NDCs in 2020, with 65 countries and major subnational economies committing to work towards achieving net zero emissions by 2050. In addition, several private companies, finance institutions and major cities announced concrete steps to reduce emissions and shift investments into low-carbon technologies. A key aim of the Summit was to secure commitment from countries to enhance their NDCs, which was met to some extent, but largely by smaller economies. With most of the G20 members visibly absent, the likely impact on the emissions gap will be limited.

As regards the scientific perspective, the Intergovernmental Panel on Climate Change (IPCC) issued two special reports in 2019: the Climate Change and Land report on climate change, desertification, land degradation, sustainable land management, food security and greenhouse gas fluxes in terrestrial ecosystems, and the Ocean and Cryosphere in a Changing Climate report. Both reports voice strong concerns about observed and predicted changes resulting from climate change and provide an even stronger scientific foundation that supports the importance of the temperature goals of the Paris Agreement and the need to ensure emissions are on track to achieve these goals.

This Emissions Gap Report has been prepared by an international team of leading scientists, assessing all available information, including that published in the context of the IPCC special reports, as well as in other recent scientific studies. The assessment production process has been transparent and participatory. 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.

1. GHG emissions continue to rise, despite scientific warnings and political commitments.

- GHG emissions have risen at a rate of 1.5 per cent per year in the last decade, stabilizing only briefly between 2014 and 2016. Total GHG emissions, including from land-use change, reached a record high of 55.3 $GtCO_2e$ in 2018.
- Fossil CO_2 emissions from energy use and industry, which dominate total GHG emissions, grew 2.0 per cent in 2018, reaching a record 37.5 $GtCO_2$ per year.

- There is no sign of GHG emissions peaking in the next few years; every year of postponed peaking means that deeper and faster cuts will be required. By 2030, emissions would need to be 25 per cent and 55 per cent lower than in 2018 to put the world on the least-cost pathway to limiting global warming to below 2˚C and 1.5°C respectively.

- Figure ES.1 shows a decomposition of the average annual growth rates of economic activity (gross domestic product – GDP), primary energy use, energy use per unit of GDP, CO_2 emissions per unit of energy and GHG emissions from all sources for Organisation for Economic Co-operation and Development (OECD) and non-OECD members.

- Economic growth has been much stronger in non-OECD members, growing at over 4.5 per cent per year in the last decade compared with 2 per cent per year in OECD members. Since OECD and non-OECD members have had similar declines in the amount of energy used per unit of economic activity, stronger economic growth means that primary energy use has increased much faster in non-OECD members (2.8 per cent per year) than in OECD members (0.3 per cent per year).

- OECD members already use less energy per unit of economic activity, which suggests that non-OECD members have the potential to accelerate improvements even as they grow, industrialize and urbanize their economies in order to meet development objectives.

- While the global data provide valuable insight for understanding the continued growth in emissions, it is necessary to examine the trends of major emitters to gain a clearer picture of the underlying trends (figure ES.2). Country rankings change dramatically when comparing total and per capita emissions: for example, it is evident that China now has per capita emissions in the same range as the European Union (EU) and is almost at a similar level to Japan.

- Consumption-based emission estimates, also known as a carbon footprint, that adjust the standard territorial emissions for imports and exports, provide policymakers with a deeper insight into the role of consumption, trade and the interconnectedness of countries. Figure ES.3 shows that the net flow of embodied carbon is from developing to developed countries, even as developed countries reduce their territorial emissions this effect is being partially offset by importing embodied carbon, implying for example that EU per capita emissions are higher than Chinese when consumption-based emissions are included. It should be noted that consumption-based emissions are not used within the context of the United Nations Framework Convention on Climate Change (UNFCCC).

Figure ES.1. Average annual growth rates of key drivers of global CO_2 emissions (left of dotted line) and components of greenhouse gas emissions (right of dotted line) for OECD and non-OECD members

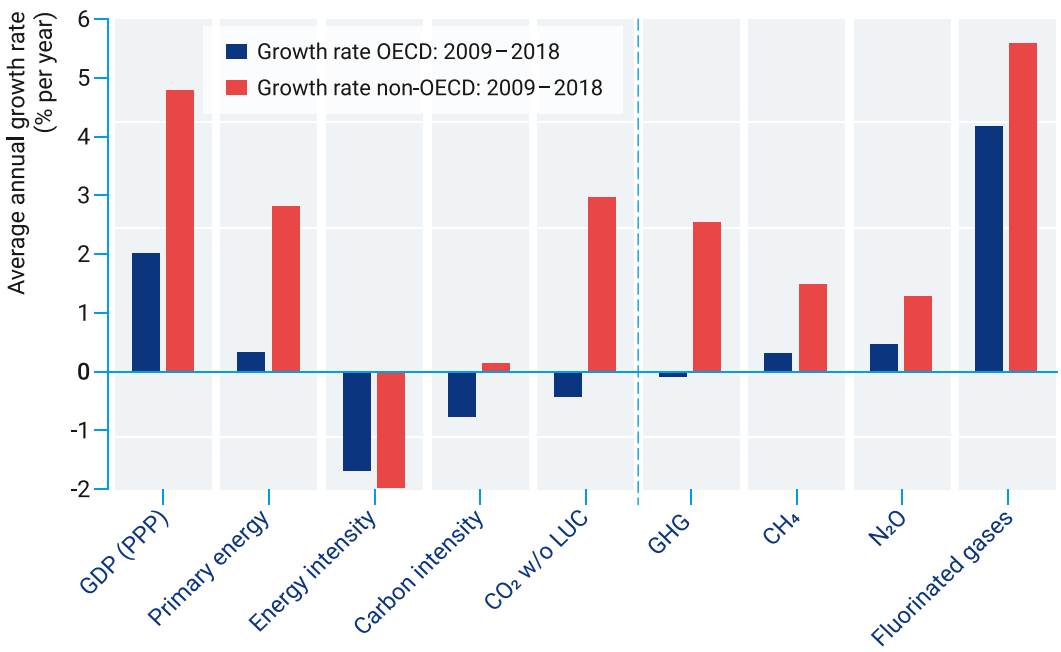
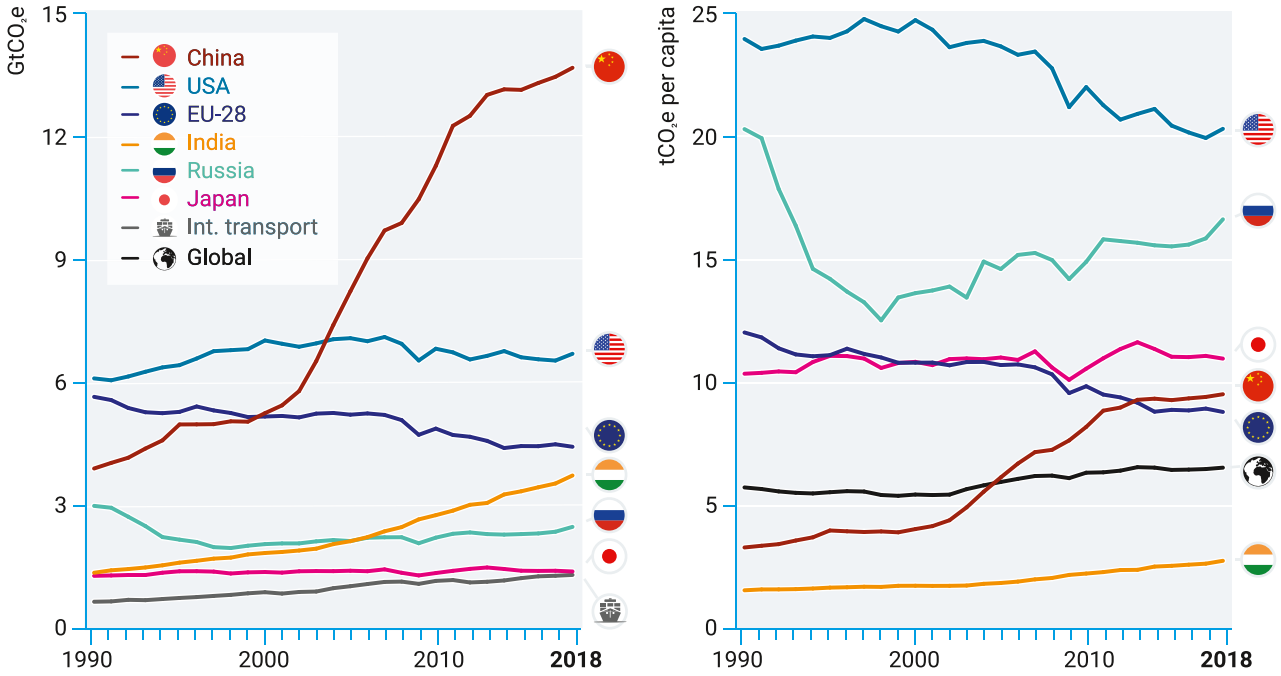


Figure ES.2. Top greenhouse gas emitters, excluding land-use change emissions due to lack of reliable country-level data, on an absolute basis (left) and per capita basis (right)



2. G20 members account for 78 per cent of global GHG emissions. Collectively, they are on track to meet their limited 2020 Cancun Pledges, but seven countries are currently not on track to meet 2030 NDC commitments, and for a further three, it is not possible to say.

- As G20 members account for around 78 per cent of global GHG emissions (including land use), they largely determine global emission trends and the extent to which the 2030 emissions gap will be closed. This report therefore pays close attention to G20 members.

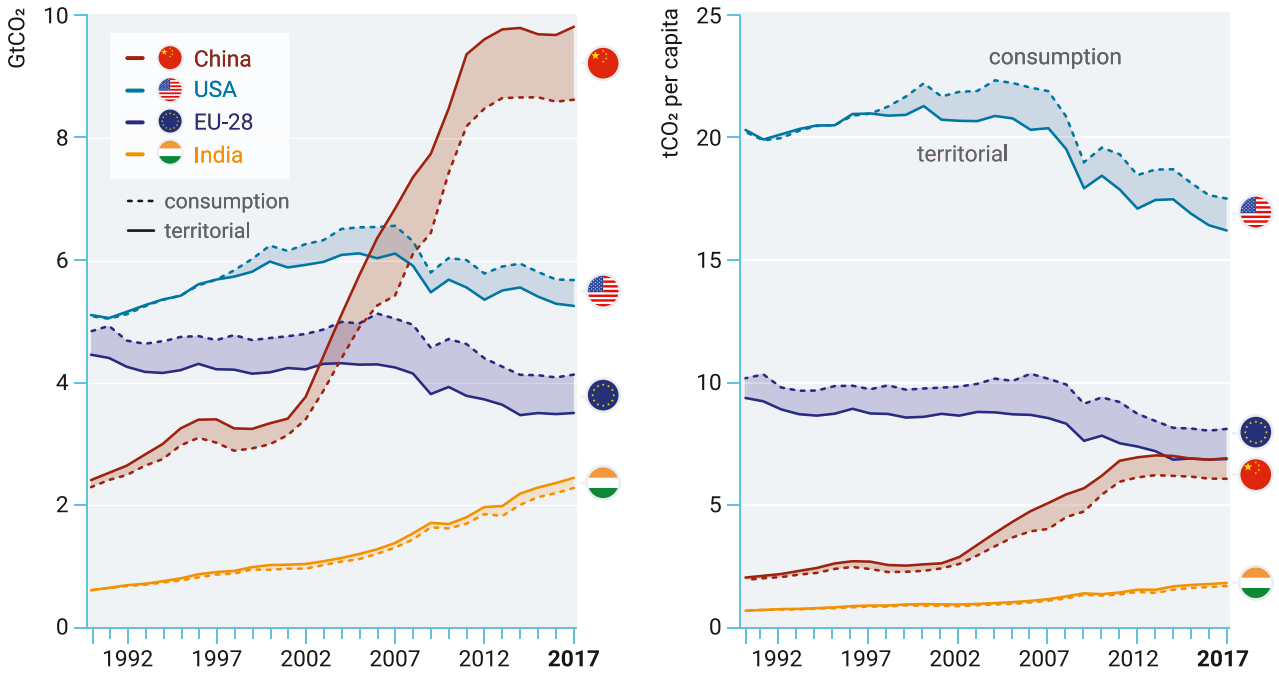
- G20 members with 2020 Cancun Pledges are collectively projected to overachieve these by about 1 $GtCO_2e$ per year. However, several individual G20 members (Canada, Indonesia, Mexico, the Republic of Korea, South Africa, the United States of America) are currently projected to miss their Cancun Pledges or will not achieve them with great certainty. Argentina, Saudi Arabia and Turkey have not made 2020 pledges and pledges from several countries that meet their targets are rather unambitious.

- Australia is carrying forward their overachievement from the Kyoto period to meet their 2020 Cancun Pledge and counts cumulative emissions between 2013 and 2020. With this method, the Australian Government projects that the country will overachieve its 2020 pledge. However, if this 'carry-forward' approach is not taken, Australia will not achieve its 2020 pledge.

- On the progress of G20 economies towards their NDC targets, six members (China, the EU28, India, Mexico, Russia and Turkey) are projected to meet their unconditional NDC targets with current policies. Among them, three countries (India, Russia and Turkey) are projected to be more than 15 per cent lower than their NDC target emission levels. These results suggest that the three countries have room to raise their NDC ambition significantly. The EU28 has introduced climate legislation that achieves at least a 40 per cent reduction in GHG emissions, which the European Commission projects could be overachieved if domestic legislation is fully implemented in member states.

- In contrast, seven G20 members require further action of varying degree to achieve their NDC: Australia, Brazil, Canada, Japan, the Republic of Korea, South Africa and the United States of

Figure ES.3. CO_2 emissions allocated to the point of emissions (territorial) and the point of consumption, for absolute emissions (left) and per capita (right)



America. For Brazil, the emissions projections from three annually updated publications were all revised upward, reflecting the recent trend towards increased deforestation, among others. In Japan, however, current policy projections have been close to achieving its NDC target for the last few years.

- Studies do not agree on whether Argentina, Indonesia and Saudi Arabia are on track to meet their unconditional NDCs. For Argentina, recent domestic analysis that reflects the most recent GHG inventory data up to 2016 projects that the country will achieve its unconditional NDC target, while two international studies project that it will fall short of its target. For Indonesia, this is mainly due to uncertainty concerning the country's land use, land-use change and forestry (LULUCF) emissions. For Saudi Arabia, the limited amount of information on the country's climate policies has not allowed for further assessments beyond the two studies reviewed.

- Some G20 members are continuously strengthening their mitigation policy packages, leading to a downward revision of current policy scenario projections for total emissions over time. One example is the EU, where a noticeable downward shift has been observed in current policy scenario projections for 2030 since the 2015 edition of the Emissions Gap Report.

3. Although the number of countries announcing net zero GHG emission targets for 2050 is increasing, only a few countries have so far formally submitted long-term strategies to the UNFCCC.

- An increasing number of countries have set net zero emission targets domestically and 65 countries and major subnational economies, such as the region of California and major cities worldwide, have committed to net zero emissions by 2050. However, only a few long-term strategies submitted to the UNFCCC have so far committed to a timeline for net zero emissions, none of which are from a G20 member.

- Five G20 members (the EU and four individual members) have committed to long-term zero emission targets, of which three are currently in the process of passing legislation and two have recently passed legislation. The remaining 15 G20 members have not yet committed to zero emission targets.

Table ES.1. Global total GHG emissions by 2030 under different scenarios (median and 10th to 90th percentile range), temperature implications and the resulting emissions gap

Scenario (rounded to the nearest gigaton)	Number of scenarios in set	Global total emissions in 2030 [$GtCO_2e$]	Estimated temperature outcomes			Closest corresponding IPCC SR1.5 scenario class	Emissions Gap in 2030 [$GtCO_2e$]		
			50% probability	66% probability	90% probability		Below 2.0°C	Below 1.8°C	Below 1.5°C in 2100
2005-policies	6	**64** (60–68)							
Current policy	8	**60** (58–64)					**18** (17–23)	**24** (23–29)	**35** (34–39)
Unconditional NDCs	11	**56** (54–60)					**15** (12–18)	**21** (18–24)	**32** (29–35)
Conditional NDCs	12	**54** (51–56)					**12** (9–14)	**18** (15–21)	**29** (26–31)
Below 2.0°C (66% probability)	29	**41** (39–46)	Peak: 1.7-1.8°C In 2100: 1.6-1.7°C	**Peak: 1.9-2.0°C In 2100: 1.8-1.9°C**	Peak: 2.4-2.6°C In 2100: 2.3-2.5°C	Higher-2°C pathways			
Below 1.8°C (66% probability)	43	**35** (31–41)	Peak: 1.6-1.7°C In 2100: 1.3-1.6°C	**Peak: 1.7-1.8°C In 2100: 1.5-1.7°C**	Peak: 2.1-2.3°C In 2100: 1.9-2.2°C	Lower-2°C pathways			
Below 1.5°C in 2100 and peak below 1.7°C (both with 66% probability)	13	**25** (22–31)	Peak: 1.5-1.6°C In 2100: 1.2-1-3°C	**Peak: 1.6-1.7°C In 2100: 1.4-1.5°C**	Peak: 2.0-2.1°C In 2100: 1.8-1.9°C	1.5°C with no or limited overshoot			

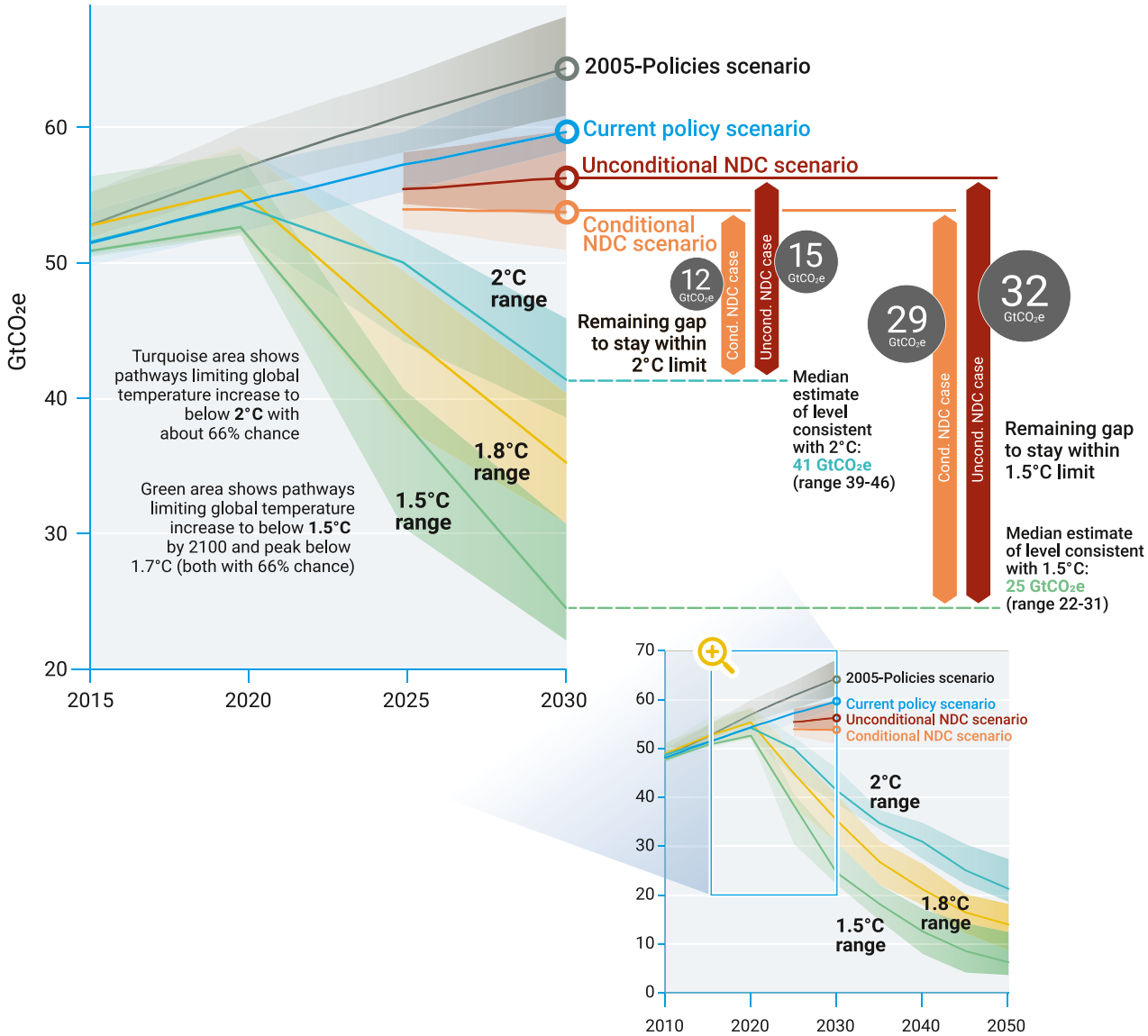
4. The emissions gap is large. In 2030, annual emissions need to be 15 $GtCO_2e$ lower than current unconditional NDCs imply for the 2°C goal, and 32 $GtCO_2e$ lower for the 1.5°C goal.

- Estimates of where GHG emissions should be in 2030 in order to be consistent with a least-cost pathway towards limiting global warming to the specific temperature goals have been calculated from the scenarios that were compiled as part of the mitigation pathway assessment of the IPCC Special Report on Global Warming of 1.5°C report.

- This report presents an assessment of global emissions pathways relative to those consistent with limiting warming to 2°C, 1.8°C and 1.5°C, in order to provide a clear picture of the pathways that will keep warming in the range of 2°C to 1.5°C. The report also includes an overview of the peak and 2100 temperature outcomes associated with different likelihoods. The inclusion of the 1.8°C level allows for a more nuanced interpretation and discussion of the implication of the Paris Agreement's temperature targets for near-term emissions.

- The NDC scenarios of this year's report are based on updated data from the same sources used for the current policies scenario and is provided by 12 modelling groups. Projected NDC levels for some countries, in particular China and India, depend on recent emission trends or GDP growth projections that are easily outdated in older studies. Thus, studies that were published in 2015, before the adoption of the Paris Agreement, have been excluded in this year's update. Excluding such studies has had little impact

Figure ES.4. Global GHG emissions under different scenarios and the emissions gap by 2030



on the projected global emission levels of the NDC scenarios, which are very similar to those presented in the UNEP Emissions Gap Report 2018.

- With only current policies, GHG emissions are estimated to be 60 $GtCO_2e$ in 2030. On a least-cost pathway towards the Paris Agreement goals in 2030, median estimates are 41 $GtCO_2e$ for 2°C, 35 $GtCO_2e$ for 1.8°C, and 25 $GtCO_2e$ for 1.5°C.
- If unconditional and conditional NDCs are fully implemented, global emissions are estimated to reduce by around 4 $GtCO_2e$ and 6 $GtCO_2e$ respectively by 2030, compared with the current policy scenario.
- The emissions gap between estimated total global emissions by 2030 under the NDC scenarios and under pathways limiting warming to below 2°C and 1.5°C is large (see Figure ES.4). Full implementation of the unconditional NDCs is estimated to result in a gap of 15 $GtCO_2e$ (range: 12–18 $GtCO_2e$) by 2030, compared with the 2°C scenario. The emissions gap between implementing the unconditional NDCs and the 1.5°C pathway is about 32 $GtCO_2e$ (range: 29–35 $GtCO_2e$).
- The full implementation of both unconditional and conditional NDCs would reduce this gap by around 2–3 $GtCO_2e$.
- If current unconditional NDCs are fully implemented, there is a 66 per cent chance that warming will be limited to 3.2°C by the end of the century. If conditional NDCs are also effectively implemented, warming will likely reduce by about 0.2°C.

5. Dramatic strengthening of the NDCs is needed in 2020. Countries must increase their NDC ambitions threefold to achieve the well below 2°C goal and more than fivefold to achieve the 1.5°C goal.

- The ratchet mechanism of the Paris Agreement foresees strengthening of NDCs every five years. Parties to the Paris Agreement identified 2020 as a critical next step in this process, inviting countries to communicate or update their NDCs by this time. Given the time lag between policy decisions and associated emission reductions, waiting until 2025 to strengthen NDCs will be too late to close the large 2030 emissions gap.

- The challenge is clear. The recent IPCC special reports clearly describe the dire consequences of inaction and are backed by record temperatures worldwide along with enhanced extreme events.

- Had serious climate action begun in 2010, the cuts required per year to meet the projected emissions levels for 2°C and 1.5°C would only have been 0.7 per cent and 3.3 per cent per year on average. However, since this did not happen, the required cuts in emissions are now 2.7 per cent per year from 2020 for the 2°C goal and 7.6 per cent per year on average for the 1.5°C goal. Evidently, greater cuts will be required the longer that action is delayed.

- Further delaying the reductions needed to meet the goals would imply future emission reductions and removal of CO_2 from the atmosphere at such a magnitude that it would result in a serious deviation from current available pathways. This, together with necessary adaptation actions, risks seriously damaging the global economy and undermining food security and biodiversity.

6. Enhanced action by G20 members will be essential for the global mitigation effort.

- This report has a particular focus on the G20 members, reflecting on their importance for global mitigation efforts. Chapter 4 in particular focuses on progress and opportunities for enhancing mitigation ambition of seven selected G20 members – Argentina, Brazil, China, the EU, India, Japan and the United States of America – which represented around 56 per cent of global GHG emissions in 2017. The chapter, which was pre-released for the Climate Action Summit, presents a detailed assessment of action or inaction in key sectors, demonstrating that even though there are a few frontrunners, the general picture is rather bleak.

- In 2009, the G20 members adopted a decision to gradually phase out fossil-fuel subsidies, though no country has committed to fully phasing these out by a specific year as yet.

- Although many countries, including most G20 members, have committed to net zero deforestation targets in the last few decades, these commitments are often not supported by action on the ground.

- Based on the assessment of mitigation potential in the seven previously mentioned countries, a number of areas have been identified for urgent and impactful action (see table ES.2). The purpose of the recommendations is to show potential, stimulate engagement and facilitate political discussion of what is required to implement the necessary action. Each country will be responsible for designing their own policies and actions.

7. Decarbonizing the global economy will require fundamental structural changes, which should be designed to bring multiple co-benefits for humanity and planetary support systems.

- If the multiple co-benefits associated with closing the emissions gap are fully realized, the required transition will contribute in an essential way to achieving the United Nations 2030 Agenda with its 17 Sustainable Development Goals (SDGs).

- Climate protection and adaptation investments will become a precondition for peace and stability, and will require unprecedented efforts to transform societies, economies, infrastructures and governance institutions. At the same time, deep and rapid decarbonization processes imply fundamental structural changes are needed within economic sectors, firms, labour markets and trade patterns.

- By necessity, this will see profound change in how energy, food and other material-intensive services are demanded and provided by governments, businesses and markets. These systems of provision are entwined with the preferences, actions and demands of people as consumers, citizens and communities. Deep-rooted shifts in values, norms, consumer culture and world views are inescapably part of the great sustainability transformation.

- Legitimacy for decarbonization therefore requires massive social mobilization and investments in social cohesion to avoid exclusion and resistance to change. Just and timely transitions towards sustainability need to be developed, taking into account the interests and rights of people vulnerable to the impacts of climate change, of people and regions where decarbonization requires structural adjustments, and of future generations.

- Fortunately, deep transformation to close the emissions gap between trends based on current

Table ES.2. Selected current opportunities to enhance ambition in seven G20 members in line with ambitious climate actions and targets

Argentina
• Refrain from extracting new, alternative fossil-fuel resources • Reallocate fossil-fuel subsidies to support distributed renewable electricity-generation • Shift towards widespread use of public transport in large metropolitan areas • Redirect subsidies granted to companies for the extraction of alternative fossil fuels to building-sector measures
Brazil
• Commit to the full decarbonization of the energy supply by 2050 • Develop a national strategy for ambitious electric vehicle (EV) uptake aimed at complementing biofuels and at 100-per cent CO_2-free new vehicles • Promote the 'urban agenda' by increasing the use of public transport and other low-carbon alternatives
China
• Ban all new coal-fired power plants • Continue governmental support for renewables, taking into account cost reductions, and accelerate development towards a 100 per cent carbon-free electricity system • Further support the shift towards public modes of transport • Support the uptake of electric mobility, aiming for 100 per cent CO_2-free new vehicles • Promote near-zero emission building development and integrate it into Government planning
European Union
• Adopt an EU regulation to refrain from investment in fossil-fuel infrastructure, including new natural gas pipelines • Define a clear endpoint for the EU emissions trading system (ETS) in the form of a cap that must lead to zero emissions • Adjust the framework and policies to enable 100 per cent carbon-free electricity supply by between 2040 and 2050 • Step up efforts to phase out coal-fired plants • Define a strategy for zero-emission industrial processes • Reform the EU ETS to more effectively reduce emissions in industrial applications • Ban the sale of internal combustion engine cars and buses and/or set targets to move towards 100 per cent of new car and bus sales being zero-carbon vehicles in the coming decades • Shift towards increased use of public transport in line with the most ambitious Member States • Increase the renovation rate for intensive retrofits of existing buildings
India
• Plan the transition from coal-fired power plants • Develop an economy-wide green industrialization strategy towards zero-emission technologies • Expand mass public transit systems • Develop domestic electric vehicle targets working towards 100 per cent new sales of zero-emission cars
Japan
• Develop a strategic energy plan that includes halting the construction of new freely emitting coal-fired power plants, as well as a phase-out schedule of existing plants and a 100 per cent carbon-free electricity supply • Increase the current level of carbon pricing with high priority given to the energy and building sector • Develop a plan to phase out the use of fossil fuels through promoting passenger cars that use electricity from renewable energy • Implement a road map as part of efforts towards net-zero energy buildings and net-zero energy houses
USA
• Introduce regulations on power plants, clean energy standards and carbon pricing to achieve an electricity supply that is 100 per cent carbon-free • Implement carbon pricing on industrial emissions • Strengthen vehicle and fuel economy standards to be in line with zero emissions for new cars in 2030 • Implement clean building standards so that all new buildings are 100 per cent electrified by 2030

policies and achieving the Paris Agreement can be designed to bring multiple co-benefits for humanity and planetary support systems. These range, for example, from reducing air pollution, improving human health, establishing sustainable energy systems and industrial production processes, making consumption and services more efficient and sufficient, employing less-intensive agricultural practices and mitigating biodiversity loss to liveable cities.

- This year's report explores six entry points for progressing towards closing the emissions gap through transformational change in the following areas: (a) air pollution, air quality, health; (b) urbanization; (c) governance, education, employment; (d) digitalization; (e) energy- and material-efficient services for raising living standards; and (f) land use, food security, bioenergy. Building on this overview, a more detailed discussion of transitions in the energy sector is presented in chapter 6.

8. Renewables and energy efficiency, in combination with electrification of end uses, are key to a successful energy transition and to driving down energy-related CO_2 emissions.

- The necessary transition of the global energy sector will require significant investments compared with a business-as-usual scenario. Climate policies that are consistent with the 1.5°C goal will require upscaling energy system supply-side investments to between US$1.6 trillion and US$3.8 trillion per year globally on average over the 2020–2050 time frame, depending on how rapid energy efficiency and conservation efforts can be ramped up.

- Given the important role that energy and especially the electricity sector will have to play in any low-carbon transformation, chapter 6 examines five transition options, taking into account their relevance for a wide range of countries, clear co-benefit opportunities and potential to deliver significant emissions reductions. Each of the following transitions correspond to a particular policy rationale or motivation, which is discussed in more detail in the chapter:

  - Expanding Renewable Energy for electrification.
  - Phasing out coal for rapid decarbonization of the energy system.
  - Decarbonizing transport with a focus on electric mobility.
  - Decarbonizing energy-intensive industry.
  - Avoiding future emissions while improving energy access.

- Implementing such major transitions in a number of areas will require increased interdependency between energy and other infrastructure sectors, where changes in one sector can impact another. Similarly, there will be a strong need to connect demand and supply-side policies and include wider synergies and co-benefits, such as job losses and creation, rehabilitation of ecosystem services, avoidance of resettlements and reduced health and environmental costs as a result of reduced emissions. The same applies for decarbonizing transport, where there will be a need for complementarity and coordination of policies, driven by technological, environmental and land-use pressures. Policies will need to be harmonized wherever possible to take advantage of interdependencies and prevent undesirable outcomes such as CO_2 leakage from one sector to another.

- Any transition at this scale is likely to be extremely challenging and will meet a number of economic, political and technical barriers and challenges. However, many drivers of climate action have changed in the last years, with several options for ambitious climate action becoming less costly, more numerous and better understood. First, technological and economic developments present opportunities to decarbonize the economy, especially the energy sector, at a cost that is lower than ever. Second, the synergies between climate action and economic growth and development objectives, including options for addressing distributional impacts, are better understood. Finally, policy momentum across various levels of government, as well as a surge in climate action commitments by non-state actors, are creating opportunities for countries to engage in real transitions.

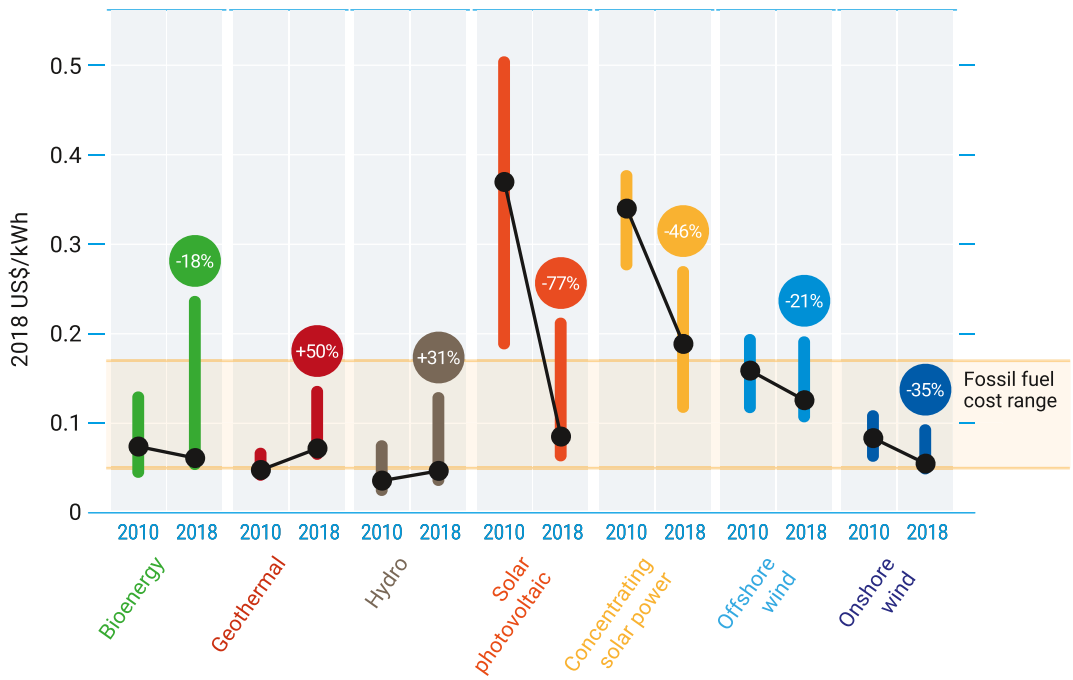
- A key example of technological and economic trends is the cost of renewable energy, which is declining more rapidly than was predicted just a few years ago (see figure ES.5). Renewables are currently the cheapest source of new power generation in most of the world, with the global weighted average purchase or auction price for new utility-scale solar power photovoltaic systems and utility-scale onshore wind turbines projected to compete with the marginal operating cost of existing coal plants by 2020. These trends are increasingly manifesting in a decline in new coal plant construction, including the cancellation of planned plants, as well as the early retirement of existing plants. Moreover, real-life cost declines are outpacing projections.

A short summary of the main aspects of each transition is presented in table ES.3.

Table ES.3. Summary of five energy transition options

Option	Major components	Instruments	Co-benefits	Annual GHG emissions reduction potential of renewables, electrification, energy efficiency and other measures by 2050
Renewable energy electricity expansion	• Plan for large shares of variable renewable energy • Electricity becomes the main energy source by 2050, supplying at least 50 per cent of total final energy consumption (TFEC) • Share of renewable energy in electricity up to 85 per cent by 2050 • Transition	• Flexibility measures to take on larger shares of variable renewable energy • Support for deployment of distributed energy • Innovative measures: cost reflective tariff structures, targeted subsidies, reverse auctions, net metering	• Greater efficiency in end-use energy demand • Health benefits • Energy access and security • Employment	• Power sector: 8.1 $GtCO_2$ • Building sector: 2.1 $GtCO_2$ • District heat and others: 1.9 $GtCO_2$
Coal phase-out	• Plan and implement phase-out of coal • Coal to renewable energy transition • Expand carbon capture usage and storage systems • Improve system-wide efficiency	• Regional support programmes • Tax breaks, subsidies • Carbon pricing • Moratorium policies • De-risking of clean energy investments • Relocation of coal workers (mines and power plants)	• Lower health hazards (air, water, land pollution) • Future skills and job creation	Share of the power emissions reduction from a coal phase-out: 4 $GtCO_2$ (range: 3.6– 4.4 $GtCO_2$), with 1 $GtCO_2$ from the OECD and 3 $GtCO_2$ from the rest of the world
Decarbonize transport	• Reduce energy for transport • Electrify transport • Fuels substitution (bioenergy, hydrogen) • Modal shift	• Pathways for non-motorized transport • Standards for vehicle emissions • Establishing of charging stations • Eliminating of fossil-fuel subsidies • Investments in public transport	• Increased public health from more physical activity, less air pollution • Energy security • Reduced fuel spending • Less congestion	Electrification of transport: 6.1 $GtCO_2$
Decarbonize industry	• Demand reduction (circular economy, modal shifts and logistics) • Electrify heat processes • Improve energy efficiency • Direct use of biomass/ biofuels	• Carbon pricing • Standards and regulations, especially on materials demand reduction	• Energy security • Savings and competitiveness	• Industry: 4.8 $GtCO_2$
Avoid future emissions and energy access	• Link energy access with emission reductions for 3.5 billion energy-poor people	• Fit and auctions • Standards and regulations • Targeted subsidies • Support for entrepreneurs	• Better access • Meet basic needs and SDGs	• N/A

Figure ES.5. Changes in global levelized cost of energy for key renewable energy technologies, 2010-2018



9. Demand-side material efficiency offers substantial GHG mitigation opportunities that are complementary to those obtained through an energy system transformation.

- While demand-side material efficiency widens the spectrum of emission mitigation strategies, it has largely been overlooked in climate policymaking until now and will be important for the cross-sectoral transitions.

- In 2015, the production of materials caused GHG emissions of approximately 11.5 $GtCO_2e$, up from 5 $GtCO_2e$ in 1995. The largest contribution stems from bulk materials production, such as iron and steel, cement, lime and plaster, other minerals mostly used as construction products, as well as plastics and rubber. Two thirds of the materials are used to make capital goods, with buildings and vehicles among the most important. While the production of materials consumed in industrialized countries remained within the range of 2–3 $GtCO_2e$, in the 1995–2015 period, those of developing and emerging economies have largely been behind the growth. In this context, it is important to keep in mind the discussion about the point of production and points of consumption (see figure ES.6).

- Material efficiency and substitution strategies affect not only energy demand and emissions during material production, but also potentially the operational energy use of the material products. Analysis of such strategies therefore requires a systems or life cycle perspective. Several investigations of material efficiency have focused on strategies that have little impact on operations, meaning that trade-offs and synergies have been ignored. Many energy efficiency strategies have implications for the materials used, such as increased insulation demand for buildings or a shift to more energy-intensive materials in the lightweighting of vehicles. While these additional, material-related emissions are well understood from technology studies, they are often not fully captured in the integrated assessment models that produce scenario results, such as those discussed in this report.

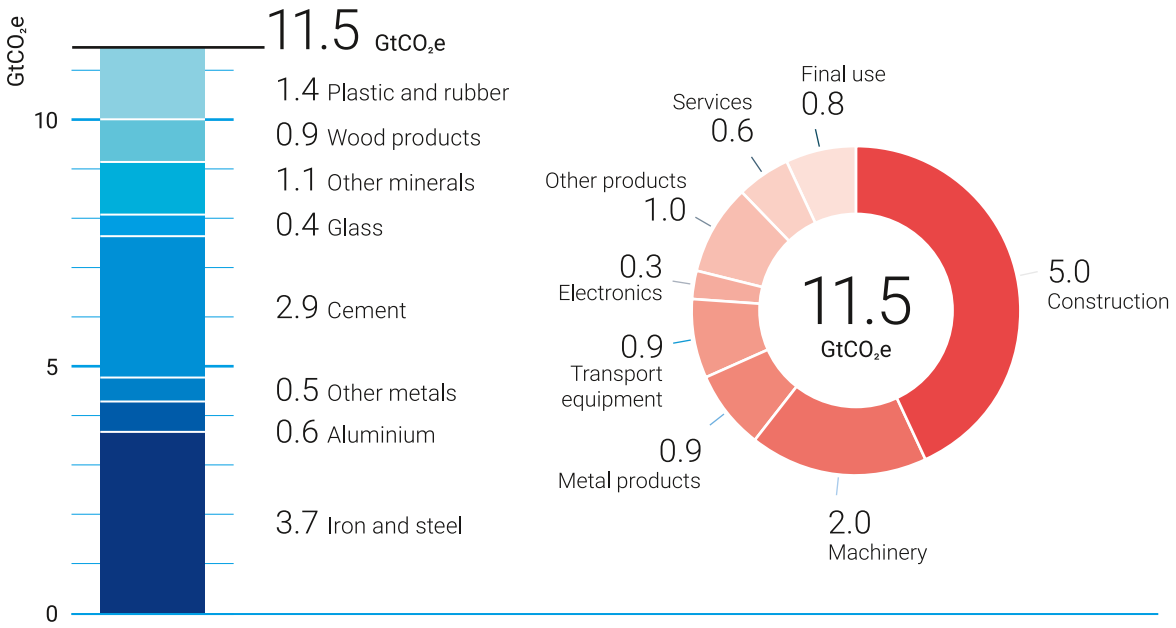
- In chapter 7, the mitigation potential from demand-side material efficiency improvements is discussed in the context of the following categories of action:

  - Product lightweighting and substitution of high-carbon materials with low-carbon materials to reduce material-related GHG emissions associated with product production, as well as operational energy consumption of vehicles.

  - Improvements in the yield of material production and product manufacture.

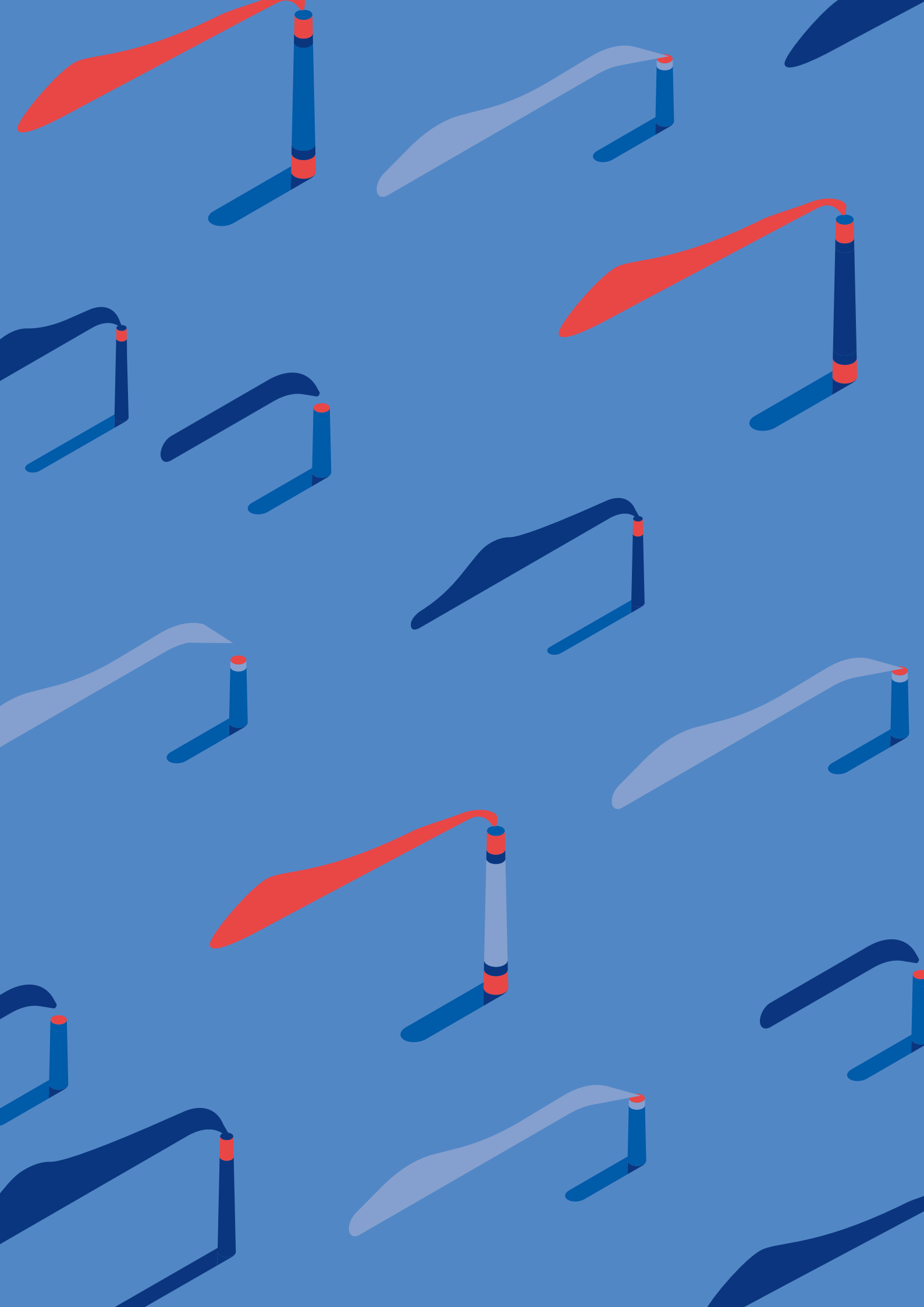
  - More intensive use, longer life, component reuse, remanufacturing and repair as strategies to obtain more service from material-based products.

Figure ES.6. GHG emissions in $GtCO_2e$ associated with materials production by material (left) and by the first use of materials in subsequent production processes or final consumption (right)



- Enhanced recycling so that secondary materials reduce the need to produce more emission-intensive primary materials.

► These categories are elaborated for housing and cars, showing that increased material efficiency can reduce annual emissions from the construction and operations of buildings and the manufacturing and use of passenger vehicles, thus contributing a couple of gigatons of carbon dioxide equivalent in emission reductions to the global mitigation effort by 2030.



1 Introduction

Authors:
Anne Olhoff (UNEP DTU Partnership) and John Christensen (UNEP DTU Partnership)

This tenth edition of the United Nations Environment Programme (UNEP) Emissions Gap Report provides an independent scientific assessment of how countries' climate pledges and actions are affecting the global greenhouse gas emissions (GHG) trend, comparing it with the emission reductions necessary to limit global warming to well below 2°C and 1.5°C in accordance with the Paris Agreement. This difference between where we are likely to be by 2030 and where we need to be has become known as the 'emissions gap'.

To mark the 10-year anniversary, a publication summarizing the lessons from a decade of emissions gap assessments (Christensen and Olhoff 2019) was published to support the United Nations Secretary-General's Climate Action Summit in September 2019. This publication shows that despite a decade of increased focus on climate change, global GHG emissions have not been curbed and the emissions gap is now larger than ever. It is clear that the world cannot afford another decade lost. Unless mitigation action and ambition are increased immediately and profoundly through enhanced nationally determined contributions (NDCs) and supported by ambitious long-term mitigation strategies, it will not be possible to avoid exceeding the 1.5°C goal, and it will become increasingly challenging to achieve the well below 2°C goal.

At the Climate Action Summit, countries and regions announced their intention to improve national and subnational action. For example, 70 countries agreed to submit enhanced NDCs by 2020, with the number of commitments to zero GHG and carbon emission targets at some point during the second half of this century increasing from around 20 countries and eight regions before the Summit to 71 countries and 11 regions after the Summit. However, these countries and regions account for just 15 per cent of global emissions, indicating that the scale and pace of climate commitments and action is still far from what is required to keep the Paris Agreement goals within reach.

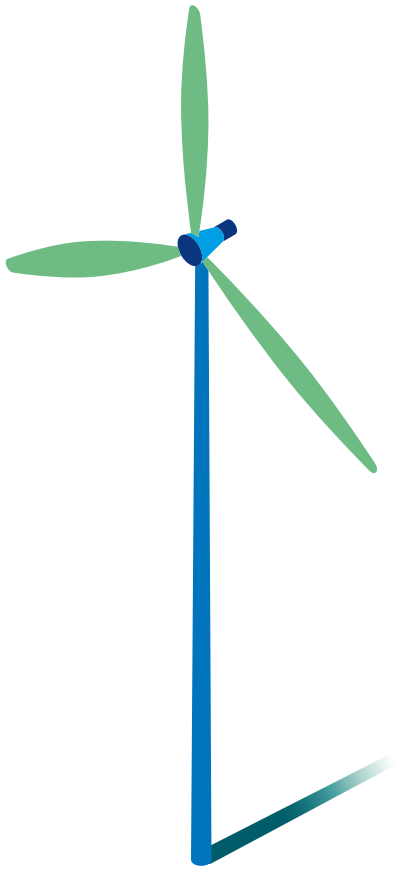
The challenge for the twenty-fifth session of the Conference of the Parties (COP 25) to the United Nations Framework Convention on Climate Change (UNFCCC) and the year to follow is thus to bring about the necessary move from incremental to transformational climate ambition and action. The year 2020, which is when countries are requested to submit new or updated NDCs and invited to communicate long-term mitigation strategies as part of the UNFCCC process, will be defining in this regard.

As in previous years, this Emissions Gap Report has been prepared by an international team comprising 57 leading scientists from 33 expert institutions across 25 countries, assessing all available information, including that published in the context of the Intergovernmental Panel on Climate Change (IPCC) special reports. The assessment process has been overseen by a distinguished steering committee and has been transparent and participatory. 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, and is structured on the questions that guided the 2018 Talanoa Dialogue: Where are we? Where do we want to go? How do we get there? In this way, chapter 2 focuses on where we are, providing an updated assessment of the status and trends of current and projected global GHG emissions, and the progress of G20 members towards their Cancun Pledges for 2020 and their NDC targets for 2030.

Addressing the issue of where we want to go and comparing it with where we are likely to be, chapter 3 assesses what the gap between estimated global emissions will be by 2030 if NDCs are fully implemented, as well as the range consistent with the well below 2°C and 1.5°C temperature goals. The chapter also considers what the temperature implications will be at the end of the century if current policies are continued, and whether global emissions by 2030 will be permissible if the current level of ambition of NDCs is not increased.

Finally, the second part of the report examines how the gap can be bridged. Chapter 4 provides a comprehensive overview of recent ambitious climate actions by national and subnational governments as well as non-state actors, and



a detailed overview of policy progress and opportunities for enhanced mitigation ambition for selected G20 members. With the aim of informing the Climate Action Summit and the preparation of new and updated NDCs, a special pre-release version of chapter 4 was published in time for the Summit. The chapter illustrates that collectively, the G20 members have not yet taken on transformative commitments at the breadth and scale necessary, highlighting that despite many positive developments, commitments are still far from what is required. Chapter 5 details the key transformations that are needed to align global trends with the Paris Agreement goals and how such transformational pathways in many cases can be synergistic with achieving other development priorities, including the Sustainable Development Goals (SDGs). Global transformation of energy systems is crucial for bridging the emissions gap. Chapter 6 reviews five transition options that are relevant for many countries, can be designed to achieve development and mitigation goals simultaneously and are associated with significant emission reduction potentials. Finally, chapter 7 assesses how material efficiency strategies for residential buildings and cars can contribute to bridging the gap.

2 Global emissions trends and G20 status and outlook

Lead authors:

Takeshi Kuramochi (NewClimate Institute, Germany), Michel den Elzen (PBL Netherlands Environmental Assessment Agency), Glen Peters (CICERO, Norway)

Contributing authors:

Andrzej Ancyger (Climate Analytics, Germany), Ankit Bhardwaj (Centre for Policy Research, India), Gabriel Blanco (National University of the Center of the Buenos Aires Province, Argentina), Taryn Fransen (World Resources Institute, USA), Andreas Geiges (Climate Analytics, Germany), Frederic Hans (NewClimate Institute, Germany), Christopher Henderson (World Resources Institute, USA), Niklas Höhne (NewClimate Institute, Germany), Kejun Jiang (Energy Research Institute, China), Maria Jose de Villafranca (NewClimate Institute, Germany), Kimon Keramidas (Joint Research Centre/European Commissions), HYPERLINK "mailto:joojin.kim@forourclimate" Joojin Kim (Solutions For Our Climate, Republic of Korea), Akihisa Kuriyama (Institute for Global Environmental Strategies, Japan), Leonardo Nascimento (NewClimate Institute, Germany), Jos Olivier (PBL Netherlands Environmental Assessment Agency), Deger Saygin (SHURA, Turkey), Ranping Song (World Resources Institute, China), Claire Stockwell (Climate Analytics, Germany), Kentaro Tamura (Institute for Global Environmental Strategies, Japan), Paola Tanguy (NewClimate Institute, Germany), Heleen van Soest (PBL Netherlands Environmental Assessment Agency), Jorge Villarreal Padilla (Iniciativa Climática de México), Ryan Wilson (Climate Analytics), William Wills (Centro Clima, Brazil), Paola Yanguas Parra (Climate Analytics, Germany)

2.1 Introduction

This chapter assesses the latest trends in greenhouse gas (GHG) emissions as well as progress of G20 economies towards both the Cancun pledges for 2020 and Nationally Determined Contributions (NDCs) for 2025 and 2030. The chapter is organized as follows: section 2.2 takes stock of the current global GHG emissions status and trends. Section 2.3 provides an assessment of whether G20 members are on track to meet their Cancun pledges and NDC targets, while section 2.4 summarizes recent policy developments of individual G20 economies. This section also serves as a basis for chapter 4, which explores opportunities for additional GHG emissions reductions that could be considered in the NDC update process by 2020 and beyond. Section 2.5 provides an overview of submitted long-term low emissions development strategies to date.

In the 2019 report, all GHG emission figures are expressed using the 100-year global warming potentials (GWPs) from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report[1], unless otherwise noted, whereas United Nations Environment Programme (UNEP) Emissions Gap Report 2018 used Global Warming Potential (GWP) values of IPCC Second Assessment Report.

2.2 Current global emissions: status and trends

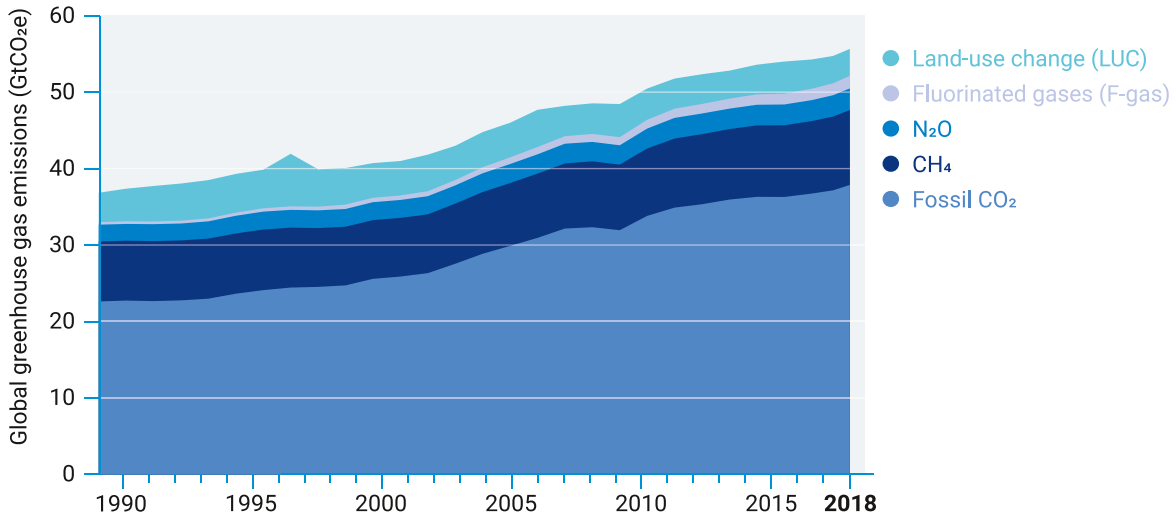
Total GHG emissions grew 1.5 per cent per year in the last decade (2009 to 2018) without land-use change (LUC) and 1.3 per cent per year with LUC, to reach a record high of 51.8 $GtCO_2e$ in 2018 without LUC emissions and 55.3 $GtCO_2e$[2] in 2018 with LUC. GHG emissions growth was 2.0 per cent in 2018 and there is no sign of a peak in any of the GHG emissions[3] (figure 2.1). GHG emissions have grown every year since the global financial crisis in 2009, with only slightly lower growth in 2015 due to big declines in coal use in both the United States of America and China. Fossil CO_2 emissions, from both energy use and industry, dominate total GHG emissions and reached a record 37.5 $GtCO_2$ per year in 2018, after growing 1.5

1 This change was made to be more in line with the decisions made at the COP in Katowice. Parties agreed on the Fifth Assessment Report (AR5) for reporting reasons at COP 24 in Katowice. A full switch to AR5 GWP was not yet possible because the literature is still not up to date on this decision.

2 GHG emissions are 1.8 $GtCO_2e$ higher than the emissions estimate in 2017 presented in recent UNEP Emissions Gap Reports. This is mainly due to the impact of GWPs (1.5 $GtCO_2e$) and the change in LUC emissions (-0.7 $GtCO_2e$), whereas the yearly change in 2018 contributes 1.0 $GtCO_2e$.

3 GHG emissions are based on EDGARv5 (Olivier and Peters 2019) and LUC emissions are from Houghton and Nassikas (2017). In this report, GWPs from the IPCC Fourth Assessment Report are used (25 for CH_4 and 298 for N_2O). This yields total GHG emissions that are 1 $GtCO_2e$ higher in 1970 and 1.5 $GtCO_2e$ higher in 2018.

Figure 2.1. Global greenhouse gas emissions from all sources



Source: Olivier and Peters (2019), Houghton and Nassikas (2017) for land-use change emissions, and Friedlingstein *et al.* (2019) for updates from 2016 to 2018

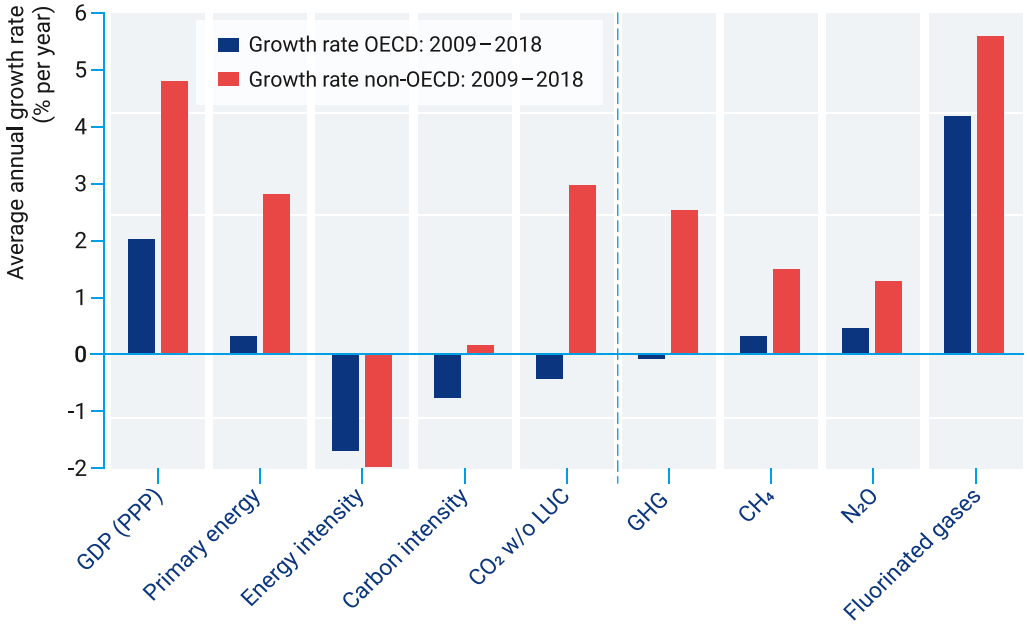
per cent per year in the last decade and 2.0 per cent in 2018[4]. The growth in fossil CO_2 emissions was due to robust growth in energy use (2.9 per cent in 2018). CO_2 emissions from LUC are about 7 per cent of total GHGs and have large uncertainty and inter-annual variability, remaining relatively flat over the last decade (IPCC 2019). Methane (CH_4) emissions, the next most important GHG, grew at 1.3 per cent per year in the last decade and 1.7 per cent in 2018. Nitrous oxide (N_2O) emissions are growing steadily, at 1.0 per cent per year in the last decade and 0.8 per cent in 2018. Fluorinated gases (SF6, HFCs, PFCs) are growing the fastest, at 4.6 per cent per year in the last decade and 6.1 per cent in 2018.

GHG emissions are growing globally, despite progress in climate policy, as the countries where emissions are declining are not able to offset the growth in emissions in other countries. A recent study found that there are 18 developed economies where CO_2 emissions are declining (Le Quéré *et al.* 2019), the United States of America and some European countries. We extend several aspects of that analysis to compare Organisation for Economic Co-operation and Development (OECD) and non-OECD economies. Figure 2.2 shows a decomposition of the growth in economic activity (Gross Domestic Product, GDP), primary energy use, the energy use per unit of GDP, the CO_2 emissions per unit of energy, and GHG emissions from all sources, for OECD (blue) and non-OECD (orange) economies. Economic activity has been much stronger in non-OECD economies, growing at over 4.5 per cent per year in the last decade compared to just 2 per cent per year in OECD economies. Since the OECD (1.7 per cent per year) and non-OECD (2 per cent per year) economies have had similar declines in the amount of energy used per unit of economic activity, economic growth means that that energy use has grown much faster in non-OECD economies (2.8 per cent per year) than OECD economies (0.3 per cent per year). OECD economies already use less energy per unit economic activity, suggesting that non-OECD economies have the potential to accelerate improvements.

Declining or flat energy use makes it easier for non-fossil energy sources, like wind and solar, to displace fossil fuels in the energy system. The flat energy use in OECD economies is one key reason that emissions have decreased in those regions (Le Quéré *et al.* 2019), with the declines accelerated due to a declining amount of CO_2 emitted per unit of energy use (-0.8 per cent per year). In non-OECD economies, slightly more CO_2 is emitted per unit of energy in the last decade (0.2 per cent per year growth), meaning that CO_2 emissions have grown slightly faster than energy use. In non-OECD economies, the rapid deployment of solar and wind power has not been strong enough to displace fossil fuels, particularly in countries with growing energy use and

4 In this report, CO_2 emissions from fossil-fuels and industry grew 2.0 per cent in 2018, using EDGARv5 (Olivier and Peters 2019). The Global Carbon Budget estimates 2018 fossil-fuel and industry emissions to grow 2.1 per cent (Friedlingstein *et al.* 2019), while for combustion-related emissions only, the Institute of Economic Affairs estimated growth of 1.7 per cent (IEA 2019) and BP estimated growth of 2.0 per cent (BP 2019).

Figure 2.2. Average annual growth rates of key drivers of global CO_2 emissions (left of dotted line) and components of greenhouse gas emissions (right of dotted line) for OECD and non-OECD economies



Source: Olivier and Peters (2019) and Global Carbon Project (Friedlingstein *et al.* 2019) for energy and economic data

globally. In total, OECD economies have seen CO_2 emissions decline by -0.4 per cent per year in the last decade, while non-OECD economies have seen emissions growing at nearly 3 per cent per year. In the near term, it is expected that energy use will continue to grow in non-OECD economies, but more rapid improvements in energy intensity, together with deployment of low-carbon energy sources, could lead to an earlier peak and then decline in CO_2 emissions.

GHG emissions are dominated by CO_2, but the non-CO_2 emissions represent over 34 per cent of total GHG emissions including LUC. OECD economies have only seen very limited growth in CH_4 and N_2O, but rapid growth in fluorinated gases, leading to an overall slight decline in GHG emissions. Non-OECD economies have seen strong growth in all non-CO_2 GHGs, leading to an overall increase in GHG emissions of 2.5 per cent per year in the last decade. While CO_2 dominates GHG emissions, reductions in other components can help achieve an earlier peak in GHG emissions.

While global emissions statistics provide important information on collective progress, they mask the dynamics at the country level (figure 2.3). The top four emitters (China, EU28, India and the United States of America) contribute to over 55 per cent of the total GHG emissions over the last decade excluding LUC, the top seven (including Japan, Russia and international transport) account for 65 per cent, while G20 members contribute 78 per cent. China emits more than one-quarter (26 per cent) of global emissions (excluding LUC), and despite contributing significantly to the slowdown in global emissions from 2014 to 2016, emissions in the country are now rising again, growing 2.5 per cent in the last decade and 1.6 per cent in 2018 to reach a record high 13.7 $GtCO_2e$ in 2018. The United States of America emits 13 per cent of global GHG emissions, with a gradual decline in GHG emissions of 0.1 per cent per year in the last decade, but an increase of 2.5 per cent in 2018 due to increased energy demand from an unusually warm summer and cold winter. The European Union emits 8.5 per cent of global GHG emissions and has had a steady decline of 1 per cent per year in the last decade and a decline of 1.3 per cent in 2018. India, accounting for 7 per cent of global emissions, continues to have rapid growth in emissions of 3.7 per cent per year in the last decade and 5.5 per cent in 2018. The Russian Federation (4.8 per cent) and Japan (2.7 per cent) are the next largest emitters, with international transport (aviation and shipping) representing around 2.5 per cent of GHG emissions. If LUC emissions were included, the rankings would change, with Brazil likely to be the largest emitter.

The ranking of countries changes dramatically when considering per capita emissions (figure 2.3, right), but less so when allocating emissions to consumption (figure 2.4). Consumption-based emissions, also known as a carbon footprint, adjusts the standard territorial emissions. As figure 2.4 shows, developed countries import more emissions than they export, with the opposite holding true in developing countries. In the 2000s, there was a growing gap between consumption-based emissions in developed countries and their territorial emissions. This gap was larger than the reductions made under the Kyoto Protocol (Peters *et al.* 2011). Since the global financial crisis in 2008, the

Figure 2.3. The top emitters of greenhouse gases, excluding land-use change emissions due to lack of reliable country-level data, on an absolute basis (left) and per capita basis (right)

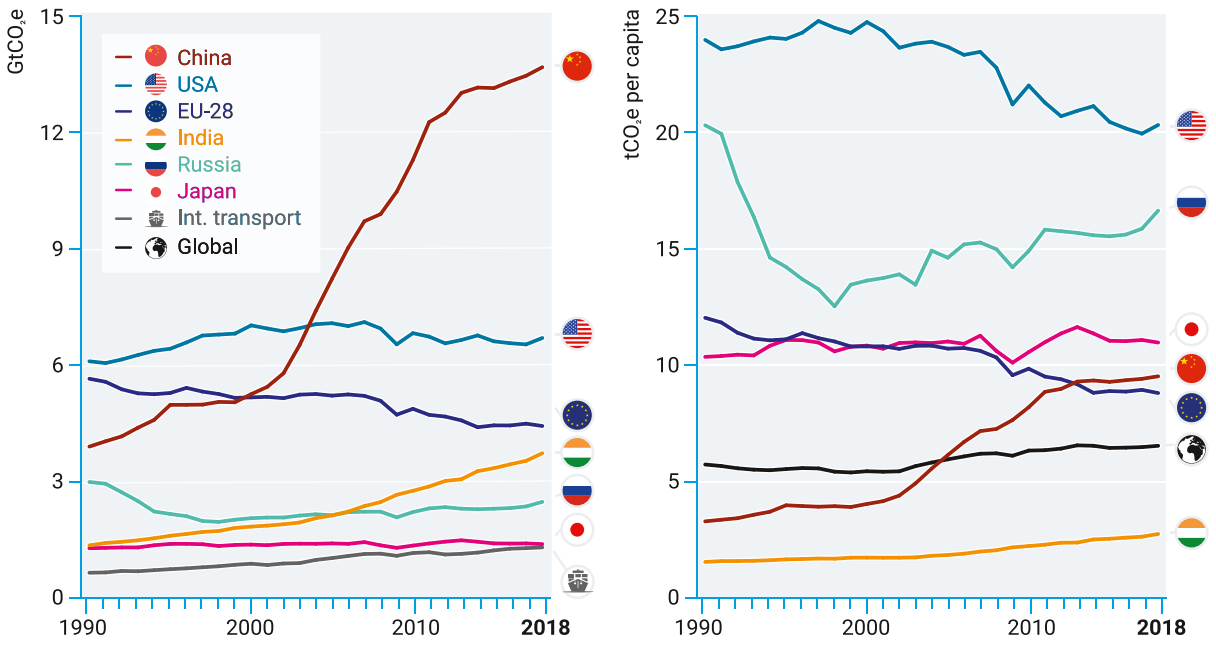
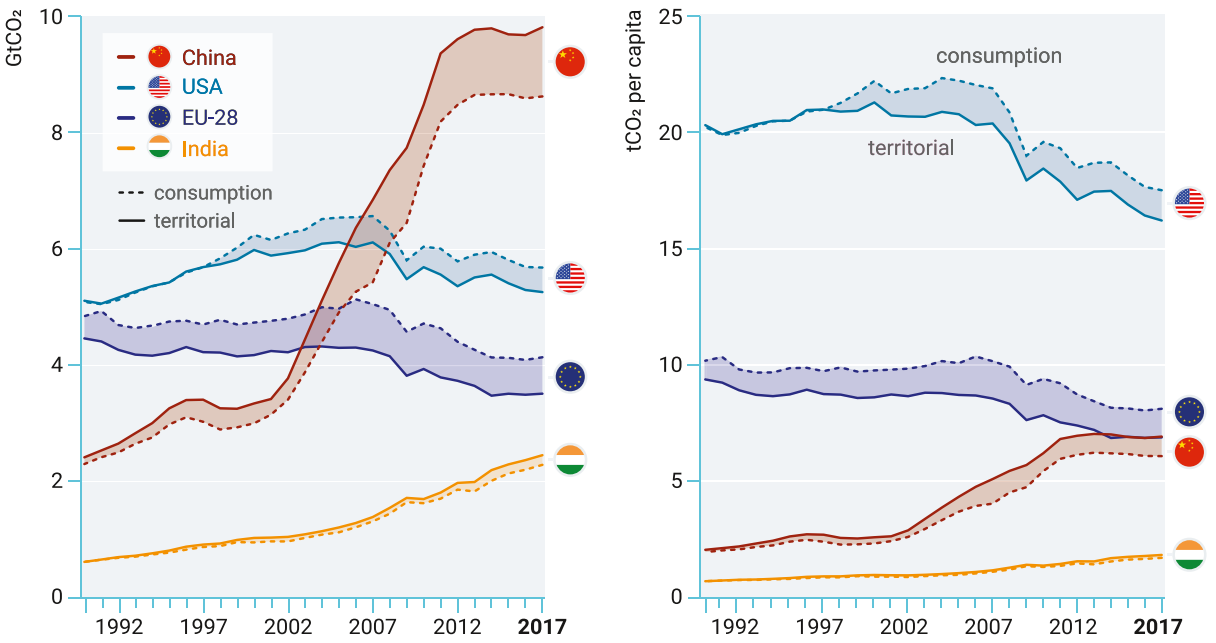


Figure 2.4. CO_2 emissions allocated to the point of emissions (territorial) and the point of consumption, for absolute emissions (left) and per capita (right)



Source: Olivier and Peters (2019), Houghton and Nassikas (2017) for land-use change emissions, and Friedlingstein *et al.* (2019) for updates from 2016 to 2018

gap has stabilized, and even declined. China contributed to most of the growth in the 2000s, but also the stabilization in the 2010s (Pan *et al.* 2017). Consumption-based emission estimates allow policymakers to focus on different policy levers and may help deal with carbon leakage under stringent climate policies.

2.3 Assessment of G20 Member progress towards Cancun pledges and NDC targets

GHG emissions projections were compiled and reviewed to assess the emission levels expected for G20 members under existing policies ("Current policies scenario") and whether they would meet their respective emissions reduction targets for 2020 and 2030. We followed the methodology of den Elzen *et al.* (2019) to enable a fair comparison of projections from different data sources, including both official data sources published by the G20 governments as well as sources published by independent research institutions.

Up-to-date emissions projections published since November 2018 were collected from countries' recently published National Communications, the third biennial reports of seven G20 members, several other new national studies and the independent global studies Climate Action Tracker (Climate Action Tracker 2019d), the Joint Research Centre (JRC) of the European Commission (Keramidas *et al.* 2018) and PBL Netherlands Environmental Assessment Agency (Kuramochi *et al.* 2018) for the current policies scenario and NDC scenario projections (see appendix A, available online, for scenario definitions). Several studies on current policies scenario projections from the UNEP Emissions Gap Report 2018 data set were excluded, as these were concluded not to be representative of the policies implemented to date (mostly those published before 2017, depending on the G20 Member). All data sources are presented in appendix A. Current policies scenario projections from studies without NDC quantification were compared to official NDC emission values in absolute terms or – when official NDC emission values are not available – to the median estimates of NDC emission levels across independent studies.

This section should be read with some important caveats in mind (den Elzen *et al.* 2019). First, whether a country is projected to achieve or miss its emissions reduction targets with existing policies depends on both the ambition level of the targets, which this study does not assess, and the strength or stringency of existing policy packages. Therefore, countries projected to achieve their NDCs with existing policies are not necessarily undertaking more mitigation action than countries that are projected to miss them. Chapter 3 of this report and the literature (Rogelj *et al.* 2010; 2016) are clear that the NDCs are collectively far from sufficient to keep warming to 2°C, let alone 1.5°C, and thus all countries have to raise the ambition of their current NDCs significantly. According to the Paris Agreement, countries are obligated to regularly update and strengthen their NDCs. The assessment conducted in this section is based on current NDCs, recognizing that they are to be revised and should be strengthened considerably by 2020 to meet the climate goal of the Paris Agreement. Second, current policies scenario projections are subject to the uncertainty associated with macroeconomic trends, such as GDP and population growth and technology developments, as well as with the impact of policies. Some Cancun pledges and NDCs are also subject to uncertainty of future GDP growth and other underlying assumptions.

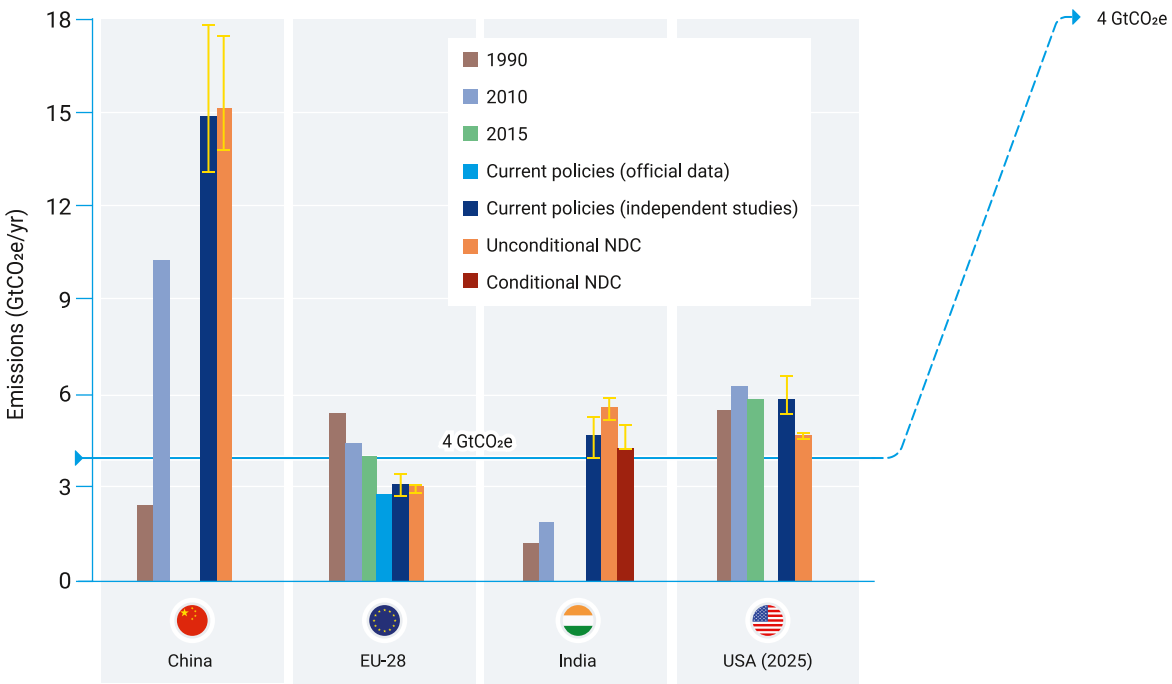
It is also worth noting that the current policies scenario projections do not reflect the likely impact of all policies implemented to date for a number of reasons. First, there is always a time lag between the date a new policy measure was implemented and the date a scenario study that considered this new policy was published. Second, it often takes time for research institutions to assess whether a new policy measure would be effectively implemented to achieve its intended objective, resulting in an even larger time lag. Third, GHG emissions projection models have limitations on the types of policies they can incorporate, which may result in an under- or overestimation of projected emissions.

On the progress of G20 economies towards their 2020 pledges, they are collectively (those who have Cancun pledges) projected to overachieve their Cancun pledges by about 1 $GtCO_2e$ per year based on the assessments from the Climate Action Tracker (Climate Action Tracker 2019d) and PBL (Kuramochi *et al.* 2018), the two studies that annually update both the 2020 pledge emission levels and current policies scenario projections. However, several individual G20 members (Canada, Indonesia, Mexico, Republic of Korea, South Africa, the United States of America) are currently projected to miss their Cancun pledges or will not achieve them with great certainty. In Australia, the Government projects that they would overachieve their 2020 pledge based on their carbon budget approach that accounts for cumulative emissions between 2013 and 2020 (Australia, Department of the Environment and Energy 2018). Argentina, Saudi Arabia and Turkey have not made 2020 pledges.

On the progress of G20 economies towards their NDC targets, six members: China, the EU28, India, Mexico, Russia and Turkey, are projected to meet their unconditional NDC targets with current policies (table 2.1). Among them, the current policies scenario emissions projections for three countries (India, Russia and Turkey) are projected to be 15+ per cent lower than the NDC target emission levels. These results suggest that the three countries have room for raising their NDC ambitions significantly. The EU28 has introduced climate legislation that achieves at least 40 per cent GHG reductions and is projected by the European Commission (European Commission 2018b) to overachieve these, if domestic legislation is fully implemented (figure 2.5).

Figure 2.5. Greenhouse gas emissions (all gases and sectors) of the G20 and its individual members by 2030 under different scenarios and compared with historical emissions

Figure 2.5a.



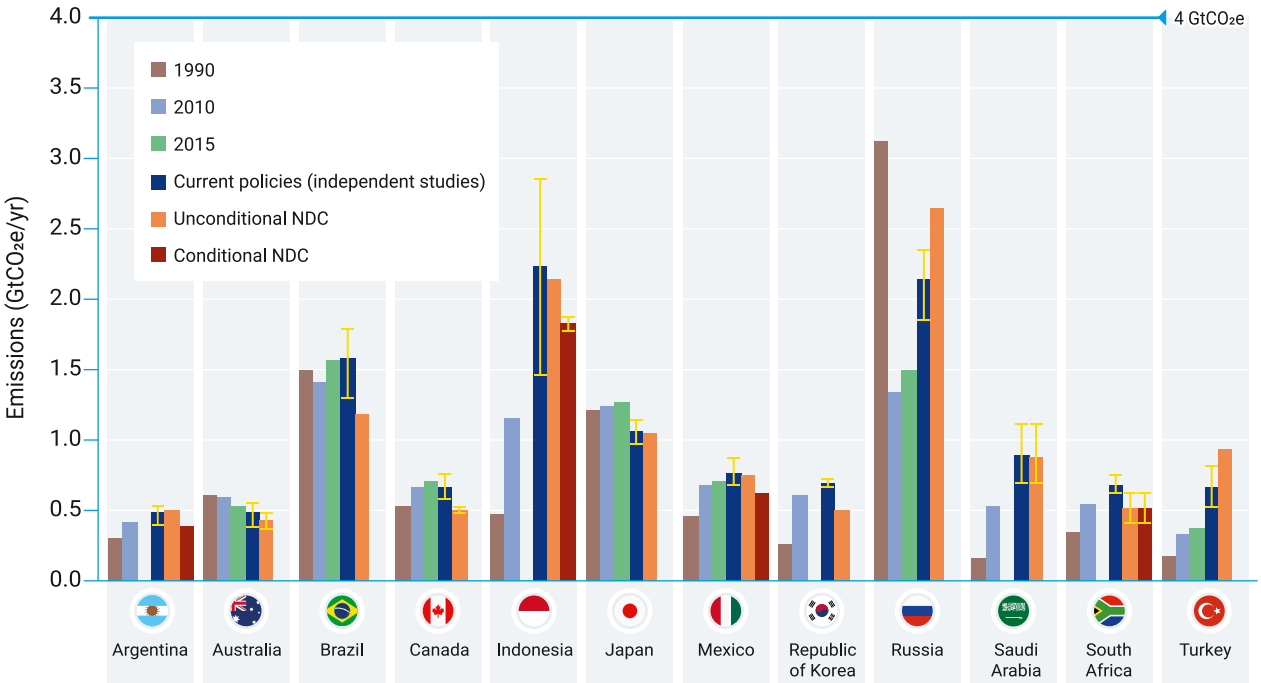
The change in assessment results for the EU28 from our 2018 report is partially due to the differences in whether and how the new policy packages adopted in recent months were considered in GHG emissions projections (see also the EU28 section and an earlier paragraph in this section). All three independent studies (Climate Action Tracker, JRC and PBL) do not take the recently adopted policy packages into account. Also, along with official publications, the European Environment Agency (EEA 2018) projects emissions based on Member state-level policies[5] and the third Biennial Report of 2017 ("With Current Measures" scenario), which projects that the EU28 would remain short of achieving its NDC target, and does not cover policies implemented in last two years. By contrast, the reference scenario in the 2018 analysis produced by the European Commission supporting the long-term vision document, which reflects recent European Union (EU)-level policies and assumes their full implementation, projects that the EU28 could reduce its GHG emissions by 48 per cent from 1990 levels including LULUCF. For this reason, the EU28 has been classified as projected to overachieve its NDC target in table 2.1, even though the independent studies do not project the EU28 to achieve its NDC target (figures 2.5 and 2.6), as they are not fully updated.

Seven G20 members require further action of varying degree to achieve their NDC targets: Australia, Brazil (new, changed compared to UNEP (2018)), Canada, Japan (new), Republic of Korea, South Africa and the United States of America. For Brazil, the projections from three annually updated publications were all revised upward, reflecting, among others, the recent turn of trends on deforestation. Japan's current policies projections have been on the borderline of achieving the NDC target for the last few years.

Studies do not agree on whether Argentina, Indonesia and Saudi Arabia (new) are on track to meet their unconditional NDCs. For Argentina, a recent domestic analysis that reflects the most recent GHG inventory data up to 2016 (Keesler, Orifici and Blanco 2019) projects that the unconditional NDC target – which was revised in 2016 with a more ambitious one – will be achieved including scenarios that are less optimistic (see annex B for details), while two other international studies project that the country will fall short of achieving its unconditional NDC with existing policies. For Indonesia, the lack of agreement is mainly due to the uncertainty on land-use, LUC and forestry (LULUCF) emissions. For Saudi Arabia, the limited amount

5 Member States who are at different stages when it comes to implementing domestic measures to meet EU legislation. It is logical that progression is achieved in these projections over time as Member States take additional actions.

Figure 2.5b.



Notes: For reporting reasons, the emission projections for China, the EU28, India and the United States of America are shown in figure 2.5a and the other countries shown in figure 2.5b, using two different vertical axes.
The current policies and NDC scenario estimates are based on average GHG emission projections. The findings regarding whether countries are projected to over- or underachieve their NDC targets under current policies may therefore differ from the assessment in table 2.1, which is based solely on the number of independent studies.

As a conservative assumption, South Africa is not considered as having a firm commitment to peak, since there is no guarantee that the conditions upon which they made the pledge will be met.
* For the United States of America, the unconditional NDC is for 2025. For Brazil, we refer to the indicative target for 2030.
** South Africa's NDC is based on an emissions trajectory with an emissions range of 398–614 $MtCO_2e$ including LULUCF over the 2025–2030 period.

of information on the country's climate policies did not allow for further assessments beyond the two studies reviewed.

Some G20 members are continuously strengthening their mitigation policy packages, leading to a downward revision of current policies scenario projections over time. One example is the EU, where a noticeable downward shift in current policies scenario projections for 2030 has taken place since the 2015 edition of the UNEP Emissions Gap Report (see section on the EU28 below for recent policy developments).

Figure 2.5 provides a detailed comparison of estimated emissions under current policies scenarios as estimated by official and independent sources and the NDC scenario for all G20 members except for the EU Member States, mapping these against 1990, 2010 and 2015 emissions. For each of the G20 members, average (median when more than five studies) GHG emission projections have been calculated for current policies and full implementation of the NDC, following the approach of den Elzen *et al.* (2019), the results of which were presented in the UNEP Emissions Gap Report 2018 (UNEP 2018) including climate change. Countries will meet again at the United Nations Framework Convention on Climate Change (UNFCCC).

As mentioned, average GHG emission projections are presented for the current policies scenarios in figure 2.5 and 2.6, whereas the assessment in table 2.1 is based solely on the number of independent studies that support a given country finding. As a result, some countries may be classified as projected to meet their NDC target according to the number of studies available (table 2.1), while they may be projected to miss their NDC

Table 2.1. Assessment of progress towards achieving the unconditional NDC targets for the G20 under current policies based on independent studies

Projected to meet the unconditional NDC target with currently implemented policies		Expected to meet the unconditional NDC target with additional policy measures and/or stricter enforcement of existing policies		Uncertain or insufficient information
Overachievement of the target by more than 15 per cent, suggesting a weak target	Overachievement of the target by less than 15 per cent	Projected emissions 0–15 per cent above the NDC target	Projected emissions 15 per cent or more above the NDC target	
• **India** (6 of 6 studies) • **Russia** (3 of 3 studies) [1)] • **Turkey** (3 of 3 studies)	• **China** (3 of 5 studies, one uncertain) [2)] • **EU28** (1 of 3 studies, one uncertain) [1),2),3)] • **Mexico** (2 of 3 studies)	• **Australia** (3 of 4 studies) [1)] • **Japan** (2 of 3 studies) • **South Africa** (3 of 3 studies) [1), 4)]	• **Brazil** (4 of 4 studies) • **Canada** (3 of 3 studies) [1)] • **Republic of Korea** (3 of 3 studies) • **United States of America** (2025) (5 of 5 studies) [1)]	• **Argentina** (1 of 3 studies projected to meet the unconditional NDC; updated NDC in 2016) • **Indonesia** (3 studies disagree) • **Saudi Arabia** (2 studies disagree)

Notes: The assessment is based on the number of independent studies that support the findings (except for the EU28, see the note below and the section analysis). These are compared to the available studies, as indicated in brackets.

1. We also examined current policies scenario projections from official publications. The number of publications that support the above findings based on independent studies are Australia: 1 of 1; Canada: 2 of 2; Russia: 1 of 1; South Africa: 1 of 1; the United States of America: 1 of 1. For the EU28, three official publications disagree (see footnote 3).
2. The Climate Action Tracker indicates that upper-end projections would miss the NDC target range.
3. The EU assessment result is based on projections fully implementing adopted EU climate and energy legislation (European Commission 2018b). For the EU28, among the three independent studies and three official studies, the evaluation was made based on a study by PBL that took into account the best recently adopted policy packages (Kuramochi *et al.* 2018) and projections from the most recent official analysis by the European Commission (European Commission 2018b).
4. South Africa's current policies scenario projections were compared to the upper-bound estimate of the NDC range.

target based on the average emission projections under the current policies scenario (and vice versa).

To supplement the findings presented above, table 2.2 presents projected per capita GHG emissions under current policies and NDC targets based on independent studies in both absolute and relative terms (compared to 2010 levels) for all G20 members excluding the four EU Member States. We find that nine G20 members, including China, are projected to emit more than 10 tCO_2e per capita annually (approximately the levels in 2010 for EU28 and Japan) in 2030 under current policies and seven members could even achieve levels under unconditional NDC targets. Among OECD members[6], the EU28 performs well in both absolute and per capita emission levels in 2030 and in their change rates compared to 2010 levels, even though the consumption-based emissions are considerably higher, as shown in figure 2.4. Mexico also performs well in terms of the projected development of per capita emissions under both current policies and NDC scenarios. As table 2.2 shows, emissions per capita annually in 2030 under the unconditional NDC targets are projected to decline between 2010 and 2030 in all G20 economies except China, India, Indonesia, the Russian Federation, Saudi Arabia and Turkey. There are also large differences in per capita emission levels. The per capita emissions of India are about half the G20 average, whereas Saudi Arabia reaches three times the G20 average.

6 Australia, Canada, the EU, Japan, Mexico, Republic of Korea, Turkey, the United States.

Table 2.2. – Overview of G20 Member status and progress, including on Cancun pledges and NDC targets*

Country	Share in global GHG emissions in 2017 excluding LULUCF and including LULUCF (in brackets) [1]	Projected per capita GHG emissions including LULUCF in 2030 (tCO_2e/cap) and change rates from 2010 levels (in brackets) [2] [3] [4]	
		Current policies scenario (central estimates [5] of independent studies)	Unconditional NDC (official values whenever available, otherwise central estimates of independent studies)
Argentina	**0.8%** (0.9%)	**10.6** (+4%)	**10.2** (-1%)
Australia	**1.2%** (1.1%)	**17.5** (-34%)	**15.1** (-43%)
Brazil	**2.3%** (2.9%)	**7.1** (-1%)	**5.3** (-26%)
Canada	**1.6%** (1.8%)	**16.0** (-17%)	**12.6** (-35%)
China	**26.8%** (25%)	**10.2** (+35%)	**10.3** (+37%)
EU28	**9.0%** (7.9%)	**6.1** (-31%)	**5.9** (-33%)
India	**7.0%** (7.1%)	**3.1** (+100%)	**3.7** (+138%)
Indonesia	**1.7%** (4.9%)	**7.4** (+56%)	**7.1** (+50%)
Japan	**3.0%** (2.9%)	**8.8** (-8%)	**8.6** (-10%)
Mexico	**1.5%** (1.5%)	**5.4** (-9%)	**5.3** (-10%)
Republic of Korea	**1.6%** (1.3%)	**13.4** (+10%)	**9.7** (-20%)
Russia	**4.6%** (4.3%)	**15.0** (+61%)	**18.5** (+99%)
Saudi Arabia	**1.5%** (1.4%)	**22.7** (+16%)	**22.2** (+14%)
South Africa	**1.1%** (1.1%)	**10.2** (-3%)	**7.8** (-26%)
Turkey	**1.2%** (1.0%)	**7.3** (+63%)	**10.4** (+132%)
USA	**13.1%** (12.5%)	**16.5** (-14%)	**11.5** (-40%)

*Emission figures include LULUCF, unless otherwise noted.

Notes:

1. Olivier and Peters (2018), excluding LULUCF/including LULUCF. LULUCF emissions based on the Food and Agriculture Organization of the United Nations (FAO) data (Food and Agriculture Organization Corporate Statistical Database [FAOSTAT] 2018).
2. The population projections are based on the medium fertility variant of the United Nations Population Prospects 2019 edition (United Nations Department of Economics and Social Affairs [UN DESA] 2019).
3. For comparison, the G20 average per capita emissions in 2010 was 7.2 tCO_2e/cap based on national GHG inventory reports submitted to the United Nations Framework Convention on Climate Change (UNFCCC) (supplemented by EDGAR and FAO (Kuramochi *et al.* 2018)). Assumptions on LULUCF emissions presented in appendix A, table A - 2.
4. Median estimates are used when more than five studies are available, otherwise average estimates.
5. Historical data based on the second Biennial Report.

Box 2.1. Comparing emission values across chapters

To compare these G20 estimates with the G20 shares of the global greenhouse gas emissions estimates of the current policies scenarios and 1.5- and 2°C-consistent global emission levels, as presented in chapter 3, we need to discuss the LULUCF CO_2 emissions. Given the difference in estimating the "anthropogenic sink" between countries and the global integrated assessment modelling community (Grassi *et al.* 2017), the LULUCF CO_2 estimates included here based on inventory data are not necessarily directly comparable with countries' land-use CO_2 emissions estimates at the global level used by the global model community. Grassi *et al.* (2017) find a current ±3 $GtCO_2e$/year difference in global LULUCF net emissions between country reports (such as greenhouse gas inventories and National Communications) and scenarios studies (as reflected in IPCC reports). Among the many possible reasons for these differences, Grassi *et al.* (2017) suggest that a key factor – which deserves further analysis – relates to what is considered "anthropogenic forest sink". At least two-thirds of the difference of 3 $GtCO_2e$, about 2 $GtCO_2e$, could be attributed to the G20 members.

The G20 total emissions projections for 2030 alone would be about 43 $GtCO_2e$/year, after correcting for the anthropogenic sink, which would exceed the 2°C-consistent global emission levels of the integrated assessment models presented in chapter 3. This G20 projected emissions level in 2030 is about 72 per cent of global emissions of the current policies (60 $GtCO_2e$) in 2030 seen in chapter 3, which is close to the 78 per cent share of G20 in the global emissions in 2018. It is lower in 2030, which was to be expected, given the increasing share of non-G20 and in-time international aviation and shipping emissions until 2030.

Figure 2.6 presents the additional effort needed according to estimates based on independent studies and shows that the main contributions would need to come in particular from the United States of America. If we assume a linear interpolation between the NDC target year (2025) and the 2050 United States of America long-term target (80 per cent reduction below 2005 levels indicated in the longterm low-carbon development strategy (LTS) document – see section 2.5) to estimate an indicative 2030 target, the required additional emissions reductions would halve if the 2030 target remained at the same level as for 2025, instead of progressing linearly towards its 2050 target as assumed in our analysis. The three countries that are projected to significantly overachieve their unconditional NDC targets (by more than 15 per cent), i.e. India, Russia and Turkey, are expected to together exceed their NDC targets by about 1.5 $GtCO_2e$ in 2030 with current policies (compared to about 1 $GtCO_2e$ in the UNEP Emissions Gap Report 2018). By contrast, the emission gaps are noticeably larger than in the 2018 assessment for the two large LULUCF emitters, i.e. Brazil and Indonesia, reflecting the recent increase of historical emissions and the political uncertainties in the two countries.

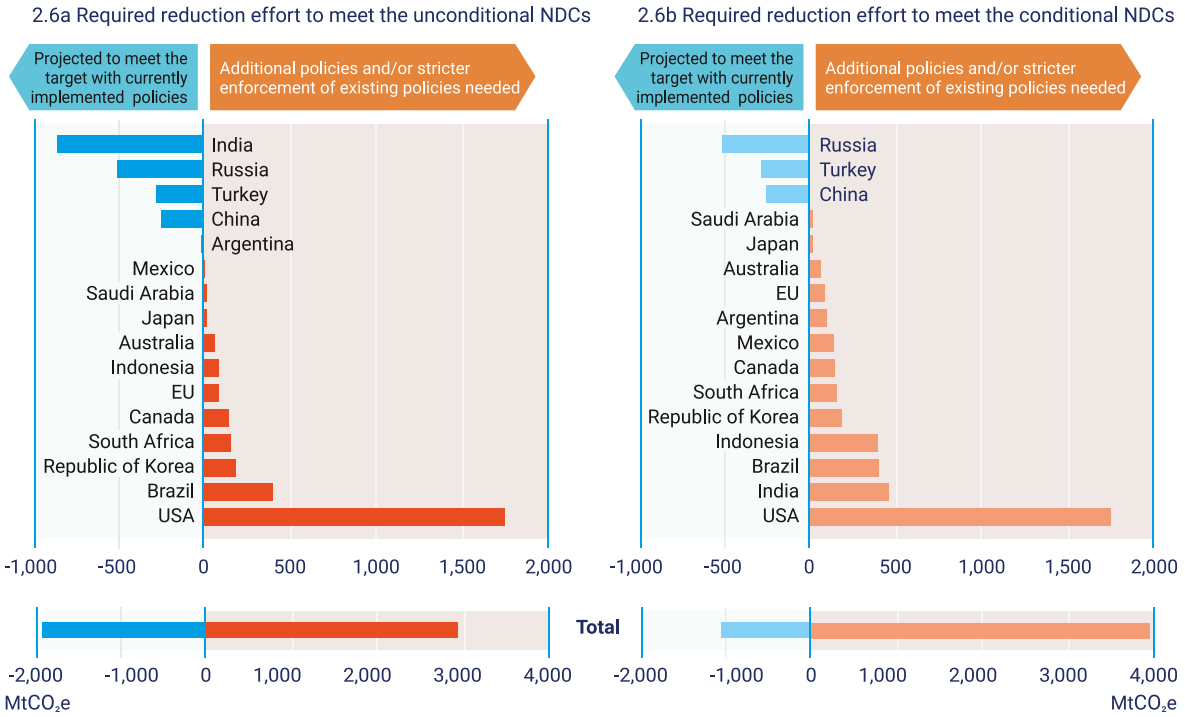
Overall, this study indicates that current policies of G20 members collectively fall short of achieving the unconditional NDCs. The total GHG emissions for G20 members are projected to be 41.0 $GtCO_2e$/year (range: 35.1 to 47.6 $GtCO_2e$/year), which is slightly lower than the projections by den Elzen *et al.* (2019) after correcting for different GWPs.

G20 members as a whole will need to reduce their GHG emissions further by about 1.1 $GtCO_2e$/year by 2030 to achieve unconditional NDC target emission levels and by about 2.9 $GtCO_2e$/year to achieve conditional NDC target emission levels. If we exclude the 1.6 $GtCO_2e$/year overachievement of unconditional NDCs by India, Russia and Turkey and assume that these countries will follow their current policies trajectory rather than that implied by their unconditional NDCs (as done in many NDC scenario projections from global models presented in chapter 3), then the G20 economies are collectively short of the unconditional NDCs by about 2.7 $GtCO_2e$/year against unconditional NDCs and by about 3.7 $GtCO_2e$/year against conditional NDCs in 2030. The estimated difference between the current policies scenario and NDC scenario projections for G20 members remains similar to that in the UNEP Emissions Gap Report 2018, but some G20 members (i.e. the EU and South Africa) have lower current policies projections than in the 2018 report (UNEP 2018), whereas others have higher projections (i.e. Brazil, and to a lesser extent, China).

2.4 Recent policy developments of G20 members

This section presents selected policy developments observed recently in individual G20 members and their potential implications on GHG emissions, where information is available. Information on main sector-level policies in selected G20 members is presented in chapter 4 and in appendix B, which is available online.

Figure 2.6. Additional emissions reduction effort required in 2030 per G20 Member to achieve NDC targets, based on current policies scenario projections of independent studies



Note: The NDC scenario projections from global models presented in chapter 3 assume that the countries that overachieve their NDCs follow their current policies trajectory. The calculations for the United States of America are based on an interpolation between its 2025 NDC and the 2050 long-term target (80 per cent reduction from 2005 levels) and for Brazil, they are based on its indicative 2030 target. As the current policies estimates of the independent studies are based on average GHG emission projections, the findings regarding whether countries are projected to over- or underachieve their unconditional NDC targets may therefore differ from the assessment in table 2.1, which is based solely on the number of independent studies.

Argentina

Unconditional NDC target projection: Uncertain or insufficient information

Argentina submitted its first NDC in 2015 and a revised version in 2016 where the country unconditionally committed to emit no more than 483 $MtCO_2e$/year in 2030. Since then, the country has established a National Climate Change Cabinet integrated by most of the ministries to design a low-carbon strategy and ensure the coherence of policies and measures. Under this institutional framework, the ministries have prepared a set of sectoral plans describing the mitigation policies and measures to be implemented to reach the NDC goals (Argentina, National Climate Change Cabinet 2019).

Policies and measures in the energy sector include the construction of several large-scale hydropower plants, three new nuclear power plants[7], various types of large-scale renewable energy power plants such as wind, solar PV and biomass, smaller renewable energy systems for distributed generation and residential solar water heaters. Implementation of these actions is behind schedule (Compañía Administradora del Mercado Mayorista Eléctrico S.A. [CAMMESA] 2019), mainly due to difficulties accessing financial resources (Gubinelli 2018). The weak infrastructure for electricity transportation is also a major barrier for the expansion of renewable, grid-connected power plants (Mercado Eléctrico 2019; Singh 2019). At the same time, the heavily subsidized exploitation of non-conventional fossil fuels from the Vaca Muerta reservoir is adding GHG emissions in a magnitude similar to the estimated emissions reductions of the renewable energy plan (Iguacel 2018). The initial exploration and future exploitation of offshore oil and natural gas is adding to the burden (Baruj and Drucaroff 2018; Boletín Oficial de la República Argentina 2019).

7 One of these three nuclear power plants, Atucha II, is already operational. The other two are currently under development.

Policies and measures have been developed for the industry and transport sectors such as energy efficiency, recycling and reuse of waste, renewable energy generation for self-consumption, promotion of low-emission urban mobility and public transport, intercity railroad restoration and efficiency improvements in road and railway freight transportation. Some of these actions are being implemented (for example, the initial implementation of hybrid and electric buses in large cities and the use of alternative fuels in cement kilns), while some other actions are behind schedule. In relation to agriculture, forestry and land-use, the key sectors for Argentina in relation to their contribution to GDP and to GHG emissions, sectoral plans have been presented with policies and measures such as conservation and restoration of native forests, sustainable forest management and fire prevention, increasing the forested area and promoting bioenergy from different biomasses. In addition to the measures proposed, Argentina urgently needs to revise the technologies and practices it has been using for decades in agricultural production to avoid further soil degradation and the impact on health of rural and suburban populations caused by using agrochemicals (Instituto National de Tecnología Agropecuaria (n.d).; Panigatti 2010). It also needs to provide the due amount of funding to finance the law that protects native forests and keep under control the rate of deforestation that increased in 2017 after several years of declination (Argentina, Ministerio de Ambiente y Desarrollo Sustentable 2018).

Australia

Unconditional NDC target projection: Emissions 0–15 per cent above target

With the re-election of Australia's conservative Government in May, there has been no recent material change in Australian climate policy. This will make achieving its NDC of a 26 per cent to 28 per cent emissions reduction below 2005 levels by 2030 challenging. However, it appears that the Australian Government intends to use carry-over permits from the Kyoto Protocol to do so, and uses a carbon budget approach that accounts for cumulative emissions between 2021 and 2030 in order to assess progress against its NDC (Australia, Department of the Environment and Energy 2018). The dropping of the proposed National Energy Guarantee in 2018 and that the renewable energy target will not be raised for years after 2020 up to 2030 (Clean Energy Regulator 2018) leaves Australia with no major policy tool to encourage emission reductions from the electricity sector in the short to medium term. There has been a 1.4 billion Australian dollar commitment to a 2 GW expansion of the Snowy Mountains hydroelectric project; however, the emission reductions stemming from this project are not expected to occur until well after 2030 (Marsden Jacob Associates 2018). In 2017, the Government's advisory body, the Climate Change Authority, concluded that other policies would be needed to deliver the structural changes necessary for Australia to decarbonize (Climate Change Authority 2017).

The latest projection published by the Government shows that emissions would remain largely unchanged up to 2030 (Australia, Department of the Environment and Energy 2018; Climate Action Tracker, 2019a). To date, much of the support from the Government's signature climate policy, the recently renamed "Climate Solutions Fund", has gone to LUC projects (Clean Energy Regulator 2017). The current Government decided earlier in 2019 to provide an additional 2 billion Australian dollars to the Climate Solutions Fund. The Australian Government estimates that these measures will contribute to an additional 100 $MtCO_2e$ of emissions reductions by 2030 (Australia, Department of the Environment and Energy 2019).

Brazil

Unconditional NDC target projection: Emissions at least 15 per cent above target

After the strong reduction in deforestation rates from 2004 (18,900 km²) to 2012 (4,656 km²), the deforestation rate grew again to 7,900 km² in 2018 (+70 per cent). Preliminary numbers indicate that in the first semester of 2019 deforestation rates continued to grow relative to the same period of 2018. President Bolsonaro significantly reduced the Ministry of Environment's budget for climate-change related activities; transferred the body responsible for identifying, defining, and registering Indigenous Territory to the Ministry of Agriculture; relaxed the rules for converting environmental fines into alternative compensations; extended deadlines for adequacy to registries that supported enforcement measures; and abolished most committees and commissions for civil participation and social control in the Federal Government (Climate Action Tracker 2019b).

Given the key role of the LULUCF sector in Brazil's NDC, which aims to reduce the country's GHG emissions by 37 per cent below 2005 levels by 2025 and to an indicative level of 43 per cent below 2005 levels by 2030, and given the huge global importance of its forests for environmental services, biodiversity and carbon sequestration, the Brazilian Government urgently needs to strengthen mitigation action in this sector. Official projections still show a decreasing trend (Programa Despoluição de Bacias Hidrográficas [PRODES] 2019), which is contrary to the observed trend. If environmental regulations and deforestation control policies are reversed or suspended, net emissions from deforestation could increase by 850-1,500 $MtCO_2e$/year by 2030 (Rochedo *et al.* 2018).

Despite the negative developments in climate policy and emissions regarding the forestry sector, Brazil has made progress in the energy sector. Market developments between 2015 and September 2019 seem to favour renewable energy over fossil fuels. Although fossil capacity was eligible in the latest auctions, no coal and only 4 GW of gas-fired power generation have been contracted since 2015 in comparison to 10 GW of renewables per cent. Wind has been the most competitive technology with concessions of 4 GW, followed by solar (3.3 GW), hydro (1.6 GW), and biomass (1.0 GW) (Brazil, Brazilian Electricity Regulatory Agency [ANEEL] 2019).

In the transport sector, the Government has launched the RenovaBio programme (Decree No. 9.308) that aims to increase the amount of biofuel in the national energy mix and has already led to an additional production of 31.9 million m^3 in 2016 and 2017 (Brazil, Ministry of Science, Technology, Innovation and Communications 2019); therefore the biofuel production in the country will probably meet the indicative targets mentioned in Brazil's NDC. President Bolsonaro also signed the first concession for the rail transport sector in 10 years. The project allows cargo to be transported from the Midwest and flow through both the Port of Itaqui (in the north) and the Port of Santos (in the southeast) (Brazil, Investment Partnerships Program 2019). The Federal Government plans to significantly increase the share that railway transport constitutes in the next eight years (from 15 per cent to 29 per cent).

Canada

Unconditional NDC target projection: Emissions at least 15 per cent above target

In its NDC, Canada pledged to reduce its GHG emissions by 30 per cent below 2005 levels by 2030. With Royal Assent of the Greenhouse Gas Pollution Pricing Act in December 2018, carbon pricing will be in place across all Canadian provinces and territories by September 2019, except the Province of Alberta, but is facing court challenges from a number of provinces (Climate Action Tracker 2019c). Alberta repealed its carbon tax in May 2019, however the federal carbon price will be applied to that Province in January 2020 (Province of Alberta Queen's Printer 2019; Vigliotti 2019). The adoption of performance standards on coal and gas-fired power stations at the end of 2018 means Canada is on track to meet its 2030 coal phase-out commitment, although it is expected that many coal-fired plants will be replaced with natural gas variants, creating a risk of future stranded assets (Climate Action Tracker 2017; Government of Canada, 2018b; 2018a). The 2019 federal budget included a 300 million Canadian dollar investment in zero-emission vehicles, while the Government has set sales targets of 10 per cent by 2025, 30 per cent by 2030, and 100 per cent by 2040 (Canada, Transport Canada 2019). According to Canada's Greenhouse Gas and Air Pollutant Emissions Projections (2018), when taking into account currently announced federal, provincial and territorial policies and measures, Canada's emissions in 2030 are projected at 592 Mt – or 223 Mt lower than what was projected before the adoption of the Pan-Canadian Framework for Clean Growth and Climate Change.

China

Unconditional NDC target projection: Overachievement of the target by less than 15 per cent

China's NDC targets include capping CO_2 emissions around 2030 and making an effort to cap them earlier, as well as a 20 per cent share of non-fossil fuels in the total primary energy demand (based on the conversion factor of the Chinese National Bureau of Statistics for renewable energy and nuclear power generation). Further targets include reducing the carbon intensity of its GDP by 60 per cent to 65 per cent below 2005 by 2030 and increasing forestry stock by 4.5 billion m^3 by 2030 compared to the 2005 level.

Since 2017, China's National Energy Administration (NEA) has developed a warning system for investment in coal power plants, which evaluates the risks of new coal power projects based on investment returns, electricity demand and environmental concerns. The system rates the feasibility of coal power projects in 38 regions as bad, moderate or good. New coal investment is banned, in principle, in regions with a bad rating. In April 2019, the NEA published the latest risk rating, which reduces the number of regions that ban new coal investment from 24 to 21 (NEA of China 2019). The change may encourage coal power development and slow down power sector decarbonization.

China's renewable energy and new energy vehicle (NEV) has experienced exponential growth in the past decade, in part thanks to generous subsidies. As the costs of the technologies fall and markets mature, China has started to phase down relevant subsidies. The Government suspended the approval of all new subsidized solar PV projects in May 2018 (NEA, National Development and Reform Commission [NDRC]; Ministry of Finance [MOF] of China 2019) and issued new regulations to reduce subsidies for solar and wind projects in 2019 (NDRC of China 2019a; 2019b.). The country also slashed the subsidy standard of 50 per cent for new energy cars in 2019 and plans to stop subsidies by the end of 2020 (He and Cui 2019). In the short-term, the efforts would result in a rush to develop renewable power projects or purchase new energy cars before phase-out of subsidies. In the midterm, utility-scale solar PV and onshore wind power can reach grid-parity by 2021 (Hang 2019; Tu *et al.* 2019). In fact, China has already approved 21 GW of wind and solar projects without subsidy (Hill 2019). The new policy will also accelerate the marketization of the NEV industry in China (Xiao 2019). In summary, the recent subsidy reform is a necessary step for the large-scale adoption of renewable energy and NEV in China.

EU28

Unconditional NDC target projection: Overachievement of the target by less than 15 per cent

The EU has adopted climate legislation to implement its NDC target of a 40 per cent reduction below 1990 levels by 2030. It has reviewed its EU emission trading system and increased its annual reduction of the cap. It has set national emission reduction targets for Member States for the sectors not covered in the EU emissions trading system. It has put in place legislation that ensures accounted LULUCF emissions are not resulting in a decrease of the EU's sink. Combined, these legislations meets the at least

40 per cent greenhouse gas reduction target of the NDC. In recent months, the EU has implemented a number of important accompanying measures that would lead to an overachievement of its NDC target. The adoption of the new renewable energy directive (Directive 2018/2002; RED II) and the new energy efficiency directive (Directive 2018/2002) (European Commission 2018c) with the respective goals of increasing the share of renewables in the energy mix and improving energy efficiency – if effectively implemented – would lead to emissions reductions of at least 45 per cent by 2030 relative to 1990 (European Commission 2018a). These two directives were parts of the package of measures called Clean Energy for all Europeans presented by the European Commission in November 2016. With the adoption of the Electricity Regulation and Electricity Directive by the Council in May 2019, European institutions finalized the work on this package, which also included a directive focusing on energy efficiency in the building sector (adopted in May 2018), and a Governance Regulation which obligates Member States to present National Energy and Climate Plans (NECPs) describing measures they are going to implement to contribute to meeting the EU's energy and climate goals. Collectively, the current draft NECPs are projected to fall short of both renewable and energy efficiency targets (European Commission 2019b). Final NECPs, taking on-board recommendations by the European Commission and featuring greater ambition where necessary, are due by the end of 2019.

Significant progress has also been made in the transport sector in which the adoption of CO_2 emissions standards for passenger cars and vans in December 2018 was followed by standards for new heavy-duty vehicles in early 2019. According to the legislation, average emissions from passenger vehicles sold by each manufacturer in 2030 will have to be 37.5 per cent lower for new cars and 31 per cent lower for new vans compared to 2021 levels (European Council 2019). Emissions from new heavy-duty vehicles should decrease by 15 per cent in the second half of the next decade and by 30 per cent in 2030 and beyond – in both cases in comparison to 2019 (European Commission 2019a). These regulations, however, may need to be strengthened after 2030 if net zero GHG emissions by 2050 as proposed by the European Commission (European Commission 2018a) are to be achieved.

Furthermore, an increasing number of countries are committing to the phase-out of coal-fired power plants; Finland has agreed on a phase-out of coal-fired power plants by 2029 (Europe Beyond Coal 2019) and Germany is discussing a phase-out (a commission advised it to do so by 2038) (Germany, Federal Ministry for Economic Affairs and Energy [BMWi] 2019). Other Member States that committed to, or announced coal phase-outs, include Austria (2025), Denmark (2030), France (2021), Ireland (2025), Italy (2025), the Netherlands (2030), Portugal (2030), Sweden (2022) and the United Kingdom (2025) (Europe Beyond Coal 2019).

India

Unconditional NDC target projection: Overachievement of the target by more than 15 per cent, suggesting a weak target

India's NDC has three numeric targets for 2030: reduce emissions intensity by 33 per cent to 35 per cent from 2005 levels, achieve an installed power capacity of 40 per cent from non-fossil fuel sources and create an additional carbon sink of 2.5–3.0 $GtCO_2e$ from forest and tree cover. India has continued its efforts towards achieving its renewable and intensity targets, though the previous year saw no substantial course change. In 2018, renewable deployment exceeded conventional fuels (Buckley and Shah 2019), though is projected to remain short of the 175 GW target by 2022 (Vembadi, Das and Gambhir 2018; Buckley and Shah 2019). The deployment of renewables has been let down by unclear, inconsistent taxation and import duty norms (Buckley and Garg 2019; Buckley and Shah 2019). Interrelated factors have stymied India's uptake of fossil fuel infrastructure, including a financial crisis that has led multiple coal power plants to be deemed as non-performing or stressed assets (India, Parliamentary Standing Committee on Energy 2018). In addition, the National Clean Air Programme released in 2019 aims to reduce $PM_{2.5}$ and PM_{10} concentrations by 25 per cent to 30 per cent, and provides additional motivation to shut down old coal power plants (India, Ministry of Environment, Forest and Climate Change [MoEFCC] 2019b).

India has simultaneously continued its efforts to broaden energy access. India reported the 100 per cent electrification of households in early 2019 (India, Ministry of Power 2019), with likely implications for the future of India's energy demand. The Kisan Urja Suraksha evam Utthaan Mahabhiyan (KUSUM) scheme launched in early 2019 is aimed at promoting solar energy in rural areas with the target to install 26 GW of solar agricultural pumps by 2022 (India, Cabinet Committee on Economic Affairs 2018). India also released an India Cooling Action Plan in 2019 to provide cooling services while keeping their GWP minimal by reducing energy and refrigerant demand (MoEFCC 2019a).

India has also begun deliberating policies to electrify public and private modes of transport. The second phase of the Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles (FAME) was launched in 2019, aiming to support the uptake of electric two-wheelers, three-wheelers, four-wheelers and buses, with projected cumulative savings of 7.2 $MtCO_2e$ (India, Cabinet on Economic Affairs 2018). India is also deliberating upon targets to ban sales of all fossil fuel powered two-, three- and four-wheeler vehicles in the next decade. India also aims to electrify all its broad gauge railway routes by 2021–2022 (India, Cabinet Committee on Economic Affairs 2018).

Indonesia

Unconditional NDC target projection: Uncertain or insufficient information

Indonesia's NDC sets an unconditional 29 per cent and a conditional 41 per cent (with sufficient international support)

reduction target on the country's GHG emissions below business-as-usual by 2030. The National Energy Policy referred to in Indonesia's NDC aims to increase the share of renewable energy in the total primary energy supply to 23 per cent by 2025 from the current 6.5 per cent (Republic of Indonesia, Ministry of Energy and Mineral Resources [MEMR] 2017), but this target will likely not be met and the country's heavy reliance on coal-fired power will likely continue under current policy measures (Climate Action Tracker 2019e). The new Electricity Supply Business Plan (RUPTL) 2019–2028 adopted in January 2019 (Republic of Indonesia 2019) also envisages the installation of almost 40 GW of fossil-fired power plants, about 27 GW of which being coal-fired, in the next 10 years. It is estimated that this 27 GW of coal-fired power alone would annually emit up to 200 $MtCO_2e$ over the next 40 years, unless they are decommissioned before the end of their lifetime.

In the land-use sector, Presential Instruction No 8 of 2018 (President of the Republic of Indonesia 2018) presents a three-year moratorium on the entire licensing process for palm oil plantations and an order for the relevant central Government ministries and regional governments to conduct a massive review of oil palm licensing data (Mongabay 2018). A recent Presidential Instruction also made the temporary moratorium on forest-clearing permits for logging and plantations issued in 2011 permanent, but the historical development of land-use GHG emissions casts doubt on the effectiveness of these measures (Jong 2019). Although the Global Forest Watch (2018) reported in 2017 that Indonesia was one of the few tropical nations to reduce its deforestation rates in 2017, this was likely due, in part, to the national peat drainage moratorium (Norway, Ministry of Climate and Environment 2016), in effect since 2016.

Japan

Unconditional NDC target projection: Emissions 0–15 per cent above target

Under its NDC, Japan aims to reduce its GHG emissions by 26 per cent by 2030 from 2013 levels. Japan's total GHG emissions seem to have peaked in the fiscal year (FY) of 2013 before decreasing for four consecutive years. In the power sector, decarbonization efforts are being strengthened only incrementally. In March 2019, the Ministry of the Environment (MOE) announced three new actions to accelerate decarbonization progress in the power sector (MOE 2019), among which is stricter enforcement of environmental impact assessments on planned coal-fired power plants. However, the downsides are the overall limited effectiveness of the measures, as the MOE cannot veto the plans, and that coal-fired power plants already under construction will be unaffected by this action.

As for renewables, the Environmental Impact Assessment Act will apply from April 2020 and will also be applicable to large-scale solar PV projects with capacities greater than 40 MW (or greater than 30 MW following a screening process based on the current status of land-use on the project site) (Ministry of Economy, Trade and Industry [METI] 2019b). The Government has also started reviewing the scope of renewable projects to be supported under the feed-in tariff (FIT) scheme, which contributed to the large increase of solar PV capacity in the last years, to control the increasing surcharge (METI 2019c). These new rules are likely to secure proper business disciplines for solar PV in Japan, despite curbing the speed at which large-scale solar projects can be deployed after the full installation of capacity with FIT approval. For wind power, the new law put into effect on 1 April 2019 (METI 2019a) allows offshore wind power developers to occupy a registered area up to 30 years after consultation with relevant ministries and local stakeholders. This will promote the development of offshore wind farms.

For the transport sector, a panel under the METI published an interim report on the long-term strategy for car manufacturing (METI 2018), which establishes a long-term goal to reduce tank-to-wheel CO_2 emissions by 80 per cent below 2010 levels by 2050 for all new vehicles produced by Japanese car manufacturers and by 90 per cent by 2050 for new passenger vehicles. The goal for new passenger vehicles assumes a near 100 per cent share of electrified vehicles (including hybrids, plug-in hybrids, battery electric vehicles and fuel cell electric vehicles). With CEOs of major car manufacturers such as Toyota, Nissan and Honda all being members of the panel, the development of these long-term goals can be considered an important step towards decarbonization of Japan's transport sector.

Mexico

Unconditional NDC target projection: Overachievement of the target by less than 15 per cent

Mexico's NDC makes an unconditional commitment to reduce GHG emissions by 22 per cent below business-as-usual in 2030, implying a net emissions peak from 2026, and a conditional commitment to reduce emissions by 36 per cent below business-as-usual in 2030. Mexico's new Administration has stalled years of progress in the energy sector with decisions that threaten to reverse progress made towards enhanced climate action through, for example, Mexico's General Climate Change law of 2012 (Mexico, Cámara de Diputados del H. Congreso de la Unión 2012) or its Energy Transition law of 2015 (Mexico, Cámara de Diputados del H. Congreso de la Unión 2015). The National Electricity Outlook (PRODESEN) 2019–2033 adopted in June 2019 (Mexico, Ministry of Energy 2019) limits deeper deployment of clean energy (including efficient cogeneration) beyond the 35.1 per cent by 2024 target (24.12 per cent in June 2018) by increasing fossil fuel-fired generation, reducing wind power and not increasing solar power growth rates. Furthermore, the Ministry has cancelled the 2018 long-term power auction and cut-off the transmission lines to evacuate renewable energy. There have been no announcements of further

auctions. Despite the recognition of the importance of reducing GHG emissions and increasing renewable energy deployment, the National Development Plan adopted in June 2019 (Mexico, Diario Oficial de la Federación 2019) adds a new additional refinery with the aim to increase gasoline, diesel and fuel oil production.

After postponing Mexico's 2018 long-term energy auction round – a policy scheme introduced in 2015 after the country's energy reform that aimed to increase its clean energy share – President Lopez Obrador cancelled the fourth auction round in January 2019 Mexico, Centro Nacional de Control de Energía 2018). Although the first three rounds of electricity auctions had led to a substantial amount of new renewable energy projects (Notimex 2019), President Lopez Obrador's plans for the power sector include the modernization of gas and coal-fired power plants previously planned for retirement and the construction of a 700 MW coal-fired plant in the short and midterm (Solís 2018a, 2018b).

President Obrador has also presented a National Refining Plan aimed at "rescuing" Mexico's oil industry and achieving energy independence through the rehabilitation of six oil refineries and the construction of a new one in Dos Bocas, Tabasco, and a plan for constructing a railroad in the Yucatan peninsula (known as the Maya Train project) (Government of Mexico 2019). These three infrastructure projects have faced national and international criticism (see, for example, Gurría (2019)).

Republic of Korea

Unconditional NDC target projection: Emissions at least 15 per cent above target

Dynamic discussions are taking place in the Republic of Korea in relation to the adequacy of its 2030 power sector emissions target. In its NDC, the Republic of Korea has committed to reducing its GHG emissions to 37 per cent below business-as-usual or to 536 $MtCO_2e$ per year by 2030 (UNFCCC 2018), and initially set up a road map in 2016 to achieve this target. However, the plan in the initial road map to procure 96 $MtCO_2e$ per year of international credits was subject to environmental integrity and economic feasibility-related criticism. In July 2018, the road map was amended, stating that 16 $MtCO_2e$ per year will be reduced by international credits rather than 96 $MtCO_2e$ per year (Republic of Korea, Ministry of Environment 2018).

Another important change to the road map was that contemplated emission reductions from the power sector were reduced from 64.5 $MtCO_2e$ per year to 23.7 $MtCO_2e$ per year (Republic of Korea, Ministry of Environment 2018), which is mainly attributable to the Moon Jae-In Administration's nuclear policy, under which 8.8 GW of new nuclear power plant construction projects were cancelled. The amended GHG road map stated that an additional emission reduction requirement of 34.1 $MtCO_2e$ per year may be imposed on the power sector depending on further discussions, which mostly relates to how ambitiously the country will decommission its operational coal power plant fleet by 2030. The additional 34.1 $MtCO_2e$ per year reduction issue has become the centre of national climate and energy policy discussions and was one of most contentious topics when establishing the Third Energy Framework Plan, under which the country aims to increase its renewables share in total electricity generation from 7.6 per cent in 2017 to 35 per cent by 2040 and to phase down coal and nuclear power (KBS 2019).

Air pollution concerns, originating from the South Chungcheong Province, where approximately 18 GW of coal power plants (half of the Republic of Korea's coal power fleet) are located, may expedite the speed of coal power plant retirements and lead to more ambitious reductions from the country's power sector. In early 2019, opposition from this Province led to the suspension of retrofits of 4.5 GW of coal power plants (Chosunilbo 2019; Chung 2019). If the retrofits were implemented, the life period of these power plants would have extended to until around 2040. The Governor of South Chungcheong Province has also committed to decommissioning coal power plants that are older than 25 years, which, if successful, will result in 14 units being decommissioned by 2026 (Powering Past Coal Alliance 2018).

Russia

Unconditional NDC target projection: Overachievement of the target by more than 15 per cent, suggesting a weak target

Russia pledged to limit GHG emissions by 15–25 per cent below 1990 levels by 2020 and by 25–30 per cent below 1990 levels by 2030, and recently announced that it will ratify the Paris Agreement (United Nations 2019). While the ratification date is uncertain, a draft Decree of the President on a new 2030 emission reduction target is to be prepared by December 2019, with a draft implementation plan to achieve the 2030 target expected in the first half of 2020 (UNFCCC 2019b). The Russian Action Plan mandates the drafting of a "low-carbon strategy until 2050" by the end of 2019 (Sauer and Collett-White 2019). However, no mention of the preparation of this draft has yet been made. The fact that only draft documents are expected provides a weak basis for tracking and assessing progress, as they may just contain principles and approaches without concrete mitigation measures and GHG targets. In December 2018, the Government introduced new draft legislation that would establish a cap-and-trade system for major carbon emitters by 2025 (Sauer and Collett-White 2019).

Saudi Arabia

Unconditional NDC target projection: Uncertain or insufficient information

In its NDC, Saudi Arabia commits to reducing emissions by up to 130 $MtCO_2e$ per year below business-as-usual

by 2030 through actions that contribute to economic diversification and adaptation. The country's actions to mitigate climate change are driven by its motive to diversify its economy (Al-Sarihi 2019). In 2016, Saudi Arabia published its Vision 2030, which included a renewable energy target of 9.5 GW by 2023 and a phase-out of fossil fuel subsidies (Kingdom of Saudi Arabia 2016). However, the implementation of this vision has been delayed for both renewable energy and the fossil fuel price reform (Nereim 2017; Krane 2019). Most recently, in March 2018, Saudi Arabia and the SoftBank Group signed a memorandum of understanding to build a 200 GW solar plant, the largest single solar project worldwide, as part of Vision 2030 (Nereim and Cunningham 2018). However, the expected tenders to implement the plan have been delayed since January 2019 (Bellini 2019). Outside the power sector, the Public Investment Fund announced in October 2018 its intention to locate an electric vehicle industry in Saudi Arabia, following an agreement to invest more than US$1 billion in an United States of America-based electric vehicle manufacturer (Torchia *et al.* 2018).

South Africa

Unconditional NDC target projection: Emissions 0–15 per cent above target

In its Cancun Pledge, South Africa aims to reduce its GHG emissions by 34 per cent below business-as-usual in 2020, and commits to achieving a peak, plateau and decline of GHG emissions in its NDC, with emissions peaking between 2020 and 2025, before plateauing at 398–614 $MtCO_2e$ per year between 2025 and 2030.

The South African Government released the long-awaited draft of its Integrated Resource Plan (Republic of South Africa, Department of Energy 2018) in August 2018. The revised plan aims to decommission 35 GW of Eskom's currently operational coal generation capacity (42 GW) by 2050, with 12 GW of this decommissioned by 2030, another 16 GW by 2040, and a further 7 GW by 2050 (Republic of South Africa, Department of Energy 2018). The 5.7 GW of coal capacity currently under construction would be completed and another 1 GW of new coal capacity would be commissioned by 2030. The significant volume of coal capacity to be decommissioned by 2030 and beyond marks a significant shift away from previous planning. The Government has not yet communicated a timeline for the Integrated Resource Plan (IRP) update's final adoption as of September 2019.

South Africa approved a carbon tax in February 2019, which covers fossil fuel combustion emissions, industrial processes and product-use emissions, and fugitive emissions (Reuters 2019). The tax has been implemented since June 2019, but a basic tax-free threshold for around 60 per cent of emissions and additional allowances for specific sectors means that tax exemptions will apply for up to 95 per cent of emissions during the first phase until 2022 (KPMG 2019).

In addition, South Africa released a draft climate change bill in June 2018 for public comment (Republic of South Africa, Department of Environmental Affairs 2018), but the Government has not yet communicated a timeline for the law's final adoption as of July 2019. The draft law aims to establish a Ministerial Committee on Climate Change to oversee and coordinate activities across all sector departments. Under the proposed legislation, the Minister of Environmental Affairs together with the Ministerial Committee on Climate Change would have to set sectoral emission targets for each GHG emitting sector in line with the national emission target every five years.

Turkey

Unconditional NDC target projection: Overachievement of the target by more than 15 per cent, suggesting a weak target

In its Intended Nationally Determined Contribution (INDC), Turkey aims to limit its GHG emissions to 21 per cent below business-as-usual or to 959 $MtCO_2e$ per year in 2030 (excluding LULUCF). Turkey's current emissions are on this trajectory. The energy sector is at the centre of the country's low-carbon transition debate, representing more than 85 per cent of its total GHG emissions in 2017, with 40 per cent of all energy sectors emissions resulting from electricity generation.

At the start of 2018, Turkey put in place an ambitious National Energy Efficiency Action Plan (NEEAP) for the 2017–2023 period, which aims to reduce the its total energy demand (in primary terms) by 14 per cent compared with the 2017 level. The six-year plan includes the six sectors that supply and demand energy, covering a comprehensive list of 55 actions. The renewable energy FIT mechanism that will still be available for new projects until the end of 2020 was successful in raising the wind and solar PV share in total electricity demand to 10 per cent (and around a third of the total demand supplied from renewables). Following the global trend, Turkey is diversifying its policy portfolio. Since 2017, three rounds of auctions have taken place for onshore wind (twice) and solar PV with favourable prices and local content requirements. The Government has indicated that auctions will be the key mechanism for renewable energy investments in the coming decade.

The Government has set an ambitious plan for new coal-fired power plants, with purchase guarantees and subsidies to investors. Among the G20 members, Turkey ranks third for new coal-fired power plant capacity being planned (37 GW), following China and India (as at January 2019). This is twice as much as Turkey's current operational capacity. However, planned capacities are not being constructed due to a lack of financing, with around only 1 GW currently under construction. More than 40 GW in planned coal-fired power plant capacity was cancelled over the 2010–2018 period. Nuclear energy has been on Turkey's agenda as an alternative source for many years. The country's first nuclear power plant is planned to have four 1.2 GW reactors, with the first reactor planned to start operation by 2023.

United States of America

Unconditional NDC target projection: Emissions at least 15 per cent above target

The current NDC target for the United States of America is to reduce emissions by 26–28 per cent from 2005 levels by 2025. However, President Trump's Government is taking actions to move the country's emissions trajectory in the opposite direction, cutting environmental regulations in favour of giving more freedom to industry. The Trump Administration recently issued the final Affordable Clean Energy (ACE) rule, its replacement for the Obama Administration's Clean Power Plan, which was meant to reduce emissions from power plants in order to achieve the country's NDC target. While the Clean Power Plan would have reduced power sector emissions by roughly 32 per cent, the ACE rule is expected to reduce them by roughly 1 per cent (Natural Resources Defense Council [NRDC] 2018).

The Trump Administration has also frozen the vehicle emissions and fuel economy standards for cars and light trucks until 2026, meaning that the average fuel economy will remain at 35 miles per gallon (mpg), rather than rising to 54 mpg. According to analysis by the Rhodium Group, this will increase emissions from the transportation sector by 28–83 $MtCO_2e$ per year by 2030, with the ultimate amount dependent upon the effect of oil prices on consumption (Larsen *et al.* 2019). However, a group of automakers recently struck a deal with the state of California to strengthen standards for gas mileage and emissions from their vehicles (Van Sant 2019).

However, despite the Trump Administration's actions, market trends have resulted in a significant drop in emissions over the past decade. The country's energy-related CO_2 emissions fell by 14 per cent between 2005 and 2017, while the economy grew by 20 per cent (U.S. Energy Information Administration [EIA] 2018). Action at state and local levels has also grown significantly since President Trump's announcement that the United States of America would leave the Paris Agreement. A group of 25 governors representing over half of the country's population and US$11.7 trillion in GDP have joined the U.S. Climate Alliance, a coalition committed to reducing GHG emissions in line with the goals of the Paris Agreement (U.S. Climate Alliance 2019).

2.5 Preparation of long-term strategies and the way forward

Another important ongoing policy process is the preparation of long-term low emissions development strategies under the Paris Agreement. As of October 2019, only seven G20 members (Canada, France, Germany, Japan, Mexico, the United Kingdom and the United States of America) had submitted their strategies to the UNFCCC and another two (the EU28 and South Africa) had published their draft strategies (UNFCCC 2019a). Of the seven long-term strategies submitted by G20 members to the UNFCCC, only Japan committed to achieving long-term net zero GHG emissions as early as possible in the second half of this century, though France and the United Kingdom have passed bills that commit to net zero GHG emissions by 2050. A few other members, including the EU28, are in the process of revising their domestic and international long-term goals. For non-annex I G20 members, there have been some indications to suggest that they would establish long-term strategies that contain timelines for achieving net zero GHG emissions. For comparison, to keep warming below 1.5°C in 2100 with a 66 per cent chance, global total net CO_2 emissions would need to be reduced to zero by around 2050 (IPCC 2018). There is an increasing number of countries that have set or are in the process of setting net zero emissions targets domestically (Energy & Climate Intelligence Unit 2019).

More long-term strategies are expected to be submitted to the UNFCCC in the coming months, which will provide a better understanding of the level of collective long-term ambition and how it will affect the pathways towards achieving the Paris Agreement's long-term temperature goals. It will also be important to scrutinize the consistency between the (revised) NDCs and long-term strategies to ensure that countries' long-term low-carbon development pathways are feasible.

3 The emissions gap

Lead authors:

Joeri Rogelj (Grantham Institute Imperial College London, UK; International Institute for Applied Systems Analysis, Austria), Michel den Elzen (PBL Netherlands Environmental Assessment Agency)

Contributing authors:

Daniel Huppmann (International Institute for Applied Systems Analysis, Austria), Gunnar Luderer (Potsdam Institute for Climate Impact Research, Germany)

3.1 Introduction

This chapter updates the annual assessment of the emissions gap in the year 2030. Consistent with previous reports, the emissions gap in 2030 is defined as the difference between projected emissions under full implementation of the nationally determined contributions (NDCs) and emissions under least-cost pathways that are in line with the Paris Agreement goals of limiting global average temperature increase to well below 2°C and pursuing to limiting it to 1.5°C. The chapter first presents the various scenarios used for the assessment of the emissions gap (section 3.2), that is, reference scenarios, NDC scenarios and scenarios consistent with limiting global warming to a specific temperature limit. The next section updates the 2030 emissions gap (section 3.3). This is followed by a discussion of the temperature implications of the emissions gap (section 3.4) and the potential impact of non-state actions on the gap (section 3.5).

3.2 Scenarios considered for the 2030 gap assessment

This section will provide an update on the scenarios considered for the year-2030 gap assessment which comprise reference scenarios, NDC scenarios and least-cost mitigation scenarios consistent with specific temperature targets.

3.2.1 Reference scenarios and updates

Reference scenarios are used as benchmarks against which progress in emission reductions can be tracked. Two reference scenarios are considered: the 2005 policies scenario and the current policy scenario.

The **2005 policies scenario** projects global greenhouse gas (GHG) emissions assuming no new climate policies are put in place from around 2005 onwards1. For 2019, the data for this scenario are updated and based on projections from six modelling studies that are also used for the current policy scenario projections from the same data source (the CD-LINKS Scenario Database, version 1.0) to maintain consistency (McCollum *et al.* 2018). Data for this scenario was available from the following international modelling groups: International Institute for Applied Systems Analysis (IIASA using the MESSAGE–GLOBIOM model), Joint Research Centre (JRC using the POLES model), National Institute for Environmental Studies (NIES using the Asia-Pacific Integrated [AIM] model), PBL Netherlands Environmental Assessment Agency (PBL using the IMAGE model), Potsdam Institute for Climate Impact Research (PIK using the REMIND–MAgPIE model) and RFF–CMCC European Institute on Economics and the Environment (RFF–CMCC using the WITCH model).

The **current policy scenario** projects GHG emissions assuming all currently adopted and implemented policies (defined as legislative decisions, executive orders, or equivalent) are realized and that no additional measures are undertaken. Updated data from eight modelling groups were available for this scenario. These include updated estimates from four modelling groups also considered in the UNEP Emissions Gap Report 2018 (United Nations Environment Programme [UNEP] 2018): Climate Action Tracker (CAT) (CAT 2019), JRC (Tchung-Ming *et al.* 2018), PBL (CD-LINKS Scenario Database) (McCollum *et al.* 2018), and the International Energy Agency (IEA) (2018). In addition, four new modelling groups (IIASA, NIES, PIK and RFF–CMCC) provided data for this scenario, available in the CD-LINKS Scenario Database (McCollum *et al.* 2018).

1 This scenario is the same as the "no policy scenario" of previous reports.

3.2.2 NDC scenarios and updates

The NDC scenarios estimate the levels of global total GHG emissions that are projected as a result of the implementation of the mitigation actions pledged by countries in their NDCs. In line with previous gap reports, two NDC scenarios are considered: the unconditional and the conditional NDC scenario. The **unconditional NDC scenario** assumes countries only implement the mitigation actions specified in their NDCs that have no conditions attached. Parties that do not have an NDC or solely have a conditional target in their NDC are assumed to follow their current policy scenario. The **conditional NDC scenario** assumes full achievement of Parties' mitigation pledges (both the conditional and unconditional actions listed as part of the mitigation contribution in their NDCs). Parties that do not have conditional mitigation targets in their NDC follow their unconditional target. Appendix A.1 (available online) provides a full overview of the studies considered for the reference and NDC scenarios.

The NDC scenario of the 2019 report is based on updated data from the same data sources as the current policies scenario and is provided by 12 modelling groups. Projected NDC levels for some countries, in particular China and India, depend on recent emission trends or gross domestic product (GDP) growth projections that quickly become outdated. Therefore, studies that were published in 2015, before the adoption of the Paris Agreement, have been omitted from the 2019 update. The emission projections of China and India for the current policies and NDC scenarios have been lowered in most studies that have updated projections of current policies on an annual basis, such as IEA, Climate Action Tracker, PBL and JRC. For China in particular, the projected peak level of CO_2 emissions has also decreased in the most recent studies compared to projections published in 2015. Nevertheless, the impact of excluding studies published before 2015 is small. The projected global emissions levels of the NDC scenarios are very similar to the levels assessed in the 2018 UNEP Emissions Gap Report[2].

3.2.3 Least-cost mitigation scenarios consistent with the Paris Agreement's temperature limits and updates in light of the IPCC Special Report on Global Warming of 1.5°C

Estimates of where GHG emissions should be in the year 2030 in order to be consistent with a least-cost pathway towards limiting global warming to specific temperature limits are calculated from the scenarios that were compiled as part of the mitigation pathway assessment of the Intergovernmental Panel on Climate Change Special Report on Global Warming of 1.5°C (IPCC SR1.5) (Rogelj *et al.* 2018), and are available online (Huppmann *et al.* 2018a; Huppmann *et al.* 2018b). Similar to the UNEP Emissions Gap Report 2018, least-cost mitigation pathways – or pathways that aim at limiting warming to specific temperature limits at the lowest overall cost[3] – are selected and grouped into **three temperature scenario groups** according to their maximum cumulative CO_2 emissions from 2018 onwards. This approach ensures that all scenarios in a specific temperature scenario group result in similar maximum warming and that there is limited overlap between the various groups. Moreover, this approach is consistent with the approach of the IPCC SR1.5 that groups scenarios in different categories based on their maximum temperature outcome (IPCC 2018; Rogelj *et al.* 2018).

Peak warming is achieved around the time of net-zero CO_2 emissions (Ricke and Caldeira 2014; Joos *et al.* 2013; Zickfeld and Herrington 2015) and current technical assessments of mitigation pathways show that some degree of carbon-dioxide removal (CDR) is required to compensate for ongoing emissions in sectors that are hard to decarbonize (IPCC 2018; Rogelj *et al.* 2018). After peak warming, global temperature rise could potentially be slowly reversed through the continued deployment of global CDR to achieve net negative CO_2 emissions (Allen *et al.* 2018; Zickfeld, MacDougall and Matthews 2016; Tokarska and Zickfeld 2015). However, CDR deployment at such scales is associated with important risks, as highlighted in earlier UNEP Emissions Gap Reports (for example, UNEP (2010)) and other assessment (de Coninck *et al.* 2018; Roy *et al.* 2018; Fuss *et al.* 2018).

The three temperature scenario groups describe a range of pathways that keep warming in the range of below 2°C–1.5°C and allow the identification of the consequences of strengthened or weakened action at various degrees of ambition, from limiting warming to roughly around 2°C over potential interpretations of "well below 2°C", to pursuing to limit warming to 1.5°C, and their corresponding emission reductions (see table 3.1). Each scenario considers a least-cost climate change mitigation pathway that starts reductions from 2020. The temperature outcomes of these scenarios are estimated using the climate model set up used in the IPCC Fifth Assessment Report (Meinshausen *et al.* 2009; Meinshausen, Raper and Wigley 2011; Rogelj *et al.* 2014; Clarke *et al.* 2014).

- **Below 2.0°C scenario:** This scenario limits maximum cumulative CO_2 emissions from 2018 until the time net-zero CO_2 emissions are reached

2 Assuming 100-year global warming potential (GWP) values of the IPCC's Fourth Assessment Report (AR4) for both datasets.

3 More specifically, least-cost pathways are calculated with integrated assessment models (that is, models that combine representations of the energy, economic, land and environment systems), and distribute the emission reductions across regions, sectors and gases in such a way that the global discounted reduction costs are minimized over time and the climate target is achieved with varying probability (see also box 3.1 in the UNEP Emissions Gap Report 2017).

(or until 2100 if net-zero is not reached before[4]) to between 900 and 1300 $GtCO_2$, and cumulative 2018–2100 emissions to at most 1200 $GtCO_2$. It is consistent with limiting end-of-century warming to below about 2.0°C with about 66 per cent or greater probability, while limiting peak global warming during the twenty-first century to below 2.0°C with about 66 per cent or greater probability. The median estimate of 2030 GHG emissions for this scenario is 41 $GtCO_2e$, which is consistent with the median 40 $GtCO_2e$ estimated for the "lower 2°C" scenario category of the IPCC SR1.5 (see table 2.4 in (Rogelj *et al.* 2018)).

- **Below 1.8°C scenario:** This scenario limits maximum cumulative CO_2 emissions from 2018 until the time net-zero CO_2 emissions are reached (or until 2100 if net-zero is not reached before) to between 600 and 900 $GtCO_2$, and cumulative 2018-2100 emissions to at most 900 $GtCO_2$. It is consistent with limiting peak and end-of-century warming to below about 1.8°C with about 66 per cent or greater probability. This scenario is included to provide additional, more granular information about how emissions reduction requirements in 2030 change with gradually increasing stringency of global mitigation action.

- **Below 1.5°C in 2100 scenario:** This scenario limits maximum cumulative CO_2 emissions from 2018 until the time net-zero CO_2 emissions are reached (all model realizations in this scenario reach net-zero before 2100) to below 600 $GtCO_2$, and cumulative 2018–2100 emissions to at most 380 $GtCO_2$, when net negative CO_2 emissions in the second half of the century are included. It is consistent with limiting global warming to below 1.5°C in 2100 with about 66 per cent probability, while limiting peak global warming during the twenty-first century to 1.6–1.7°C with about 66 per cent or greater probability. This class of scenarios is consistent with the scenarios in the IPCC 1.5°C Special Report that limit warming to 1.5°C with no or limited overshoot (as explained in box 3.2, UNEP Emissions Gap Report 2018; see also characteristics in table 3.1). The median estimate of 2030 emissions of 25 $GtCO_2e$ is well within the median estimate range of 22–28 $GtCO_2e$ of the IPCC SR1.5 for the 1.5°C with no or limited overshoot (see table 3.1).

Table 3.1 shows the 2030 global GHG emission levels for the three scenarios.

3.3 The 2030 emissions gap

In line with previous reports, the emissions gap for 2030 is defined as the difference between global total GHG emissions from least-cost scenarios that keep global warming to 2°C and 1.5°C with varying levels of likelihood and the estimated global total GHG emissions resulting from a full implementation of the NDCs. To allow for a more nuanced interpretation of the Paris Agreement's temperature targets, this assessment includes a below 1.8°C scenario. This section updates the gap based on estimated levels of GHG emissions in 2030 for the scenarios described in section 3.2. Table 3.1 provides a full overview of 2030 emission levels for the seven scenarios considered in this assessment, as well as the resulting emissions gap. A change compared to 2018 is that all emission projections have been aggregated with the 100-year global warming potential (GWP) values of the IPCC AR4[5], whereas UNEP Emissions Gap Report 2018 used the GWP values of the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC SAR). The difference between SAR and AR4 GWPs leads to a difference in both scenarios for 2°C, 1.8 °C and 1.5°C and current policy and NDC levels (typically 1–2 $GtCO_2e$), so that the effect on the size of the emissions gap will be limited.

Table 3.1 indicates that in the absence of further climate action since 2005 – that is, under a **2005-policies scenario** – the global total GHG emissions in 2030 would be 64 $GtCO_2e$ (range of 60–68 $GtCO_2e$). **Current policies** are estimated to reduce global emissions in 2030 to around 60 $GtCO_2e$, which is 4 $GtCO_2e$ lower compared to the **2005-policies scenario**.

The estimates of global emissions in 2030 under the **current policy scenario** have decreased slightly since 2015, when the UNEP Emissions Gap Report first introduced the current policies emission projection until 2030. The UNEP Emissions Gap Report 2015 estimated global emissions under a **current policy scenario** projection of about 62 $GtCO_2e$[6] (range of 59.5–63.5 $GtCO_2e$) in 2030 (UNEP 2015), which has been lowered to 60 $GtCO_2e$ (range of 58–64 $GtCO_2e$) in 2019, indicating that studies show slight progress of about 2 $GtCO_2e$ (range of 0.5–2 $GtCO_2e$) in policy implementation since the adoption of the Paris Agreement. The emissions projections of the current policies scenario of the Climate Action Tracker and PBL show a similar decrease over time. The **current policy scenario** estimate for 2030 is around 0.5 $GtCO_2e$ lower than the 2018 report estimate, when the implications of switching to the GWP values of the IPCC AR4 are taken into account, which is similar to the updated estimates of individual studies from the Climate Action Tracker and PBL. Overall, this implies that countries are still not on track to deliver their NDCs (see chapter 2 and chapter 4 for a discussion of G20 members'

4 If a scenario does not achieve net-zero CO_2 emissions before 2100 while still holding warming to below a specific temperature threshold, it is assumed that global CO_2 emissions will reach net-zero emissions immediately or shortly after 2100.

5 This change was made to be more in line with the decisions made at COP24 in Katowice, where the Parties agreed on AR5 for reporting reasons. A full switch to AR5 GWP was not yet possible because the literature is not yet up-to-date regarding this decision.

6 The numbers are based on the estimates of UNEP (2015) of 60 $GtCO_2e$ (range of 58–62 $GtCO_2e$), assuming 100-year GWP values of the IPCC SAR. Here, these estimates are converted using 100-year GWP values of the IPCC AR4, leading to an adjustment of 1.5 $GtCO_2e$.

Table 3.1. Global total greenhouse gas emissions in 2030 under different scenarios (median and 10th to 90th percentile range), temperature implications and the resulting emissions gap.

Scenario (rounded to the nearest gigaton)	Number of scenarios in set	Global total emissions in 2030 [$GtCO_2e$]	Estimated temperature outcomes			Closest corresponding IPCC SR1.5 scenario class	Emissions Gap in 2030 [$GtCO_2e$]		
			50% probability	66% probability	90% probability		Below 2.0°C	Below 1.8°C	Below 1.5°C in 2100
2005-policies	6	**64** (60–68)							
Current policy	8	**60** (58–64)					**18** (17–23)	**24** (23–29)	**35** (34–39)
Unconditional NDCs	11	**56** (54–60)					**15** (12–18)	**21** (18–24)	**32** (29–35)
Conditional NDCs	12	**54** (51–56)					**12** (9–14)	**18** (15–21)	**29** (26–31)
Below 2.0°C (66% probability)	29	**41** (39–46)	Peak: 1.7-1.8°C In 2100: 1.6-1.7°C	**Peak: 1.9-2.0°C In 2100: 1.8-1.9°C**	Peak: 2.4-2.6°C In 2100: 2.3-2.5°C	Higher-2°C pathways			
Below 1.8°C (66% probability)	43	**35** (31–41)	Peak: 1.6-1.7°C In 2100: 1.3-1.6°C	**Peak: 1.7-1.8°C In 2100: 1.5-1.7°C**	Peak: 2.1-2.3°C In 2100: 1.9-2.2°C	Lower-2°C pathways			
Below 1.5°C in 2100 and peak below 1.7°C (both with 66% probability)	13	**25** (22–31)	Peak: 1.5-1.6°C In 2100: 1.2-1-3°C	**Peak: 1.6-1.7°C In 2100: 1.4-1.5°C**	Peak: 2.0-2.1°C In 2100: 1.8-1.9°C	1.5°C with no or limited overshoot			

Note: The gap numbers and ranges are calculated based on the original numbers (without rounding), and these may differ from the rounded numbers (third column) in the table. Numbers are rounded to full $GtCO_2e$. GHG emissions have been aggregated with 100-year GWP values of the IPCC AR4 (to be consistent with Table 2.4 of IPCC Special Report on Global Warming of 1.5°C, whereas UNEP Emissions Gap Report 2018 used GWP values of IPCC SAR). The NDC and current policy emission projections are updated from the presented numbers in cross-chapter Box 11 of IPCC Special Report on Global Warming of 1.5°C (Bertoldi *et al.* 2018), with new studies that were published after the literature cut-off date of IPCC. Pathways were grouped into three categories depending on whether their maximum cumulative CO_2 emissions were less than 600, 600–900 or 900–1300 $GtCO_2$, respectively, from 2018 onwards until net-zero CO_2 emissions are reached, or until the end of the century if the net-zero point is not reached before. The estimated temperature outcomes represent estimates of global average surface air temperature (GSAT), most consistent with the impact assessment of the IPCC Fifth Assessment Report. Pathways assume limited action until 2020 and cost-optimal mitigation thereafter. Estimated temperature outcomes are based on the IPCC AR5 method (Meinshausen, Raper and Wigley 2011; Clarke *et al.* 2014).

Box 3.1. The remaining carbon budget as a tool for scenario classification

The IPCC SR1.5 provided an updated assessment of the remaining carbon budget, that is, the total amount of carbon dioxide that can be emitted if global warming is to be kept to a specific level relative to pre-industrial levels (Rogelj *et al.* 2018). Owing to advances and improvements in methods to estimate remaining carbon budgets, the IPCC SR1.5 reported median estimates that were larger than those reported five years earlier by the IPCC Fifth Assessment Report (Stocker *et al.* 2013; IPCC 2014). Despite these larger estimates of the remaining carbon budget by the IPCC, the emission pathways corresponding to the Paris Agreement limits used in the UNEP Emissions Gap Reports did not require a strong adjustment. How can this be the case?

The updates of the remaining carbon budget estimates in the IPCC SR1.5 were based on three main methodological advancements (Rogelj *et al.* 2018; Rogelj *et al.* 2019): (i) accounting for the latest estimates of anthropogenic global warming to date (Allen *et al.* 2018); (ii) a more formal description of the uncertainty in the ratio of global warming projected per cumulative ton of CO_2 (Stocker *et al.* 2013); and (iii) a more precise estimate of the warming due to emissions other than CO_2 at the time of peak warming (Rogelj *et al.* 2018; Huppmann *et al.* 2018a).

However, each of these methodological improvements were to some degree already taken into account in the emission pathways of the UNEP Emissions Gap Reports, which previously used a reduced-complexity climate model set up (Meinshausen *et al.* 2009; Meinshausen, Raper and Wigley 2011; Rogelj *et al.* 2014; Clarke *et al.* 2014). This model set up applied the methodological improvements that formed the basis for updating the IPCC SR1.5 carbon budgets. Specifically, it (i) accounted for recent estimates of warming to date by expressing temperature projections relative to a recent reference period (the 1986–2005 period) (Clarke *et al.* 2014); (ii) had a better coverage of the uncertainty in the ratio of global warming to cumulative CO_2 emissions by using an observationally constrained probabilistic climate model set up (Meinshausen *et al.* 2009); and (iii) used integrated assessment mitigation scenarios with internally consistent evolutions of all GHGs, also at the time of peak warming (Clarke *et al.* 2014). Previous UNEP Emissions Gap Reports were thus based on assumptions regarding temperature projections that were to some degree consistent with the methodological improvements implemented for the SR1.5 remaining carbon budget assessment, explaining why the emission pathways of the UNEP Emissions Gap Reports have not changed so much.

status and progress). Full implementation of the unconditional and conditional NDCs is estimated to reduce global emissions in 2030 by about 4 and 6 $GtCO_2e$, respectively, compared to the **current policy scenario** (table 3.1).

The emissions gap between estimated total global emissions in 2030 under the NDC scenarios and under pathways limiting warming to below 2°C and 1.5°C is illustrated in Figure 3.1. The full implementation of the unconditional NDCs is estimated to result in a gap in 2030 of 15 $GtCO_2e$ (range of 12–18) compared to the below 2°C scenario with a 66 per cent probability that warming stays below 2°C. The emissions gap between unconditional NDCs and below 1.5°C pathways is about 32 $GtCO_2e$ (range of 29–35). Taking into consideration the full implementation of both unconditional and conditional NDCs would reduce this gap by about 3 $GtCO_2e$. The estimates are similar to the gap assessed in the 2018 UNEP Emissions Gap Report. The only change compared to the 2018 report is that the gap between the conditional NDCs and the 2°C scenario is 1 $GtCO_2e$ lower in 2019.

In summary, the updated analysis and review of the progress set against national commitments under the Paris Agreement makes clear that the current pace of national action is insufficient for achieving the Paris Long-term Temperature Goal or even for achieving the emissions reductions implied by the NDC pledges. Increased emissions and lagging action mean that the gap figure for the 2019 report remains very large, and similar to the 2018 report. Translated into climate action, the analysis reconfirms that nations must triple their current efforts, – as reflected in the difference in projected emissions between current policies and conditional NDCs – to limit warming to 2°C and multiply their current efforts by at least five times to align global climate action and emissions with limiting warming close to 1.5°C[7].

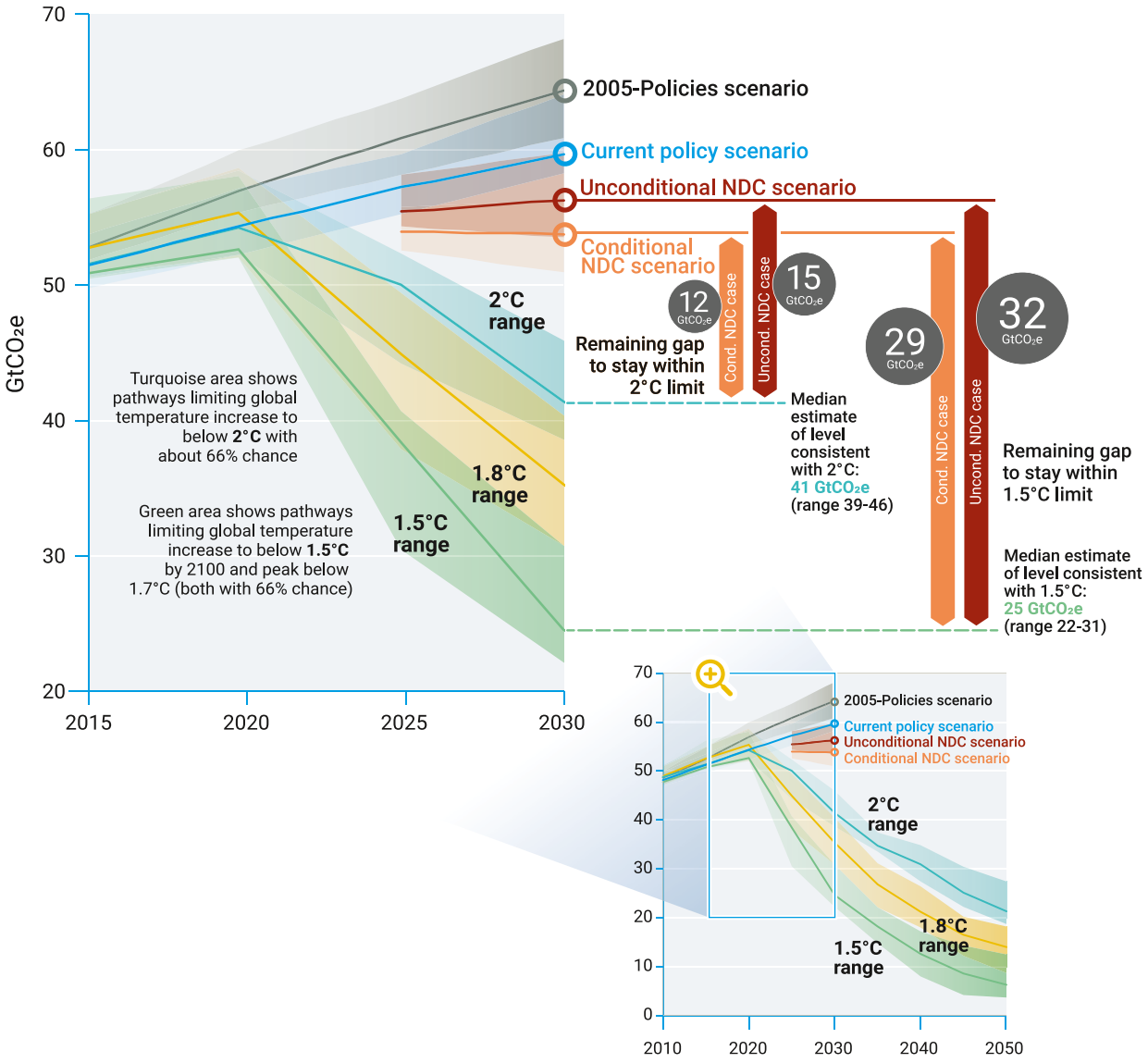
3.4 Implications of the emissions gap

3.4.1 Implications of postponing action

There are several implications of the projected 2030 GHG emissions under the current policies scenario and the

7 This statement is based on the quantitative evidence that conditional NDCs would reduce global GHG emissions relative to projections of current policies by 6 $GtCO_2e$, while the gap between current policies and the 2°C and 1.5°C scenarios amounts to 18 and more than 30 $GtCO_2e$, respectively (see table 3.1). This translates in the efforts that are currently being made to move from current policies to the conditional NDCs having to be multiplied by a factor of three and greater than five for global GHG emissions to be in line with a pathway towards limiting warming to around 2°C and 1.5°C, respectively.

Figure 3.1. Global greenhouse gas emissions under different scenarios and the emissions gap in 2030 (median estimate and 10th to 90th percentile range).



NDC scenarios. The high GHG emissions until 2030 result in a higher reliance on CDR, stronger potential trade-offs with sustainable development goals and lock-in of carbon-intensive infrastructure, which will make subsequent emissions reductions harder and more costly. Section 3.5 of the UNEP Emissions Gap Report 2018 provides an overview of these issues.

The long-term implications and the inadequacy of the current policies and NDCs are also apparent if viewed from a slightly broader perspective and when considering the required global emissions reductions until mid-century. The lower ("zoom-out") part of figure 3.1 indicates how a failure to reduce GHG emissions adequately in the next decade will frustrate and undermine the possibility of achieving the deep emissions reductions that are required by 2050 in order to keep emissions in line with the temperature goal of the Paris Agreement.

The implications of postponing adequate climate action are clear from the past decade of UNEP Emissions Gap Reports. The data underlying the gap assessment indicate that had serious climate action begun in 2010, the emissions reductions required per year to meet the emissions levels in 2030 consistent with the 2°C and 1.5°C scenarios would only have been 0.7 per cent and 3.3 per cent per year on average. However, since this did not happen, the required cuts in emissions are now 2.7 per cent per year from 2020 to year-2030 for the 2°C goal and 7.6 per cent per year on average for the 1.5°C goal.

Box 3.2. Comparing emission estimates across chapters - Part II

Under the current policies scenario used for the assessment of the emissions gap, global GHG emissions in 2018 are estimated to be about 53.2 $GtCO_2e$. This is lower than the 2018 estimate of global GHG emissions of 55.3 $GtCO_2e$ provided in chapter 2 (see also box 2.1). Although this difference is relatively small and well within the uncertainty range surrounding the emissions estimates, it is worth exploring. Both estimates show a similar increase of about 10–15 per cent compared with 2010 levels.

There could be multiple reasons why the median emissions projections of the models are lower than the estimates of the historical emissions database. Some models may be calibrated to an earlier base-year. For example, for 2010, the calibration may be based on other emissions databases (such as IEA or PRIMAP), or the models may not include all emissions sources, or use the latest emissions factors. The six global models used for the current policies scenario of the UNEP Emissions Gap Report show a wide range in global GHG emissions in 2010 of [46;50] $GtCO_2e$, whereas the historical emissions database has an estimate of 50 $GtCO_2e$.

3.4.2 Temperature implications

Emissions until 2030 do not fully determine the warming until the end of the century, but the trend until 2030 can be used to project the warming, assuming this trend would continue until 2100. As in previous UNEP Emissions Gap Reports, this report uses internally consistent long-term emissions projections and relates the GHG emissions in the year 2030 to outcomes over the entire century (Rogelj *et al.* 2016). This approach provides temperature estimates for a wide range of 2030 GHG emissions levels (Jeffery *et al.* 2018) that are consistent with the wider integrated scenario literature.

Assuming that climate action continues consistently throughout the twenty-first century, a continuation of current policies would lead to a global mean temperature rise of 3.5°C by 2100 (range of 3.4–3.9°C, 66 per cent probability). This corresponds roughly to a tripling of the current level of warming as assessed by the IPCC (2018). The current unconditional NDCs as assessed in this report are consistent with limiting warming likely to 3.2°C (range 3.0–3.5°C) by the end of the century (66 per cent probability). These values are reduced by about 0.2°C if both conditional and unconditional NDCs are implemented. It is clear that neither current policies nor NDCs are adequate to limit warming to the temperature limits included in the Paris Agreement.

Temperature implications of the current NDCs can also be looked at from the perspective of the carbon budget that would be emitted until 2030 under the current NDCs. The IPCC SR1.5 reported that for limiting warming to 1.5°C with 50 per cent probability, the remaining carbon budget from 2018 onward amounts to 580 $GtCO_2$. This would be further reduced to 420 $GtCO_2$ for having a 66 per cent probability of success of limiting warming to 1.5°C. Further taking into account reinforcing Earth-system components, such as permafrost thawing, could reduce these estimates by a further 100 $GtCO_2$[8]. Starting from a current level of global CO_2 emissions of 41.6 $GtCO_2$ in 2018 (Le Quéré *et al.* 2018) and assuming a straight trajectory to 2030, the current unconditional NDC scenario implies cumulative emissions of about 510 $GtCO_2$ (range of 495–528 $GtCO_2$) until 2030. Therefore, current unconditional NDCs until 2030 already go beyond the carbon budget limits set for 1.5°C. Together with the knowledge that the current status of policies and measures that are being implemented by countries would lead to even more emissions, this leaves no doubt that the current NDCs are blatantly inadequate to achieve the climate goals of the Paris Agreement.

8 Note that the "below 1.5°C in 2100" scenario category applies a peak carbon budget limit of 600 $GtCO_2$, which in itself is not sufficient to limit warming to 1.5°C with a high likelihood, but it limits peak warming with greater than 66 per cent probability to no more than 1.7°C (see table 3.1). In addition, the "below 1.5°C in 2100" scenario category applies an end-of-century carbon budget limit of 380 $GtCO_2$ to limit warming to 1.5°C with a high likelihood. This reflects the 420 $GtCO_2$ remaining carbon budget for limiting warming to 1.5°C with 66 per cent probability, which is further reduced by specific Earth system feedbacks. A value of about 40 $GtCO_2$ is applied for this correction because the stringency of these scenarios suggest a lower impact of these processes than the 100 $GtCO_2$ that was assessed for warming up to 2°C.

4 Bridging the gap: Enhancing mitigation ambition and action at G20 level and globally

Lead authors:

Niklas Höhne (NewClimate Institute, Germany), Taryn Fransen (World Resources Institute, USA), Frederic Hans (NewClimate Institute, Germany)

Contributing authors:

Ankit Bhardwaj (Centre for Policy Research, India), Gabriel Blanco (National University of the Center of the Buenos Aires Province, Argentina), Jesse Burton (University of Cape Town, South Africa), Michel den Elzen (PBL Netherlands Environmental Assessment Agency, the Netherlands), Markus Hagemann (NewClimate Institute, Germany), Christopher Henderson (World Resources Institute, USA), Maria Daniela Keesler (National University of the Center of the Buenos Aires Province, Argentina), Jiang Kejun (Energy Research Institute (ERI), National Development and Reform Commission, China), Akihisa Kuriyama (Institute for Global Environmental Strategies (IGES), Japan), Fu Sha (National Centre for ClimateChange Strategy, China), Ranping Song (World Resources Institute, China), Kentaro Tamura (IGES, Japan), Jorge Villarreal (Iniciativa Climática de México, Mexico), William Wills (EOS Estratégia e Sustentabilidade, Brazil).

4.1 Introduction

In the lead-up to the 2019 Climate Action Summit, United Nations Secretary-General António Guterres called on leaders to "announce the plans that they will set next year to reduce greenhouse gas emissions for 2030 and to achieve net zero emissions by 2050" (Farand 2019). The Secretary-General's message echoed the growing popular movement for transformative, ambitious climate action.

The focus on ambition and action is well founded, as illustrated by the gap assessment in Chapter 3. This chapter provides a comprehensive overview of recent ambitious climate actions by national and subnational governments as well as non-state actors, and a detailed overview of policy progress and opportunities for enhanced mitigation ambition for selected G20 members. The objective is to inform the preparation of new and updated nationally determined contributions (NDCs) that countries are requested to submit by 2020. The chapter addresses the following questions:

- How has the global situation changed since the Paris Agreement was adopted and how does this affect opportunities to increase ambition?
- How many and what type of ambitious climate commitments have been adopted by national governments, as well as by cities, states, regions, companies and investors to date?
- Among selected G20 members, what progress has been made recently towards ambitious climate action and what are the key opportunities for additional action?

The primary focus of this chapter is on ambitious climate targets and actions, which are defined as those that unambiguously contribute towards the transformations required to align global greenhouse gas (GHG) emissions pathways with the Paris Agreement goals. Section 4.2 summarizes the global opportunity to enhance ambition and action and provides an overview of the status of ambitious climate mitigation commitments made by G20 members as well as countries and non-state actors globally.

As G20 members account for 78 per cent of global GHG emissions, they largely determine global emission trends and the extent to which the 2030 emissions gap will be closed. This chapter therefore also pays particular attention to G20 members, with section 4.3 focusing on progress and opportunities for enhancing mitigation ambition of nine selected G20 members: Argentina, Brazil, China, the European Union, India, Japan, Mexico, South Africa and the United States of America, which represented around 56 per cent of global GHG emissions in 2017.[1] The selection of the G20 members was based entirely on the availability of expertise in the author team. Supplementing this chapter, annex B provides a detailed overview of the status of ambitious climate mitigation commitments made by G20 members as

1 Using the latest inventory data for all G20 members in the Electronic Data Gathering, Analysis, and Retrieval (EDGAR) (Olivier and Peters 2018) and latest reported national inventory data for each country for LULUCF emissions.

well as countries and non-state actors globally, while annex C provides a detailed update of recent policy developments of the nine selected G20 members, considering ambitious climate actions, as well as actions that are incremental. Both annexes are available online.

4.2 The global opportunity to enhance ambition and action

4.2.1 The scale and type of transformation needed to enhance climate ambition and action are clear

The Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C (Intergovernmental Panel on Climate Change [IPCC] 2018) concluded that limiting the temperature increase to 1.5°C with no or limited overshoot would mean reducing global CO_2 emissions by about 45 per cent from 2010 levels by 2030 and reaching net zero around 2050. To align with the 2°C limit, global CO_2 emissions would need to decline by about 25 per cent from 2010 levels by 2030 and reach net zero around 2070.

Under the Paris Agreement, countries are invited to submit long-term low GHG emission development strategies by 2020 and are requested to submit updated or new NDCs also by 2020. Considering the update of NDCs in the context of the development of long-term mitigation strategies is an important means to ensure consistency between short-term mitigation policies and targets and long-term goals. The IPCC Special Report on Global Warming of 1.5°C provides clear guidance on the economy-wide and sector transformations that are needed to limit the temperature increase to 1.5°C by the end of the century (see also chapter 5).

Although the time frame for global emission reductions consistent with the 2°C limit is slightly longer, the major long-term sectoral transformations needed to reach net zero GHG emissions globally are essentially the same and can be summarized under the following headings:

- Full decarbonization of the energy sector, based on renewable energy and electrification across sectors – this includes phasing out coal-fired power plants.
- Decarbonization of the transport sector in parallel with modal shifts to public transportation, cycling and walking.
- Shifts in industry processes towards electricity and zero carbon and substitution of carbon-intensive products.
- Decarbonization of the building sector, including electrification and greater efficiency.
- Enhanced agricultural management as well as demand-side measures such as dietary shifts to more sustainable, plant-based diets and measures to reduce food waste.
- Zero net deforestation and the adoption of policies to conserve and restore land carbon stocks and protect natural ecosystems, aiming for significant net CO_2 uptake in this sector (IPCC 2018; UNEP 2017).

Transformations in these areas will require major shifts in investment patterns and financial flows, as well as several sectoral and economy-wide policy targets. The ambitious climate targets considered in section 4.2.3 are based on these overall areas of transformation and important sub-targets. A full overview is provided in annex B.

4.2.2 Drivers of ambition have evolved since the Paris Agreement

Compared with the run-up to the Paris Agreement in 2015, when countries prepared their intended NDCs, many drivers of climate action have changed, with several options for ambitious climate action becoming less costly, more numerous and better understood. Changes within three main categories in particular could facilitate greater NDC ambition today (UNEP 2018) including climate change. Countries will meet again at the United Nations Framework Convention on Climate Change (UNFCCC). First, technological and economic developments present opportunities to decarbonize the economy, especially the energy sector, at a cost that is lower than ever. Second, the synergies between climate action and economic growth and development objectives, including options for addressing distributional impacts, are better understood. Finally, policy momentum across various levels of government, as well as a surge in climate action commitments by non-state actors, is creating opportunities for countries to enhance the ambition of their NDCs.

The cost of renewable energy is declining more rapidly than was predicted just a few years ago. Renewables are currently the cheapest source of new power generation in most of the world, with the global weighted average purchase or auction price for new utility-scale solar power photovoltaic (PV) systems and utility-scale onshore wind turbines projected to compete with the marginal operating cost of existing coal plants by next year (International Renewable Energy Agency [IRENA] 2019. See also Chapter 6). These trends are increasingly manifesting in a decline in coal plant construction, including the cancellation of planned plants, as well as the early retirement of existing plants (Jewell *et al.* 2019; Smouse *et al.* 2018). Moreover, real-life cost declines are outpacing projections. The 2019 costs of onshore wind and solar PV power are 8 and 13 per cent lower respectively than IRENA predictions from just one year ago in 2018 (IRENA 2019). These cost declines, along with those of battery storage, are opening possibilities for utility-scale solar power.

Although technological progress has been uneven across sectors, with the industry and buildings sectors in particular lagging behind (International Energy Agency [IEA] 2019), the

benefits extend beyond power generation. For example, as a result of falling battery costs, predictions forecast that electric vehicles will achieve price parity with internal combustion engine vehicles by the mid-2020s and lead global sales between 2035 and 2040 (Bloomberg NEF 2018).

Aside from advancements in technology, a growing body of research has documented that ambitious climate action, economic growth and sustainable development can go hand-in-hand when well managed. Analysis by the Global Commission on the Economy and Climate estimates that ambitious climate action could generate US$26 trillion in economic benefits between now and 2030 and create 65 million jobs by 2030, while avoiding 700,000 premature deaths from air pollution (The New Climate Economy 2018). Similarly, the IPCC (2018) found that, if managed responsibly, most mitigation options consistent with limiting warming to 1.5°C could have strong synergies with the Sustainable Development Goals (SDGs), especially those related to health, clean energy, cities and communities, responsible consumption and production, and oceans (IPCC 2018. See also chapter 5).

Momentum at all levels of government and parts of the business sector increases the potential to reflect greater ambition in the NDCs. At the subnational level, for example, over 70 large cities housing 425 million people have committed to go carbon-neutral by 2050 or sooner (see table B-1). At the national level, 13 countries have communicated long-term, low GHG emissions development strategies to the UNFCCC (UNFCCC 2019), with many more under development or developed at the national level but not communicated internationally (WRI 2019). At the international level, the Kigali Amendment to the Montreal Protocol outlines phase-down schedules for production and consumption of hydrofluorocarbons (HFCs). Businesses are increasingly moving towards zero emissions, 100 per cent renewables and 100 per cent emission-free transport (see annex B).

Taken together, cost-competitive technologies, potential synergies with development and economic growth, and strong action from the subnational to international levels provide a strong basis for more ambitious NDCs by 2020.

4.2.3 An increasing number of countries and regions are adopting ambitious goals in line with the transformation needed, but the scale and pace are far from sufficient

Several national and subnational governments and non-state actors have embarked on ambitious climate action in different policy areas that can help initiate the transformational change required to meet the long-term goals of the Paris Agreement. Although recent developments send promising signals, the adoption of ambitious climate targets is far from the scale and rate urgently required.

This section presents an overview of the extent to which G20 members, as well as and countries and regions worldwide, have committed or are in the process of committing to ambitious climate targets and actions. These targets and actions are defined as unambiguously supporting a move towards the major long-term sectoral transformations required to meet the well-below 2°C and 1.5°C temperature limits of the Paris Agreement, as outlined in section 4.2.1. Expanding on the key types of policy targets and actions that would support such major transformations, this section provides an overview of the status of commitments to the following ambitious climate targets organized in six main categories (table 4.1). A detailed overview of commitments made as of October 2019 for the above targets by individual countries, regions, businesses and investors is provided in annex B.

It should be noted that the overview of targets and commitments provided in this section and in the annex is not exhaustive. Rather, it builds on a broad range of literature to identify ambitious climate action in the different categories (Kuramochi *et al.* 2018), but given the scope of existing policies and rapid changes in policymaking, the overview may not be completely up-to-date. The list of targets is also incomplete. Notably, it is beyond the scope of this chapter to provide an overview of ambitious climate targets and commitments for agriculture. Finally, no attempt has been made to assess whether individual commitments are aligned with global least cost-effective emissions pathways to the 1.5°C or 2°C targets. Commitments differ in various respects, including the extent to which they are legally binding, the percentages and target years adopted, whether they refer to GHG or CO_2 emissions and whether they are net targets.[2] These specifications are important for a detailed picture of the individual commitments and are provided in annex B.

Ambitious climate targets and actions adopted by countries and regions to date are prime examples of climate action that others can follow. Dynamics to adopt legally binding targets differ between target categories and sectors. Most of the recent increase in national and subnational commitments is related to the adoption of economy-wide zero emission targets by 2050 or sooner (see figure 4.1), 100 per cent renewable energy or electricity targets (see figure 4.2) and a 100 per cent share of new zero-emission motorbikes, cars and/or buses (see figure 4.3). To date, countries, regions and subnational actors have mostly refrained from adopting legally binding ambitious targets in other sectors, such as industry, buildings or heavy transport, except for a few first movers.

Overall, the number of countries and states that are committing to zero emission targets is increasing fast, though it is still far from the scale and pace required, as

2 For this reason, reference is made to 'zero emissions targets' and the reader is referred to annex B, table B-1 for further detail.

Table 4.1. Overview of the number of ambitious climate actions and targets by countries, regions, cities and businesses

Overarching economy-wide climate actions	Countries	Regions	Cities	Businesses
Achieve zero emissions by year x	**71**	**11**	**>100**	**>500**
Implement ambitious comprehensive CO_2 pricing in all sectors by year x	(32 but not comprehensive)	(25 but not comprehensive)		
Phase out all fossil-fuel subsidies by year x	(Decision by G20 in 2009 yet to be implemented)			
Make all finance flows consistent with the Paris Agreement goals by year x	(>1 initial steps)			**>10**
Electricity production				
Reach 100 per cent renewable electricity or 100 per cent carbon-free electricity by year x	**53**	**33**	**>120**	**>180**
Phase out coal-fired power plants by year x with just a transition plan	**13**	**16**	**6**	**28**
Stop financing and insuring coal-fired power plants elsewhere as of year x	**-**			**>20**
Other energy industry				
Stop new fossil-fuel explorations and production as of year x	**6**			**>5**
Commit to zero fugitive emissions target for year x	(32 support zero routine flaring)			**>14**
Industry				
Ensure all new installations are low- carbon/ zero-emission and maximize material efficiency as of year x	-			**>3**
Implement ambitious carbon pricing for industry by year x	**1**	-		
Transport				
Shift to x per cent public transport by year x	**4**	-	**>5**	
Shift to 100 per cent share of new zero-emission motorbikes, cars and/or buses as of year x	**21**	**5**	**>52**	**>50**
Shift to 100 per cent carbon-free heavy goods transport and ships as of year x	-	-		**>10**
Shift to 100 per cent carbon-free aviation as of year x	(1 short haul)	(1 domestic)		-
Buildings				
Shift to 100 per cent (near-) zero energy buildings for new buildings as of year x	**3**	**7**	**>23**	**>23**
Fully decarbonize the building sector by year x	**1**	**6**	**>23**	**>23**
Phase out fossil fuels (for example, gas) for residential heating by year x	**1**	-	**>3**	
Increase the rate of zero-energy renovations to x per cent per year	(1 public building)	-		
Agriculture and forestry				
Zero net deforestation by year x	**>67**	**21**		**>12**

Note: Greyed cells indicate that no (relevant) data is available. For full details, see annex B. Given the scope of existing policies and rapid change in policymaking, the table makes no claim to be exhaustive.

Figure 4.1. Overview of ambitious overarching economy-wide climate actions and targets by G20 members, countries and regions (for full details, see annex B)

OVERARCHING

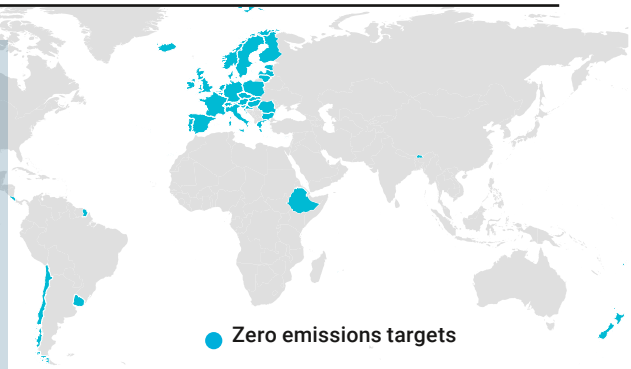
An increasing number of countries and regions are commiting to zero carbon dioxide or greenhouse gas emission targets, but not at the scale and pace required. Other economy-wide climate action such as completely phasing out fossil fuel subsidies, introducing comprehensive and ambitious carbon pricing and making all finance flows consistent with the Paris Agreement remains inadequate.

Target categories	G20 countries	Country level	Regional level
Zero emissions by year x	**2 G20** members (France, UK) have passed legislation **3 G20** members (EU and Germany and Italy as part of EU[1]) currently in process of passing legislation **15 G20** members have no binding (net-) zero-emission targets	71 countries	33 regions
Ambitious comprehensive CO_2 pricing in all sectors by year x [2]	**No G20** member has implemented ambitious comprehensive CO_2 pricing in all sectors, but 9 G20 members have implemented carbon pricing as ETS or carbon tax with partial coverage and/or lower CO_2 prices (as at August 2019)	No country ✖	No regions ✖
Phase out all fossil fuel subsidies by year x	**No G20** member has existing reform plans to fully phase out all fossil fuel subsidies, but the G20 took a decision in 2009 to gradually phase out fossil fuel subsides with an annual peer-review among G20 members	No country ✖	No regions ✖
Make all finance flows consistent with the Paris Agreement goals by year x *	**No G20** member has made all finance flows fully aligned with the Paris Agreement goals, but the UK has published a Green Finance Strategy in 2019 as an example of intermediate action	No country ✖	No regions ✖

* Non-state actor example

10 Multilateral Development Banks (MDBs) are currently working towards aligning their financing activities with the Paris Agreement goals. The MDBs will develop relevant methods and tools with the objective of presenting a joint Paris alignment approach and individual MDB progress towards alignment at COP 25 in 2019.

More information:
http://pubdocs.worldbank.org/en/784141543806348331/Joint-Declaration-MDBs-Alignment-Approach-to-Paris-Agreement-COP24-Final.pdf



The zero emissions targets include legally binding targets, legally binding targets that are currently under consideration, and non-legally binding targets.

Note: [1] Italy is not currently pursuing a process to pass national legislation on a zero-emissions target, but will be covered under the European Union target, if adopted.

[2] The Report of the High-Level Commission on Carbon Prices of 2018 recommends an average economy-wide price of at least US$40–80/t$CO_2$ by 2020 and US$50–100/t$CO_2$ by 2030 to close the emissions gap in order to meet the 2°C target (High-Level Commission on Carbon Prices 2017; UNEP 2018). For this reason, economy-wide carbon prices would need to be higher in the respective years to close the emissions gap in order to meet the Paris Agreement's temperature goal of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels".

illustrated in figure 4.1. To date, 71 countries and 11 regions, accounting for about 15 per cent of global GHG emissions in total[3], have long-term objectives to achieve net-zero emissions, differing in scope, timing and the degree to which they are legally binding. Before the 2019 Climate Action Summit, the number of countries and states committing to zero emission targets was 21 and 8 respectively. Five G20 members have committed to long-term net-zero emissions targets, of which three (the European Union, and Germany and Italy, as part of the European Union) are currently in the process of passing legislation, with two G20 members (France and the United Kingdom) having recently passed legislation. The remaining 15 G20 members have not yet committed to net-zero emission targets.

Economy-wide climate action remains extremely limited in other areas, such as a complete phase-out of fossil-fuel subsidies, comprehensive and ambitious carbon pricing and making finance flows consistent with the Paris Agreement. In 2009, the G20 members adopted a decision to gradually phase out fossil-fuel subsidies, though no country has yet committed to fully phasing these out by a specific year. Similarly, while carbon pricing is expanding, no country has established a comprehensive and ambitious system for this. At present, carbon tax and emissions trading system initiatives at the national and regional levels represent about 20 per cent of global GHG emissions (World Bank 2019). However, only 10 per cent of global emissions from fossil fuels are estimated to be priced at a level consistent with limiting global warming to 2°C (UNEP 2018). Furthermore, no country has explicitly committed to making their finance flows consistent with the Paris Agreement, though several multilateral development banks are currently working towards aligning their financing activities with the Paris Agreement goals (World Bank 2018).

In terms of electricity production (figure 4.2), 53 countries have committed or are in the process of committing to a 100 per cent renewables target. The number of countries increased from 10 countries before the 2019 Climate Action Summit. However, these countries accounted for less than 1 per cent of global CO_2 emissions from electricity generation in 2016.[4] Five G20 members have also committed to long-term net-zero emissions targets and, in turn, to fully decarbonizing their electricity sectors. In addition, 33 states and regions, including California (by 2045), and accounting for around 1 per cent of global from electricity generation[5], as well as an increasing number of cities and companies, have committed to 100 per cent renewable electricity targets.

The 13 countries that have currently committed or are in the process of committing to a full phase-out of coal accounted for around 5 per cent of global CO_2 emissions from coal-based electricity generation in 2016.[6] Five G20 members are among these 13 countries: Canada, France and Italy have already passed legislation, while Germany and the United Kingdom are in the process of passing legislation. A few non-state actors show high ambition, including 22 banks that have stopped direct financing to new coal mine projects and 23 banks that have stopped direct financing to new coal plant projects worldwide.

An increasing number of countries, states and cities are pledging to phase out combustion engines for vehicles and initiate substantial modal shifts towards public transport, though to date, no such commitments have been made for aviation, shipping and freight transport (figure 4.3). However, there are several interesting examples of non-state actors committing to ambitious climate action for these transport modes, as the figure shows. For example, Norway is aiming to make domestic flights carbon-free by 2040 and several companies are working on zero-emission tanker and port infrastructure.

At present, countries and states are largely refraining from ambitious target-setting in the heavy and extractive industry sector (see annex B). Six countries, including one G20 member (France), are currently committed to stopping new fossil-fuel explorations and production. In addition, a few European (re-) insurance companies have recently implemented policies to stop investments, insurance cover and underwriting for new and ongoing fossil-fuel projects. No countries have committed to zero fugitive emissions targets or to ensuring that all new installations are low-carbon or zero emissions and maximize material efficiency. Only Sweden has set a target for ambitious carbon pricing in the industry sector. Some major steel and cement producers have recently pledged to zero emissions by 2050 for their operations. Such commitments and technology road maps could serve as a starting point to define targets in the entire industry sector, following the frontrunners.

The buildings sector shows only scattered policy action at high levels of mitigation ambition, mainly centred on policymaking in the European Union (see annex B). In addition, six states and more than 23 cities have recently committed to zero targets for the buildings sector as part of the World Green Building Council's Net Zero Carbon Buildings Commitment by 2050. In general, there is a lack of targets for phasing out fossil fuels in heating, zero emissions in the sector and deep retrofits of existing buildings.

3 The zero emission targets considered cover legally binding, legally binding but under consideration, and non-legally binding pledges and participation in respective alliances. The share of these countries has been calculated on latest available EDGAR data and FAO data for LULUCF emissions (FAOSTAT 2018; Olivier and Peters 2018). For regions, their self-reported were used.

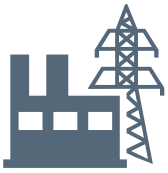
4 The share of these countries has been calculated on emissions data for CO_2 emission from electricity generation provided by IEA's CO_2 emission form fuel combustion dataset (IEA 2018).

5 The share of these regions has been calculated based on self-reported values.

6 The share of these countries has been calculated on emissions data for CO_2 emission from coal-based electricity generation provided by IEA's CO_2 emission from fuel combustion dataset (IEA 2018).

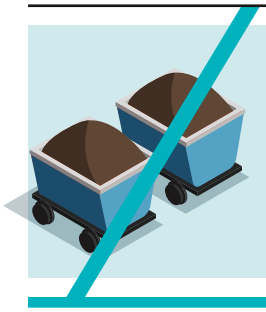
Figure 4.2. Overview of climate actions and targets in the electricity generation sector by G20 members, countries and regions (for full details, see annex B)

ELECTRICITY PRODUCTION



Several countries and regions have communicated 100% renewable electricity targets to fully decarbonize their electricity supply sector. Several are phasing out coal-fired power plants, but these are predominantly countries with already low shares of coal.

Target categories	G20 countries	Country level	Regional level
100% renewable electricity or 100% carbon free electricity by year x	**No G20** member has committed to a 100% renewable electricity or 100% carbon-free electricity target, but some regions within G20 members such as California (by 2045) or Fukushima (by 2040) have done so.	**53 countries**	**22 regions**
Phase out coal-fired power plants by year x with just transition plan	**3 G20** members (Canada, France, Italy) have passed legislation **2 G20** members (Germany, UK) currently in process of passing legislation **15 G20** members have no binding phase-out plan, but some have initiated action to limit coal use (e.g. China and India)	**13 countries**	**16 regions**
Stop financing and insuring of coal-fired power plants elsewhere as of year x *	**No G20** member with legally binding legislation to fully stop financing and insuring of coal-fired power plants elsewhere	**No country** ✖	**No regions** ✖



* Non-state actor example

22 banks have stopped providing direct financing to new coal mine projects worldwide and 23 banks have stopped directly financing new coal plant projects worldwide as at August 2019. Some more banks and (national) development banks are currently in the process of making such commitments.

More information: https://www.banktrack.org/page/list_of_banks_which_have_ended_direct_finance_for_new_coal_minesplants#_

Figure 4.3. Overview of ambitious overarching economy-wide climate actions and targets by G20 members, countries and regions (for full details, see annex B)

TRANSPORT

While an increasing number of countries, regions, and cities pledge to phase out combustion engines and initiate substantial modal shifts towards public transport, no such commitments have been made for aviation, shipping, and freight transport to date.

Target categories	G20 countries	Country level	Regional level
100% share of new zero-emission motorbikes, cars and/or buses as of year x	**5 G20** members (Canada, France, Japan, Mexico, UK) have announced target **2 G20** members (India, Indonesia) have announced target but confirmation is pending **13 G20** members have not announced target for 100% new zero-emission motorbikes, cars and/or buses	21 countries	5 regions
Shift to x% public transport by year x *	**3 G20** members (China, India, Indonesia) with distinct modal shift targets No conclusion possible for all other G20 members	4 countries	No regions
100% carbon-free heavy transport and ships as of year x **	**No G20** member with legally binding target for 100% carbon-free heavy transport and ships	No country	No regions
100% carbon-free aviation as of year x ***	**No G20** member with legally binding target for 100% carbon free aviation	No country	No regions

* Non-state actor example

52 cities have targets for 100% electric cars and/or busses, e.g. Shenzen has already electrified all busses and taxis, Paris aims for 100% fossil free cars and busses in the city by 2025. 49 companies have pledged to accelerate their transition to electric vehicles under the EV100 initiative.

More information: https://www.theguardian.com/cities/2018/dec/12/silence-shenzhen-world-first-electric-bus-fleet
https://www.theclimategroup.org/ev100-members

** Non-state actor example

Several companies have recently announced their plans to develop zero emission container ships, for example by entirely powering tankers by hydrogen produced from renewable energy sources. For example, Maersk, the world's largest container shipping company, has committed to making carbon-neutral vessels commercially viable by 2030 by using energy sources such as biofuels and will cut its net carbon emissions to zero by 2050.

More information: https://www.maersk.com/news/articles/2019/06/26/towards-a-zero-carbon-future

*** Non-state actor example

Norway and Scotland both aim to decarbonize their domestic aviation sector by 2040. Avinor, Norway's airport operator, has announced a switch to electric air transport for all domestic flights as well as those to neighbouring Scandinavian capitals. Scotland plans to becoming the world's first net-zero aviation region by 2040, with trials of low or zero emission flights to begin in 2021.

More information: http://www.airport-business.com/2019/06/avinor-domestic-air-transport-norway-electrified-2040/
https://www.bbc.com/news/uk-scotland-scotland-politics-49556793?utm_source=CP+Daily&utm_campaign=66d62ab006-CPdaily03092019&utm_medium=email&utm_term=0_a9d8834f72-66d62ab006-110247033

Many countries, including most G20 members, have committed to zero net deforestation targets in the last decades (see annex B), though these commitments are often not supported by action on the ground. Countries, states, business and investors urgently need to ensure that they implement their various commitments, including those under the New York Declaration on Forests, the World Wide Fund for Nature's (WWF) call for zero net deforestation by 2020 and the Soft Commodities Compact.

To summarize, G20 members urgently need to step up their commitments on ambitious climate action. As this section shows, there are many opportunities to adopt economy-wide and sector-specific climate action targets as called for by the United Nations Climate Summit in September 2019, and to reflect such targets in the upcoming ambition-raising cycle and submission of long-term strategies under the Paris Agreement by 2020.

The G20 members could follow other national and subnational frontrunners driving ambitious climate action in several areas. Only a few G20 members, including France and the United Kingdom, have recently adopted legally binding legislation in multiple sectors, such as energy, transport and buildings, in addition to an economy-wide net-zero emissions target by 2050. The national and subnational actors already committed to ambitious climate action should inform policymakers in G20 member nations to accelerate their target-setting in different sectors of the economy. This is particularly true for sectors that are difficult to decarbonize, where subnational actors are showing promising frontrunner action aimed at long-term decarbonization in line with the Paris Agreement.

4.3 Opportunities to enhance ambition in selected G20 members

This section provides a summary of country-specific opportunities for enhanced climate ambition and action of nine selected G20 members: Argentina, Brazil, China, the European Union, India, Japan, Mexico, South Africa and the United States of America. The selection of G20 members is based entirely on the availability of data and expertise of the author team. The country-specific opportunities represent possible next steps in the policymaking process based on the current situation. The list of actions is not exhaustive and other actions, including those identified in the previous section and in annex B, would also need to be implemented to achieve global emission reductions at the scale required to maintain progress towards achieving the targets set out in the Paris Agreement.

Several steps were followed to identify the opportunities. First, an overview of the main policies affecting GHG emissions was generated for each country. Annex C, available online, provides a detailed update for each G20 member covered in this chapter. To the extent possible,

Table 4.2. Selected current opportunities to enhance ambition in seven G20 members in line with ambitious climate actions and targets as identified in annex B. For details, see annex C.

Argentina
• Refrain from extracting new, alternative fossil-fuel resources • Reallocate fossil-fuel subsidies to support distributed renewable electricity-generation • Shift towards widespread use of public transport in large metropolitan areas • Redirect subsidies granted to companies for the extraction of alternative fossil fuels to building-sector measures
Brazil
• Commit to the full decarbonization of the energy supply by 2050 • Develop a national strategy for ambitious electric vehicle (EV) uptake aimed at complementing biofuels and at 100 per cent CO_2-free new vehicles • Promote the 'urban agenda' by increasing the use of public transport and other low-carbon alternatives
China
• Ban all new coal-fired power plants • Continue governmental support for renewables, taking into account cost reductions and accelerate development towards a 100 per cent carbon-free electricity system • Further support the shift towards public modes of transport • Support the uptake of electric mobility, aiming at 100 per cent CO_2-free new vehicles • Promote near-zero emission building development and integrate it into Government planning

European Union[8]

- Adopt an EU regulation to refrain from investment in fossil-fuel infrastructure, including new natural gas pipelines
- Define a clear endpoint for the EU emissions trading system (ETS) in the form of a cap that must lead to zero emissions
- Adjust the framework and policies to enable 100-per cent carbon-free electricity supply by between 2040 and 2050
- Step up efforts to phase out coal-fired plants
- Define a strategy for zero-emission industrial processes
- Reform the EU ETS to more effectively reduce emissions in industrial applications
- Ban the sale of Internal Combustion Engine (ICE) cars and buses and/or set targets to move towards 100-per cent of new car and bus sales being zero-carbon vehicles in the coming decades
- Shift towards increased use of public transport in line with the most ambitious Member States
- Increase the renovation rate for intensive retrofits of existing buildings

India

- Plan the transition from coal-fired power plants
- Develop an economy-wide green industrialization strategy towards zero-emission technologies
- Expand mass public transit systems
- Develop domestic electric vehicle targets working towards 100 per cent new sales of zero-emission cars

Japan

- Develop a strategic energy plan that includes halting the construction of new freely emitting coal-fired power plants, as well as a phase-out schedule of existing plants and a 100 per cent carbon-free electricity supply
- Increase the current level of carbon pricing with high priority given to the energy and building sector
- Develop a plan to phase out the use of fossil fuels through promoting passenger cars that use electricity from renewable energy
- Implement a road map as part of efforts towards net-zero energy buildings and net-zero energy houses

Mexico

- Increase the share of clean energy power generation in the electricity mix up to 48 per cent by 2027, 53 per cent by 2030 and 60 per cent by 2050, which will require the reactivation of the electricity market and the expansion of the interconnection grid infrastructure
- Phase out coal-based power generation by 2030
- Expand sustainable mass public transport and non-motorized options, as well as a transportation demand management policy to reduce the motorization rate
- Reach the 0 per cent deforestation target by 2030

South Africa

- Halt new proposed coal-fired power plants contained in the draft Integrated Resource Plan (IRP) for electricity
- Commit to a 2040 target for the phase-out of coal in the power sector
- Develop a climate-compatible industrial development plan for the long-term decarbonization of industry
- Accelerate the shift of freight transport from road to rail and to low-carbon road transportation such as hydrogen and electricity-powered options
- Continue to tighten standards to reach zero-emission buildings by 2030 and enforce existing and future standards

USA

- Introduce regulations on power plants, clean energy standards and carbon pricing to achieve an electricity supply that is 100 per cent carbon-free
- Implement carbon pricing on industrial emissions
- Strengthen vehicle and fuel economy standards to be in line with zero emissions for new cars in 2030
- Implement clean building standards so that all new buildings are 100 per cent electrified by 2030

8 As policies in the European Union are already quite advanced, many of the opportunities to enhance ambition are evidently ambitious.

changes in policies since the adoption of the Paris Agreement that are expected to be associated with the highest emissions impacts are highlighted in annex C, supported by quantitative estimates from the literature reviewed to give a sense of the magnitude of the actions. No attempt has been made to provide mitigation potential per G20 member, as it is difficult to provide values that are comparable across members.

Using the current policy situation in each country as a starting point, political areas that would be obvious to pursue for development of the next steps were identified. For example, consideration was given to whether policy proposals had already been put forward by relevant actors. Subsequently, the opportunities were checked against the major actions that must be taken to put the world on a path that is compatible with the Paris Agreement long-term temperature goal as summarized in section 4.2.3 and listed in annex B. Finally, the opportunities were cross-checked with several country experts.

Table 4.2 provides an overview of selected opportunities for enhancing mitigation ambition identified for the seven G20 members considered in this publication. The selection is based on expert judgements regarding the extent to which these opportunities are in line with ambitious climate actions and targets as defined and outlined in section 2.3. The country sections provide additional examples of country-specific opportunities.

We find that the G20 members have ample opportunity to increase the ambition of their climate and energy policies, considering where they are today. There are some common features. For almost all analysed countries, a logical next step would be to plan for a 100 per cent emission-free electricity sector and an associated phase-out of coal-fired power plants. All the analysed countries could also work on incentivizing modal shift in transport, supporting electric vehicles or working towards zero-emission buildings. In other areas, the logical next steps are very country-specific, for example, prohibiting new fossil fuel extractions, eliminating fossil fuel subsidies, enhancing action in industry or taking action to reduce deforestation.

5 Bridging the gap: Transformations towards zero-carbon development pathways

Lead authors:

Nebojsa Nakićenović (International Institute for Applied Systems Analysis and Vienna University of Technology, Austria), Charlie Wilson (Tyndall Centre for Climate Change Research, UK)

Contributing authors:

Bill Colglazier (American Association for Advancement of Science), Owen Gaffney (Potsdam Institute for Climate Impact Research, Germany), Dirk Messner (United Nations University), Narasimha Rao (Yale School of Forestry & Environmental Studies, USA), Caroline Zimm (International Institute for Applied Systems Analysis, Austria)

5.1 The great transformation towards net zero greenhouse gas emissions

The previous chapters and the underlying studies of development pathways aligned with the goals of the Paris Agreement indicate alarming inconsistencies between current nationally determined contributions (NDCs) and the long-term goal of reaching net zero emissions by mid-century.

Closing the emissions gap in 2030 and reaching net zero greenhouse gas (GHG) emissions by 2050 will require unprecedented efforts to transform our societies, economies, infrastructures and governance institutions. By necessity, this will require profound change in how energy, food and other material-intensive services are supplied. These systems of provision are entwined with the preferences, actions and demands of people as consumers, citizens and communities. Deep-rooted shifts in values, norms, consumer culture and underlying worldviews are inescapably part of the necessary sustainability transformation.

Such transformations are disruptive and cannot be achieved through an accumulation of incremental and gradual improvements, as Schumpeter indicates in his vivid example "add as many mail-coaches as you please, you will never get a railroad by so doing" (Schumpeter 1935).

Past and current mitigation efforts have been insufficient to slow the global growth of emissions. Chapter 2 showed that global GHG emissions increased by 2 per cent in 2018, which is almost exactly aligned with the long-term exponential growth rate since the beginning of the Industrial Revolution. For many decades, science has made it clear that stabilizing temperatures at any level requires net zero emissions, as the global mean temperature is in the first approximation proportional to cumulative emissions (see chapter 3).

Countries are exceedingly late for achieving pathways to close the emissions gap, with most policies and measures so far having been incremental and gradual. As a result, deep transformations are now needed to peak global emissions immediately and commence the rapid decline towards net zero emissions by 2050. This has been termed the 'carbon law' (Rockström *et al.* 2017) for halving emissions every decade, starting with a 50 per cent decline by 2030 (Intergovenmental Panel on Climate Change [IPCC] 2018).

Closing the gap in this way could, with proper policy design, also enhance the United Nations 2030 Agenda with its 17 Sustainable Development Goals (SDGs), which provides a holistic vision of a sustainable future for all humanity within planetary boundaries, and thus acts as a new social contract for the world.

5.2. Multiple co-benefits of closing the emissions gap for sustainable development

There are thousands of pathways in the literature reviewed that show which strategies, policies and measures would enable fundamental transformations towards complete decarbonization. Constructing alternative pathways is an important way to understand inherent complexities and uncertainties of transformations and to develop robust strategies to navigate them. Multiple pathways could therefore be taken to achieve global decarbonization across spatial and temporal scales.

Pathways can be generated by narrative storytelling, model-based quantification or a combination of both. Integrated modelling is particularly useful for characterizing and quantifying interlinkages between options for meeting SDGs (IPCC 2018; Nakićenović *et al.* 2000; Riahi *et al.* 2017; The World in 2050 [TWI2050] 2018; TWI2050 2019; van Vuuren *et al.* 2017).

The Intergovernmental Panel on Climate Change (IPCC) recently synthesized evidence on the sustainable development impacts of pathways which limit warming to 1.5°C (Rogelj *et al.* 2018). Figure 5.1 distinguishes interactions between SDGs and three sectoral climate change mitigation strategies: (a) energy supply (e.g. biomass and non-biomass renewables, carbon capture and storage with bioenergy or fossil fuels); (b) energy demand (e.g. fuel switching and efficiency in transport, industry, and buildings); and (c) land use (e.g. sustainable diets and reduced food waste, soil sequestration, livestock and manure management, reduced deforestation).

Despite remaining uncertainty about the magnitude and likelihood of interactions in some areas, figure 5.1 provides two important insights. First, there are multiple benefits from achieving climate change goals for other SDGs, with these synergies being more pronounced than trade-offs, especially if implementation is holistic and concurrent (McCollum *et al.* 2018). Second, energy demand-related mitigation strategies are most consistently and strongly associated with broader sustainability benefits. The World in 2050 (TWI2050) reports demonstrate in more detail the synergies between achieving deep decarbonization and SDGs in unison (Sachs *et al.* 2019; TWI2050 2018; TWI2050 2019).

The basic strategies for closing the emissions gap are clear. In the case of energy supply, a rapid 'exponential' transformation is required towards zero-emission energy resources, particularly renewables (Global Energy Assessment [GEA] 2012; Rockström *et al.* 2017). In the case of energy demand, a rapid shift is required towards more energy and materially-efficient services that raise or maintain living standards (Grubler *et al.* 2018) (See also chapter 6 and chapter 7). In terms of land, sustainable agriculture and the 'return' of land to nature are important measures that can also result in net negative emissions.

In all cases, advanced technologies and sustainable behaviours are essential for delivering the transformational change required. The digital revolution could become an important enabler of this transformation if it proves amenable to 'social steering' towards decarbonization (TWI2050 2019).

The remainder of this chapter explores six exemplary entry points for closing the emissions gap through transformational change. These entry points are derived from the six major transformations developed in TWI2050 (2018): (a) air pollution, air quality, health; (b) urbanization; (c) governance, education, employment; (d) digitalization; (e) energy- and material-efficient services for raising living standards; (f) land use, food security, bioenergy.

5.3. Entry points for achieving SDGs with climate co-benefits

5.3.1 Air pollution, air quality, health

Indoor air pollution is responsible for around 4 million premature deaths each year, with outdoor air pollution accounting for a similar number according to the World Health Organization (WHO) (2019). Clean cooking and universal access to electricity improves health and also reduces GHG emissions if traditional fuels are replaced by renewables, electricity, liquefied petroleum gas (LPG) or natural gas (see chapter 6).

Fossil fuel-related emissions account for two thirds of the excess mortality rate attributable to outdoor air pollution. A global fossil fuel phase-out could avoid over 3 million premature deaths each year from outdoor air pollution, or well over 5 million premature deaths per year if other anthropogenic GHGs, including non-fossil emissions from agriculture and industry, are also controlled (Lelieveld *et al.* 2019).

Transformational pathways show huge synergies between eliminating air pollution and limiting climate change, as well as improving energy security. One study found that the annual policy costs of achieving these three energy-related challenges together would be about 40 per cent lower than the sum of the policy costs for each challenge pursued independently (GEA 2012; McCollum *et al.* 2011).

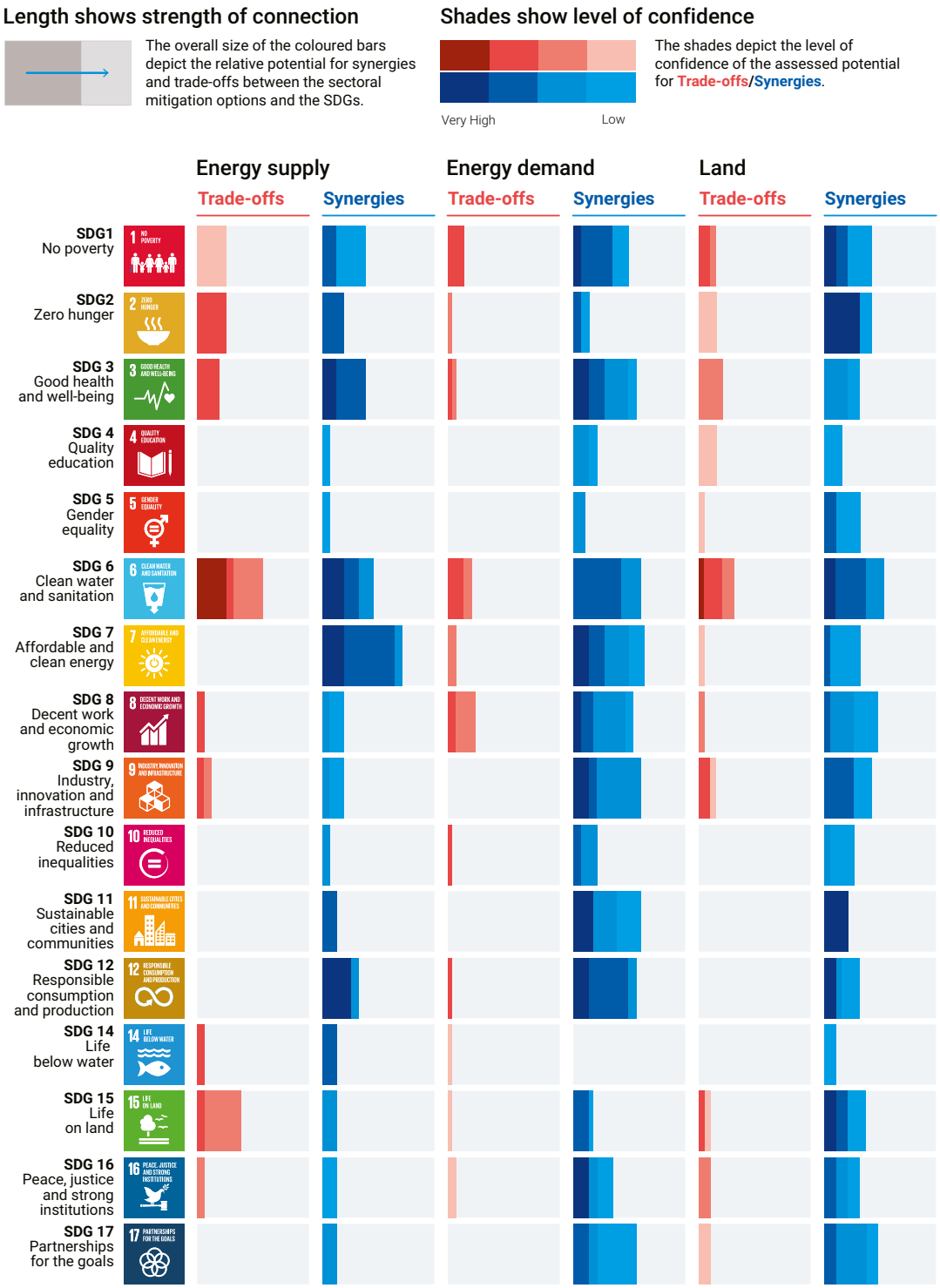
However, policy has to be done right as there are also significant trade-offs. Reducing air pollution from end-of-pipe particulate matter, sulfur and nitrous oxides can increase CO_2 emissions. Small particles and sulfur aerosols also mask anthropogenic temperature rise. Removing all pollution particles could result in an increase of warming by around 0.7°C globally, reaching around 2°C regionally over North America and North-East Asia, according to one estimate (Lelieveld *et al.* 2019). However, a reduction in tropospheric ozone and methane will significantly moderate this rise by around 0.35°C.

5.3.2. Urbanization and settlements

Urban areas are currently home to around 55 per cent of the world's population and 70 per cent of global economic output, though these figures are projected to grow to 70 per cent and up to 85 per cent respectively by 2050, particularly in small to medium-sized cities in the developing world (United Nations, Department of Economic and Social Affairs, Population Division 2018). Cities are hotspots of the global carbon cycle, with considerable fossil fuel and cement-related emissions from the provision (9.2 $GtCO_2e$) and use (9.6 $GtCO_2e$) of urban infrastructure equivalent to around half of current GHG emissions (Creutzig *et al.* 2015). What happens in existing and emerging cities, towns and municipal regions will therefore determine the prospects for sustainable development and closing the emissions gap.

Many rapidly growing urban areas are following the least sustainable model of all: urban sprawl (Grubler *et al.* 2012; Seto *et al.* 2014). Sustainable transformation is needed across all settlements, not merely in mega-conurbations, such as the Tokyo-Osaka corridor, Pearl River Delta or the Boston-Washington corridor. Many cities lack the basic urban infrastructure needed for economic productivity,

Figure 5.1. Potential synergies and trade-offs between the sectoral climate change mitigation options and the SDGs



Note: The strength of positive connections (synergies) and negative connections (trade-offs) across all individual options within a sector are aggregated into sectoral potentials for the whole mitigation portfolio. The (white) areas outside the bars, which indicate no interactions, have low confidence due to the uncertainty and limited number of studies exploring indirect effects. The bars denote the strength of the connection and do not consider the strength of the impact on the SDGs.

Source: Figure SPM4 in IPCC (2018)

social inclusion and the promise of basic services, such as sanitation, electricity, clean heating and cooking fuels, education, mobility, security and health care. Informal cities and slums account for a quarter of the urban population.

The transformation to sustainable cities and communities requires an integrated set of actions in urban areas around the world. Transport, buildings and industry are the key sources of energy demand and emissions within city boundaries. Certain characteristics of urban transformation are likely to be shared widely.

First, more compact urban form tends to reduce energy consumption and increase opportunities for more efficient district heating and cooling systems (Lucon 2014), transportation infrastructure and energy supply networks, and integrated management across different vectors (mobility, electricity, gas, heat).

Second, low-carbon infrastructure, including emissions-free electricity, public transportation, broadband connectivity and efficient road networks, is essential for delivering high-quality, affordable and universally accessible public services from health care and education to security and utilities (power, water, connectivity).

Third, short journeys account for two thirds of transport emissions in urban areas and could be replaced by active modes (Preston *et al.* 2013). Electrification of the vehicle fleet alongside mass transit and micromobility can replace diesel and petrol cars, making cities more liveable with lower pollution levels.

These examples of urban transformations demonstrate that there are many opportunities for integrating climate protection with initiatives to improve human well-being.

5.3.3. Governance, equity and social mobilization for change

Governance for sustainable development needs to build alliances for change, overcome vested interests, invest in new governance capacities, create visions of attractive futures, ensure justice and promote equity, and adopt a range of economic policy instruments to steer the economy and society towards the SDGs (TWI2050 2018). Transformative governance includes three critical elements.

First, economic instruments and political innovations are the tools or means of government. Road maps linking means to desired ends help create clear and stable expectations for the private sector and citizens alike, and therefore serve as coordination mechanisms within government to leverage systemic changes.

Second, the legitimacy of sustainable transformation depends on equity, justice and fairness in the distribution of costs and benefits at an individual, sectoral or regional level (Sachs *et al.* 2019). A particular challenge for transformative governance is how to respond to disruptive changes in technologies, economic sectors and labour markets (TWI2050 2019). Disruption creates uncertainties, instabilities and losers as well as winners, who – if organized and powerful – can act as strong barriers to change. In other cases, safety nets are needed to manage adverse distributional effects until the transformation towards sustainability can be achieved for all.

Third, new constellations of actors, partnerships and opportunities for citizens, cities, businesses and science are needed to drive proactive change and overcome inertias and path dependencies in incumbent systems. Large-scale transformation depends on social movements to build and reflect widespread public acceptance. This, in turn, depends on compelling visions of the multiple benefits of sustainable lifestyles, an area where research to-date has fallen short (Creutzig *et al.* 2016).

These elements of transformative governance can create a virtuous cycle: social movements depend on a widening arc of public awareness and understanding in which effective science communication can play an important role. Widespread social and moral commitment to sustainable development challenges interests vested in the unsustainable status quo. Civic engagement and popular support underpin the strong national alliances needed for sustainable development. Likeminded cooperation-oriented actors – governments, city alliances, civil society organizations, scientific institutions – can scale up coordinated action, embed joint learning processes and support vulnerable populations impacted by climate change.

Global governance beyond the local and national levels is also a necessity to achieve carbon neutrality globally by mid-century. Joint action and global rules are needed to stabilize planetary commons, such as the oceans, biodiversity and agricultural soil. Broad-based support for global governance comes from transnational alliances of pioneering actors of transformative change.

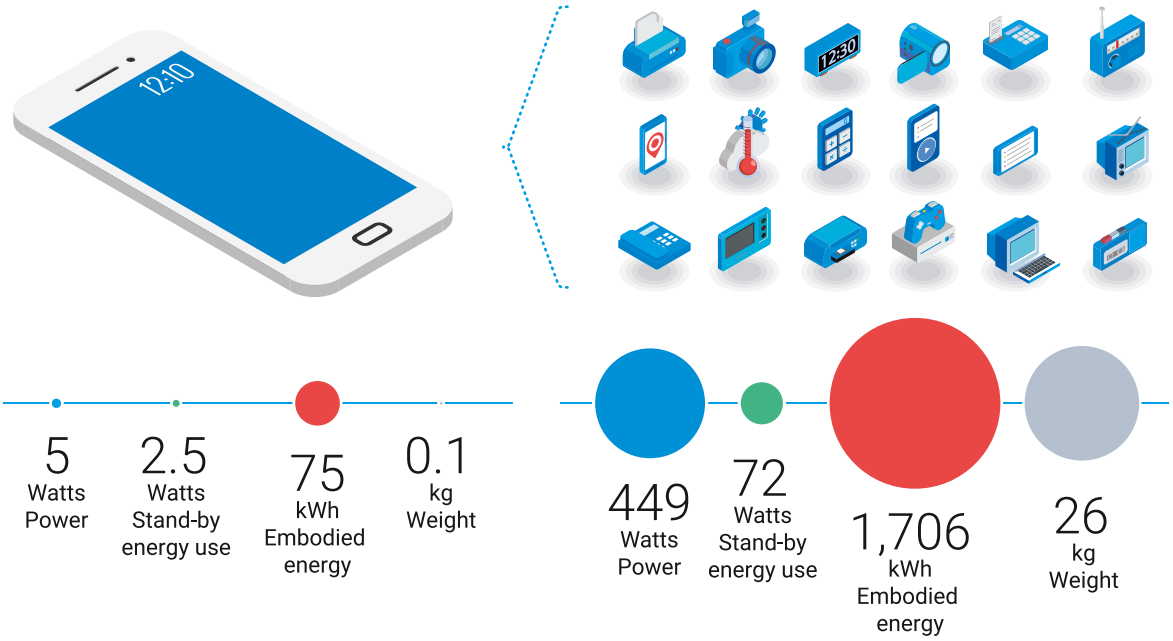
5.3.4. Digitalization and disruptive technological change

Disruptive technological change can enable sustainable development with co-benefits for closing the emissions gap, but can also exacerbate unsustainable patterns of resource use. This is most clearly evidenced by the promises and risks of the digital revolution, constituted by ongoing advances in information and communication technologies, machine learning and artificial intelligence, connectivity, the Internet of Things (IoT), additive manufacturing (3D printing), virtual and augmented reality, blockchain, robotics and synthetic biology.

TWI2050 (2018; 2019) analysed in depth the impacts of digitalization on consumption and production, and resulting GHG emissions. Three trends are particularly important.

First, additional units of information-based services can be provided at an almost zero marginal cost, increasing

Figure 5.2. The energy and material benefits of accessing services via a multipurpose smartphone (left) over owning an array of single-purpose goods (right)



Note: In-use power savings are factor 90 (blue circles), standby power savings are factor 30 (orange), embodied energy savings are factor 25 (green) for a weight reduction of factor 250 (grey).
Source: Grubler *et al.* (2018), based on a visualization by Tupy (2012) array of single-purpose goods (right)

affordability for poorer segments of society. Virtual communication and interaction can also potentially replace a large fraction of long-distance and carbon-intensive business travel.

Second, the possibility of matching supply and demand in real time through digital coordination platforms offers step-change improvements in asset utilization, improved quality of service and potentially lower emissions. This is also the underlying principle of a service-based economy in which 'ownership' of goods shifts to 'usership' of services (e.g. shared vehicle fleets and ride-sharing services, see chapter 7). Figure 5.2 illustrates the potential resource savings from displacing the ownership of many single-purpose analogue devices if equivalent services can be accessed through a single multifunctional interface.

Third, global communication infrastructures and the next generation of virtual spaces can connect people around the globe, accelerate global learning processes and support transnational alliances for sustainable futures. Just as the printing press enabled learning, science, the era of enlightenment, democracy and the Industrial Revolution, digital infrastructures can pave the way towards a global sustainable society.

However, as with all transformational strategies, digitalization also carries significant risks. A lack of access to digital infrastructure and services reinforces the digital divide, marginalization and inequality of opportunity. Conversely, cheaper and more accessible services could lead to 'take-back' (or economic 'rebound'), which further increases in-service demand with resource impacts. Digitalization and automation also further reduce the need for human labour. Big data-driven applications and services raise privacy concerns and enable social control by governments or monopolistic technology providers.

Clear governance and ethical and management strategies are needed to minimize these risks and avoid digital dystopias. Public policy is critical, particularly in the early formative phase of developing new technologies and business models, in terms of regulating standards, data access and privacy, competition, and, above all, infrastructure development, as well as ensuring equitable access. Effective governance of digitalization towards sustainability requires a comprehensive and rapid investment in the digital capabilities of public and regulatory organizations.

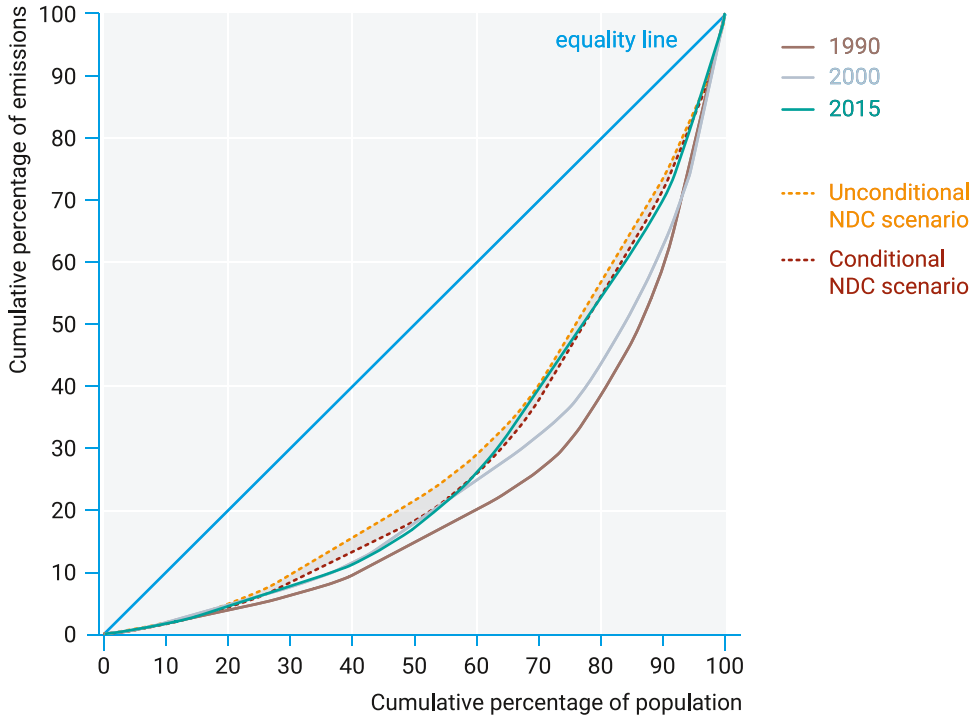
5.3.5. Resource-efficient services for raising living standards

A recent low energy demand (LED) scenario explored the potential for closing the emissions gap while raising living standards in the global South through radical changes in the type and efficiency of energy services (Grubler *et al.* 2018). Unlike other 1.5°C pathways, the LED scenario shows how the ambition of the Paris Agreement is reachable by lowering energy demand by 40 per cent, while at the same time increasing the provision of energy services without having to rely on negative emission technologies or carbon capture and storage (Rogelj *et al.* 2018). The LED scenario was found to have the strongest synergies with other SDGs. This is consistent with other analysis, which shows that energy, land and material-efficient pathways impose the fewest trade-offs with other SDGs (Bertram *et al.* 2018).

The sustainable transformation described by the LED scenario is immensely challenging, with the same services and quality of life taken for granted in modern developed economies becoming available to more people. This depends on seven main strategies for resource-efficient development: (a) electrify energy end use, including vehicles and heat pumps to improve end-use efficiency; (b) digitalize energy-using products and services to optimize infrastructure and resource use; (c) converge onto fewer numbers of multifunctional goods to improve service quality and convenience; (d) shift from ownership to usership to reduce material needs; (e) utilize consumer goods, vehicles and physical infrastructures at higher rates to accelerate the introduction of improved alternatives; (f) innovate business models offering low energy services to appeal to consumers, while making sense commercially; and (g) tighten efficiency standards continually upward to deliver cost, performance, health and other benefits.

The resulting expansion of energy services in the Global South would address historical inequalities created by GHG-intensive development in industrialized countries, where 2 billion people lack improved sanitation (World Health Organization [WHO] and United Nations Children's Fund [UNICEF] 2017), 800 million people go hungry every night (Food and Agriculture Organization [FAO] *et al.* 2018), roughly the same number of people do not have access to electricity, and almost 3 billion cook and heat with solid fuels (International Energy Agency [IEA] 2018). This striking global inequality in living standards is reflected in the marked global inequality in GHG emissions (figure 5.3).

Figure 5.3. Lorenz curves showing inequality in the global distribution of annual per capita GHG emissions for selected past years and two NDC scenarios



Note: The diagonal represents perfect equality. Half of the global population accounts for only 15–20 per cent of global emissions.
Source: Zimm and Nakićenović (2019)

This emissions inequality has reduced slightly in recent history (1990-2015) and looks set to continue through the NDCs. Strengthened action to close the emissions gap can be consistent with social and economic development objectives, if the emissions-intensive development pathways of the top emitters can be avoided.

5.3.6. Sustainable land use, food security and bioenergy

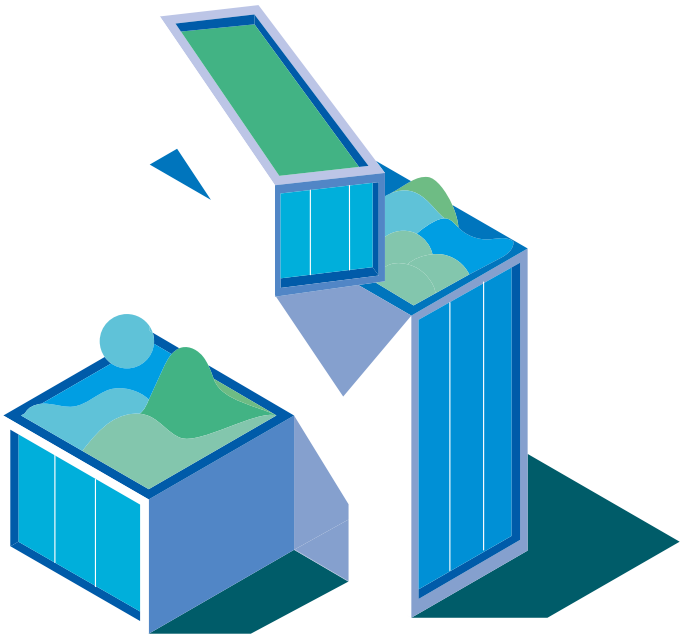
The biologist and naturalist E.O. Wilson has called for protecting half the Earth's land and seas, a project known as Half-Earth (Wilson 2016). Feeding humanity while mitigating human-caused environmental degradation must essentially occur on already transformed and existing agricultural land. This allows the remaining 'Half-Earth' to be safeguarded as natural forest and other ecosystems providing essential services, protecting biodiversity and ensuring resilience.

The global sustainable transformation of agricultural systems and fisheries faces the challenge of providing more and healthier food through sustainable intensification on existing farmland and reducing food waste (TWI2050 2018). For land in agricultural use as croplands, pastures and managed forests, this means widespread adoption of agricultural practices that minimize environmental damage and maximize resilience, including: precision farming to economize on resource inputs while boosting yields; no-till farming to protect soil quality; agroecology to optimize the crop mix in order to sustain biodiversity and resist the dangers of pests and pathogens; and improved harvesting and storage practices to reduce post-harvest losses.

A revolution is also needed in food consumption culture and practices to improve diets and reduce waste, as around a third of food produced currently ends up being wasted (Gustavsson *et al.* 2011). Healthier diets can be promoted by removing subsidies for harmful production techniques, public awareness campaigns and careful management of land use, oceans and other environmental resources (TWI2050 2018).

This agricultural revolution, encompassing both production and consumption, must unfold alongside a massive programme of returning land to nature, including tree planting on degraded land (Bastin *et al.* 2019). For example, over the last 40 years, China has undertaken major projects to enhance soils and regenerate and reforest land (Bryan *et al.* 2018). To close the emissions gap, land use must transition rapidly from being a net source of emissions to a net sink.

There are clear potential synergies between SDG 2 (zero hunger), SDG 7 (affordable and clean energy) and SDG 13 (climate action). Strategies include increasing agricultural productivity, reducing forest clearance for agriculture and shifting diets to healthier, less land-intensive and lower carbon foods. Conversely, the singular pursuit of SDG 13 to close the emissions gap without pursuing sustainable development more holistically can lead to trade-offs. Conversion of agricultural and forest land for bioenergy crop production negatively impacts food security. Such tensions are a particular hallmark of climate mitigation pathways reliant on negative emissions from combining bioenergy combustion with carbon capture and storage.



6 Bridging the gap: Global transformation of the energy system

Lead authors:

Yacob Mulugetta (Department of Science, Technology, Engineering & Public Policy, University College London, UK), Pablo E. Carvajal (International Renewable Energy Agency, Germany), James Haselip (UNEP DTU Partnership), Thomas Spencer (The Energy and Resources Institute, India)

Contributing authors:

Edo Abraham (Delft University of Technology, the Netherlands), Simon Batchelor (Gamos Ltd, UK), Brigitte Knopf (Mercator Research Institute on Global Commons and Climate Change, Germany)

6.1 Key issues and options for transforming the global energy system

The energy sector will be essential in the enhanced global mitigation efforts required to bridge the emissions gap in 2030 and reach net-zero emissions by 2050. This will necessitate a complete transformation of the way energy is produced and consumed.

To illustrate the scale of the challenge, coal-fired power plants were the single largest contributor to emissions growth in 2018, an increase of 2.9 per cent compared with the previous year and surpassing annual total emissions of 10 $GtCO_2$ (International Energy Agency [IEA] 2019a).

The transformation will be challenged by the fact that demand for energy services will grow 30 per cent by 2040, according to the IEA (2018a). However, primary energy demand will grow by a lesser rate or actually fall, depending on the achieved rate of energy efficiency improvement.

The current global energy system is still highly carbon-intensive with coal, oil and natural gas meeting 85 per cent of all energy needs (IEA 2019e). If the necessary transition does not occur, greenhouse gas (GHG) emissions will continue to increase year-on-year.

In light of this, what needs to happen? Long-term scenarios all point to rapid upscaling of renewables and energy efficiency, in combination with electrification of many new end-uses, as the key ingredients of a successful energy transition driving down energy-related CO_2 emissions (Gambhir *et al.* 2019; Bogdanov *et al.* 2019).

This chapter reviews five key transition options, based on their relevance to a wide range of countries, clear co-benefit opportunities and potential to deliver significant emission reductions. Each transition corresponds to a particular policy rationale or motivation, namely:

1) Easy wins: expanding renewable energy for electrification

2) Broad policy consensus: coal phase-out for rapid decarbonization of the energy system

3) Large co-benefits: decarbonizing transport

4) Hard to abate: decarbonizing energy-intensive industry

5) Leapfrogging potential: avoiding future emissions and ensuring energy access

6.2 Options to decarbonize the energy sector

The energy transition will include several elements, while approaches to transition will vary from one region and country to another. Transition strategies will need to be developed and adapted to fit the specific context, as few parts can be directly copied. Sharing and learning will be important for rapid action.

6.2.1 Easy wins: expanding renewable energy for electrification

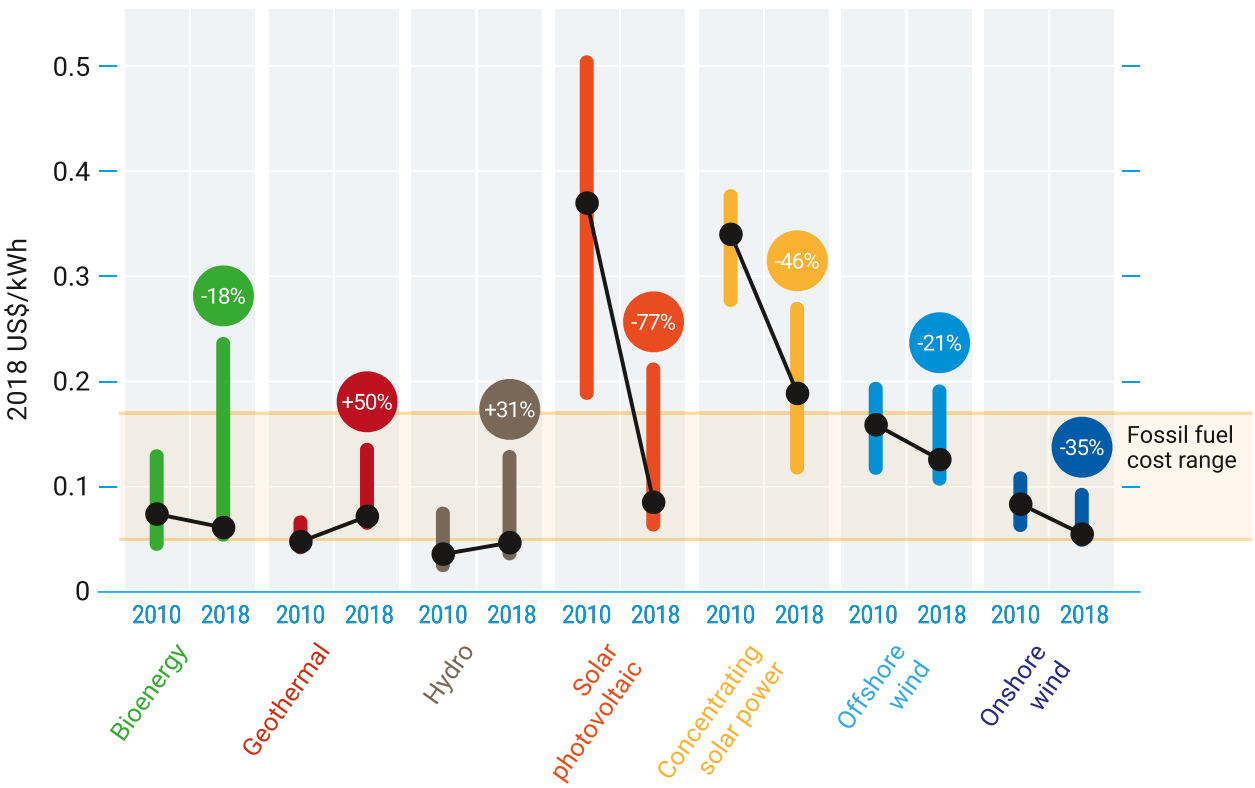
Technologically speaking, the three pillars of any strategy to decarbonize the power sector are: i) a vast expansion of renewable electricity generation; ii) a smarter and much more flexible electricity grid, and iii) huge increases in the numbers of products and processes that run on electricity (in buildings, transport and industry). The basic technologies needed for expanding electrification based on renewable energy technologies already exist and thus represent a relatively "easy win" for substantial short-term reductions of energy-related CO_2 emissions.

Regarding renewable energy expansion, the world added a record 167 gigawatts (GW) of new capacity in 2018

(excluding large hydropower), with solar photovoltaic (PV) additions hitting a record of 108 GW and wind power an estimated 50 GW. Global investment in renewable energy capacity in 2018 was US$272.9 billion, which was about three times higher than investment in coal and gas-fired generation capacity combined. This allowed for renewable energy (excluding large hydropower) to raise its share of global electricity generation to 12.9 per cent in 2018, helping the world to avoid an estimated 2 gigatons of carbon dioxide emissions (Frankfurt School-United Nations Environment Programme [UNEP] Collaborating Centre and BloombergNEF [BNEF] 2019). Yet, renewables need to grow six times faster to meet climate targets (International Renewable Energy Agency [IRENA] 2019a).

The main enabler for the accelerated deployment of renewable energy in the last decade has been the continued and rapid decline in capital costs. In most parts of the world today, renewables have become the lowest-cost source of new power generation and are generally competitive without incentives when directly compared with fossil alternatives. Since 2010, the global weighted-average levelized costs of electricity (LCOE) from solar photovoltaic, onshore and offshore wind projects, bioenergy and geothermal, have all reduced and are approaching the lower range of fossil-fuel-fired power generation costs (figure 6.1). Continued cost declines are expected during the following decades (IRENA 2019c). The key to integrating larger shares of variable renewable energy into the power supply is system flexibility. Electricity systems with large shares of renewables require investments to address the short- and medium-term variability of both solar and wind energy. There are several categories of power system assets that can be utilized to provide flexibility. Conventional power plants, gas-fired generation and hydropower with reservoirs are currently the predominant sources of system flexibility in modern power systems, but other options will increasingly become important such as electricity networks, battery storage, distributed energy resources and enhanced predictability. Studies show that the cost of flexibility to integrate variable renewable energy is generally quite small (+5 to +13 US$/MWh), with higher values for inflexible systems with dominant shares of coal or nuclear generation (Agora Energiewende 2015). However, beyond enhanced power infrastructure, measures to support power system flexibility can be readily applied and adapted to power systems. These include modifications to "energy strategies, legal frameworks, policies and programmes, regulatory frameworks, market rules, system operation protocols, and connection codes" (IEA 2019c). There are now several examples of countries that have achieved 100 per cent renewable energy electricity for short periods of time (days), with large shares of variable solar and wind (for example, Costa Rica, Denmark, Ireland and Uruguay).

Figure 6.1. Global LCOE of utility-scale renewable power generation technologies, 2010-2018



Source: International Renewable Energy Agency (IRENA) (2019c).

Box 6.1. Germany's coal phase-out

Despite growing its share of renewables in electricity generation from 20 per cent in 2011 to 37.8 per cent in 2018, Germany is Europe's largest coal consumer, accounting for 35 per cent of total power sector emissions in 2018, with 42.6 GW of lignite and hard coal-fired power generation capacity. This means that Germany will most certainly not reach its national target of 40 per cent GHG reduction by 2020 compared with 1990 levels (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety [BMU] 2018).

In January 2019, following a long consultation process, a Government-appointed commission proposed a total phase-out of coal in Germany by 2038 (Federal Ministry for Economic Affairs and Energy [BMWi] 2019). The proposed decommissioning road map foresees a net reduction of 12.5 GW of coal capacity by 2022. By 2030, total coal power capacity should be reduced to a maximum of 17 GW, equal to a total reduction of 25.6 GW compared with 2017. Reviews are proposed for 2023, 2026 and 2029 to take stock of progress and to address concerns over security of supply, especially since Germany has committed to decommission all nuclear power by 2022.

The most important proposed measures to implement the coal phase-out are to cancel the industry's CO_2 certificates issued within the European Emission Trading Scheme and to ensure the expansion of renewable electricity to a share of 65 per cent by 2030. The phase-out plan includes a €40 billion economic package offered to affected coal regions, including alternative industry investment projects and state aid for coal workers.

The Commission's proposal is now in the legislative process. The federal Government has already decided on the law for financing structural change in the coal regions and will officially adopt the decision to phase-out coal by 2038 in November (Cabinet of Germany 2019)

Harnessing the synergy between low-cost renewable power and enhanced end-use electrification is key to driving down energy-related CO_2. According to the International Renewable Energy Agency (IRENA), renewable energy and electrification can deliver 75 per cent of the required emission reductions to bring the temperature rise to the well-below 2°C climate goal (IRENA 2019a). This means that by 2050, 86 per cent of electricity generation would need to be renewable and that the share of electricity in final energy would increase from just 20 per cent today (IRENA 2019a) to almost 50 per cent by 2050. The share of electricity consumed in industry and buildings would need to double (mainly through electric heating and cooling), with transport seeing potentially the largest transformation (see section 6.2.3).

The electrification of the energy system creates the need for enhanced digitalization of end-use technologies, large-scale electrical and heat storage technologies and the need to develop "electro fuels" with green electricity, to be able to substitute liquid fossil fuels (IRENA 2019b). All these technologies exist and are rapidly spreading, especially within Organisation for Economic Co-operation and Development (OECD) economies, and also serve to mitigate the risk of blackouts caused by unfavourable weather.

6.2.2 Broad policy consensus: coal phase-out for rapid decarbonization of the energy system

The combustion of coal currently accounts for 30 per cent of global CO_2 emissions (IEA 2019a). Behind these figures is the reality that globally, about 27 per cent of primary energy needs are met by coal, including around 40 per cent of all electricity generation (BP 2019). After declining consecutively for three years, global coal production increased by 2.8 per cent to 7,428 Mt in 2017 and then rose again by a marginal 0.2 per cent to 7,575 Mt in 2018 (Enerdata 2019), resulting from stronger global economic growth leading to increased industrial output and electricity use. This highlights two obvious but critical points: i) much of the growth in demand was concentrated in Asia, showing a regional shift in consumption and production and thus some headroom for growth; ii) the rapid rate of growth in electricity demand limits the pace at which the power sector can decarbonize, even with high uptake rates of renewables, which reinforces the importance of energy efficiency to keep total demand within the reach of achievable renewables growth.

If operated until the end of their lifetime and not retrofitted with carbon capture and storage (CCS), "committed emissions" from existing coal-fired power plants, built before the end of 2016, are estimated to emit roughly 200 $GtCO_2$ by 2050 (Rogeli *et al.* 2018). Coal-based power plants that are planned or under construction would add a further 100–150 $GtCO_2$ (Edenhofer *et al.* 2018), effectively using up a large share of the remaining carbon budget to stay below two degrees.

Therefore, one of the main challenges for the required energy sector transformation will be to find nationally appropriate solutions for the fast and socially responsible reduction in coal-fired power generation by 2030 and a phase-out by 2050 (Rogeli *et al.* 2018). Box 1 illustrates the complexity of such a phase-out process, using the experience of Germany.

Policies should also look beyond the demand-side considerations to include supply-side interventions (Spencer *et al.* 2018; table 6.1). Supply-oriented considerations are critical given the importance of the coal mining sector in terms of employment, revenues and its place within broader regional economies. Hence, managing coal transitions means not just focusing on "stranded assets", as relating to physical or financial capital in the demand-side policy literature, but also to paying attention to the notion of "stranded regions" where workers, regional governments and the regional economy more broadly are dependent on the coal sector (Spencer *et al.* 2018). This holistic vision is at the heart of a "just transition" that considers the impact of technological change on workers and communities (Caldecott *et al.* 2017), as well as the coal owners and industry, as a way to negotiate a politically feasible reduction in coal power generation, and eventually phase it out altogether (Jordaan *et al.* 2017).

6.2.3 Large co-benefits: decarbonizing transport

Transport accounted for 28 per cent of global final energy demand and 23 per cent of global energy-related CO_2 emissions in 2014 (IEA 2017b). Transport sector emissions are growing rapidly and increased by 2.5 per cent annually between 2010 and 2015 (Rogeli *et al.* 2018), largely driven by economic growth, behavioural changes and population increase. The sector accounts for about 65 per cent of global oil demand, with 92 per cent of final transport energy demand consisting of oil products, making it the least diversified of the major energy end-use sectors.

Deep decarbonization of the transport sector will require a radical shift in the nature and structure of transport demand, major improvements in energy efficiency, changing vehicle types and significant and rapid transitions in the energy mix used (see also chapters 4 and 7).

Aggressive action now would lay the foundation and maintain a healthy momentum towards the longer-term goal. Some of the transport-related climate change mitigation actions that can yield substantial decarbonization as well as economic benefits include: i) compact urban planning; ii) reducing passenger travel demand; iii) shifting passenger travel modes and expanding public transit; iv) improving passenger car efficiency and shifting to electrical engines; v) improving freight logistics; and vi) improving freight vehicle efficiency and electrification (Dhar, Pathak and Shukla 2018; Gouldson *et al.* 2018).

One of the key technical mitigation options, namely electrification of the transport sector, is projected to play a major role in meeting ambitious climate targets. Rapid growth in electric passenger vehicles (EVs) across the members of the G20 has been occurring since 2010, with global cumulative sales of light-duty plug-in vehicles exceeding 5 million units at the end of December 2018 (Vieweg *et al.* 2018; Watson 2019). This amounts to a market share of 2.1 per cent (compared with less than 1 per cent in 2016). China has the largest fleet of EVs with over 2.2 million units, while Norway leads in terms of the market share for new cars, approaching 60 per cent (Williams 2019). In road freight transport (trucks), systemic improvements (for example, in supply chains, logistics, and routing) would also benefit from these innovations, but would need to be combined with efficiency improvement of vehicles.

Shipping and aviation account for 40 per cent of all transport-related emissions but will be significantly more challenging to decarbonize and electrify than road transport (Martinez Romera 2016). Both modes will see high demand growth and would need to pursue ambitious efficiency improvements and use of low-carbon fuels. This would mean the use of advanced biofuels and low-carbon liquid fuels (synthetic fuels) in the near and medium term, with hydrogen fuel for shipping a likely solution in the longer term (IRENA 2019a; IEA 2017b).

While progress has been made, it is far from the scale required to decarbonize transport. Specifically, it will

Table 6.1. Framework of policy challenges related to coal transition

	Policy challenge	Example policy approach
Supply side	Importance of the coal sector as a (regional) employer and generator of added value	Regional diversification plans or coal sector restructuring plans
	Importance of export revenues from coal export	Economic diversification strategies
Demand side	Economic and technological aspects of substitution to move away from coal use	Payments for closure of coal plants; carbon pricing; renewables support schemes

Source: Spencer *et al.* (2018)

require the share of electricity in final energy for transport to increase from just 1 per cent today to 40 per cent by 2050 (IRENA 2019a)[1].

At the same time, decarbonizing transport can deliver multiple significant co-benefits and is one of the sectors in which there are strong links between local and global pollution and human well-being. Specifically, the transportation sector is a major source of particulate matter ($PM_{2.5}$), ozone and nitrogen dioxide concentrations, which are major causes of premature deaths. In 2015, emissions attributed to transport contributed to 385,000 premature deaths out of which 114,000 and 74,000 were in China and India, respectively (Anenberg *et al.* 2019). With vehicle numbers projected to double by 2040, the costs associated with premature mortality are likely to increase in both these countries. However, some solutions are beginning to emerge. For example, there is significant potential for electric two- and three-wheelers as a short-distance transport solution in India, which could enable India to develop a large EV industry and stimulate investment in charging infrastructure that can facilitate diffusion of larger EVs (Dhar, Pathak and Shukla 2017; see also chapter 7).

6.2.4 Hard to abate: decarbonizing energy-intensive industries

Energy-intensive industries, such as steel and cement, account for about 17 per cent of total CO_2 emissions from energy and industrial sources (Energy Transitions Commission [ETC] 2019). These sectors are difficult to decarbonize for a number of reasons. Firstly, there are technical barriers, due to the lack of cost-effective mitigation technologies to reduce emissions from the combustion of fossil fuels to provide high-grade process heat or from the industrial process itself. Secondly, there are political economy barriers, due notably to the international competition for some of these industries and hence the risk of "carbon leakage", as well as the low level of innovation and stock turnover in these sectors[2]. As a result, energy-intensive industries have typically been exempted from national climate policies. Competitiveness pressures and the importance of energy as an input have, however, driven significant energy efficiency improvements, but this has not been enough to move towards decarbonization of these sectors. For example, while the CO_2 intensity of global electricity production has declined by 9.3 per cent between 2000 and 2016, the CO_2 intensity of global crude steel production has increased by 2.8 per cent in the same period[3].

This is concerning because the significant demand for materials will continue, as countries like India and many African countries develop the infrastructure and housing required as a result of their development. Without further policy, emissions from the heavy industry sectors could increase from 17 per cent of global emissions today to 20 per cent by 2050 (ETC 2019). Mitigation of energy-intensive industries requires going beyond incremental improvements in energy efficiency and moving towards more fundamental mitigation options.

Broadly speaking, these options can be broken down into three categories. The first is demand reduction through recycling, materials substitution and dematerialization (see chapter 7). An example of the latter would be lightweighting of automobiles while improving fuel economy and downsizing the powertrain, in order to reduce steel consumption. Significant potential exists to reduce virgin material demand, which could cut emissions from heavy industry by 40 per cent by 2050, compared with a business as usual (BAU) case (ETC 2019; also discussed extensively in chapter 7). This can have the benefit of reducing reliance on more costly mitigation options like carbon capture and storage/use (CCSU) (IEA 2019b).

The second category involves mitigation of emissions in the context of the existing industrial process, the archetypal example of which is the deployment of CCSU. While alternatives to CCSU are emerging in some heavy industry sectors, the deployment of CCSU is likely to be necessary in the cement industry, even given aggressive deployment of clinker substitutes and the development of currently non-commercial alternative cement technologies[4]. The third category of options entails a fundamental transition in the industrial process itself, an example of which would be the substitution of coking coal as a fuel and reducing agent in steel manufacture with hydrogen produced from zero-carbon electricity (Vogl *et al.* 2018).

Therefore, what are the prospects for energy-intensive industry mitigation? The first point to note is that the available technological options are currently at a low level of commercial readiness, necessitating significant progress in research, demonstration and commercialization. Secondly, unlike in other sectors where zero-carbon options may be economically competitive with their fossil alternatives (for example, renewable electricity or electric vehicles), decarbonization of energy-intensive industry appears likely to entail net costs. These costs are likely to be negligible at the level of the macroeconomy and the end-consumer, but significant at the producer level (ETC 2019). This raises questions of managing the implementation of stringent policies to decarbonize heavy industry in the absence of stronger global climate policies and a level playing field. Some form of trade protective measures, such as border adjustments, may be required. Finally, a comprehensive portfolio of policies is likely to be required, ranging from carbon pricing and research and demonstration

1 This is consistent with REN21 (2018) as the bulk of renewable energy used in the sector is biogasoline at 2.5 per cent; biodiesel at 1.4 per cent; and renewable electricity at 0.3 per cent of demand in 2016.

2 For an excellent summary of the challenges of mitigation in the energy intensive industries, see Bataille *et al.* (2018).

3 Calculated on the basis of data from Enerdata (2019) and World Steel Association (2018).

4 For a comprehensive survey of cement mitigation options, see Scrivener *et al.* (2018).

Box 6.2. Clean cooking as an important mitigation option

The Intergovernmental Panel on Climate Change Special Report on 1.5°C (IPCC SR1.5) states that lack of access to clean and affordable energy for cooking is a major policy concern in many countries where major parts of the population still rely primarily on solid fuels for cooking (Roy *et al.* 2018). The amount of fuelwood burned across Africa is estimated to be over 400 million m^3 a year (May-Tobin 2011), releasing over 760 million tons of CO_2e into the atmosphere*, and globally non-renewable biomass fuels alone account for significant emissions. This will continue to increase with the rise in population, as the population of sub-Saharan Africa is projected to double by 2050 (United Nations Department of Economic and Social Affairs [UN DESA] 2019). Black carbon from residential solid fuel burning is estimated to add the equivalent of another 8–16 per cent of the global warming caused by CO_2 (Bailis *et al.* 2015). It is also important to recognize the complexity associated with accounting in terms of the time it takes for replacement trees to sequester the CO_2 emitted by burning a felled tree, and the rate of change in CO_2 sequestration as trees mature. Clean cooking solutions address the most basic needs of the poor. Furthermore, reducing black carbon, methane and other short-lived climate pollutants would have substantial co-benefits on health and local air quality, but can in the short-term contribute significantly to limiting global warming to 2°C and 1.5°C (de Coninck *et al.* 2018; Batchelor *et al.* 2019). A key driver is the trajectory of costs that show "clean" cooking (i.e. with electric or gas) has the potential to reach a price point of affordability with associated reliability and sustainability within a few years.

* Burning 1 kg wood emits 1.9 kg of CO_2. See https://www.transitionculture.org/2008/05/19/is-burning-wood-really-a-long-term-energy-descent-strategy/.

funding to standards and regulation, for example, to promote material demand reduction. For all of this to occur, the salience of energy-intensive industry decarbonization needs to increase in global and national policy discussions.

6.2.5 Leapfrogging potential: avoiding future emissions and ensuring energy access

The issue of energy access and energy poverty is now on top of the global policy agenda. Among Least Developed Countries (LDCs), over 60 per cent of the population have no access to electricity with the figure rising to 80 per cent for people in rural areas (Least Developed Countries Renewable Energy and Energy Efficiency Initiative for Sustainable Development [LDC REEEI] 2019). In non-LDC developing countries, the figure is still significant, at 10 per cent of the population. Those who do have access to electricity often endure problems of unreliable access and frequent blackouts. Beyond electricity, nearly three billion people rely on traditional fuels (such as wood or charcoal) and technologies for cooking and heating. This has severe implications for health (especially the health of women and children), economic livelihoods and the environment, both at a global and local level (Batchelor *et al.* 2019). The burning of non-renewable biomass fuels[5] alone generates a gigaton of CO_2e per year (Bailis *et al.* 2015), about a 2 per cent share of global emissions (see chapter 2). Box 2 discusses the GHG emissions associated with cooking and potential trends for the future.

Improving access to reliable energy services for households and for productive purposes is thus a central policy objective in many LDCs and developing countries. This is explicitly recognized by United Nations Sustainable Development Goal 7 (SDG 7) that calls for action to "ensure access to affordable, reliable, sustainable and modern energy for all", which include targets on renewable energy and energy efficiency. As such, there is evidence of synergies between about 85 per cent of the SDG targets and efforts to achieve SDG 7, as well as some evidence of trade-offs between SDG 7 and about 35 per cent of the SDG targets (Fuso-Nerini *et al.* 2018). However, despite the energy sector's large share of global GHG emissions, achieving universal access to modern energy does not lead to increases in global GHG emissions (Dagnachew *et al.* 2018; IEA *et al.* 2019). Using two scenarios, the New Policies Scenario (NPS) and the Sustainable Development Scenario (SDS)[6] derived from the IEA's World Energy Outlook, reflect the simultaneous pursuit of universal access in sub-Saharan Africa for both electricity and clean cooking solutions yielding net savings of GHG emissions amounting to 45 $MtCO_2e$ and 200 $MtCO_2e$, respectively.

Going beyond addressing energy for basic human needs (i.e. lighting and cooking) to pushing mechanical power, mobility and energy for other productive uses required to drive development and transformation will generate increasing

5 To imply the extraction of biomass from a land area is not sustainable where carbon stocks on the land area decrease over time.

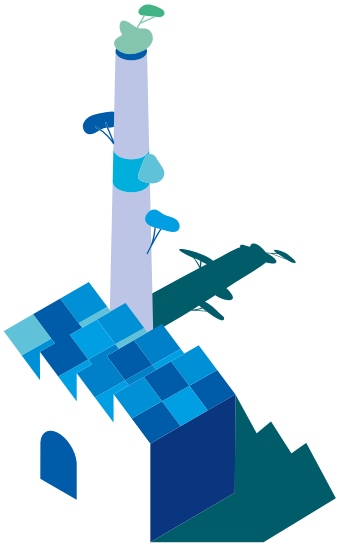
6 The NPS accounts for current and planned policies with a high likelihood of being implemented, including the GHG- and energy-related components of the NDCs pledged under the Paris Agreement. The SDS combines the fundamentals of sectoral energy policy with three closely associated but distinct policy objectives related to the SDG 7 (energy access), SDG 3 (air pollution) and SDG 13 (climate action).

Table 6.2. Transition options and their elements

Option	Major components	Instruments	Co-benefits	Annual GHG emissions reduction potential of renewables, electrification, energy efficiency and other measures by 2050
Renewable energy electricity expansion	• Plan for large shares of variable renewable energy • Electricity becomes the main energy source by 2050, supplying at least 50 per cent of total final energy consumption (TFEC) • Share of renewable energy in electricity up to 85 per cent by 2050 • Transition	• Flexibility measures to take on larger shares of variable renewable energy • Support for deployment of distributed energy • Innovative measures: cost reflective tariff structures, targeted subsidies, reverse auctions, net metering	• Greater efficiency in end-use energy demand • Health benefits • Energy access and security • Employment	• Power sector: 8.1 $GtCO_2$ • Building sector: 2.1 $GtCO_2$ • District heat and others: 1.9 $GtCO_2$
Coal phase-out	• Plan and implement phase-out of coal • Coal to renewable energy transition • Expand carbon capture usage and storage systems • Improve system-wide efficiency	• Regional support programmes • Tax breaks, subsidies • Carbon pricing • Moratorium policies • De-risking of clean energy investments • Relocation of coal workers (mines and power plants)	• Lower health hazards (air, water, land pollution) • Future skills and job creation	• Share of the power emissions reduction from a coal phase-out: 4 $GtCO_2$ (range: 3.6–4.4 $GtCO_2$), with 1 $GtCO_2$ from the OECD and 3 $GtCO_2$ from the rest of the world
Decarbonize transport	• Reduce energy for transport • Electrify transport • Fuels substitution (bioenergy, hydrogen) • Modal shift	• Pathways for non-motorized transport • Standards for vehicle emissions • Establishing of charging stations • Eliminating of fossil-fuel subsidies • Investments in public transport	• Increased public health from more physical activity, less air pollution • Energy security • Reduced fuel spending • Less congestion	• Electrification of transport: 6.1 $GtCO_2$

Decarbonize industry	• Demand reduction (circular economy, modal shifts and logistics) • Electrify heat processes • Improve energy efficiency • Direct use of biomass/ biofuels	• Carbon pricing • Standards and regulations, especially on materials demand reduction	• Energy security • Savings and competitiveness	• Industry: 4.8 $GtCO_2$
Avoid future emissions and energy access	• Link energy access with emission reductions for 3.5 billion energy-poor people	• FiT and auctions • Standards and regulations • Targeted subsidies • Support for entrepreneurs	• Better access • Meet basic needs and SDGs	• N/A

Source: Energy Transitions Commission (2017, 2018); International Renewable Energy Agency (2019a); Climate Analytics (2016)



energy demand. Poor but fast-growing countries in east and south-east Asia have traditionally deployed emissions-intensive coal to meet this demand. However, for countries and regions that host the world's energy-poor, there remains significant scope to shape their energy transitions as they are yet to be locked into a particular pathway (Mulugetta, Ben Hagan and Kammen 2018). Moreover, rapid technological progress in renewable energy is opening up an unprecedented opportunity for a wide range of applications and business models, including electrification through decentralized generation and mini-grids, with rapidly declining costs for photovoltaic modules, batteries, LEDs, smart metering, mini-grids and pay-as-you-go technology (United Nations Conference on Trade and Development [UNCTAD] 2017).

Policymakers in developing countries understand that making a rapid transition sometimes relies on a much slower process of technological and organizational change, for example, to build capacities and knowledge about the technologies required to 'leapfrog'. Moreover, the quality of the transition matters in terms of creating additional value beyond the provision of energy such as good quality jobs and building industrial capacity. For example, while the growth in solar PV markets across Africa is to be welcomed from an energy delivery perspective, a significant proportion of the global value chain for PV has been captured elsewhere, for example, in manufacturing (principally China), as well as financing and engineering services, often provided by institutions in OECD countries (Byrne, Mbeva and Ockwell 2018; Lema *et al.* 2018; Ockwell *et al.* 2018).

More broadly, effort is required to actively connect private business leaders with government-led and donor-backed forums to communicate and unlock new commercial opportunities in PV systems, as has occurred successfully in Kenya and Uganda (Bhamidipati, Haselip and Hansen 2019). However, this requires building innovation systems with the mission to strengthen knowledge and skills base, raise patient capital and mobilize technical assistance, to build strong partnerships with financial providers and domestic entrepreneurs with a deep interest in new and clean technologies (Truffer, Murphy and Raven 2015; Wieczorek 2017).

6.3 Beyond technical measures: pursuing system-wide transformation

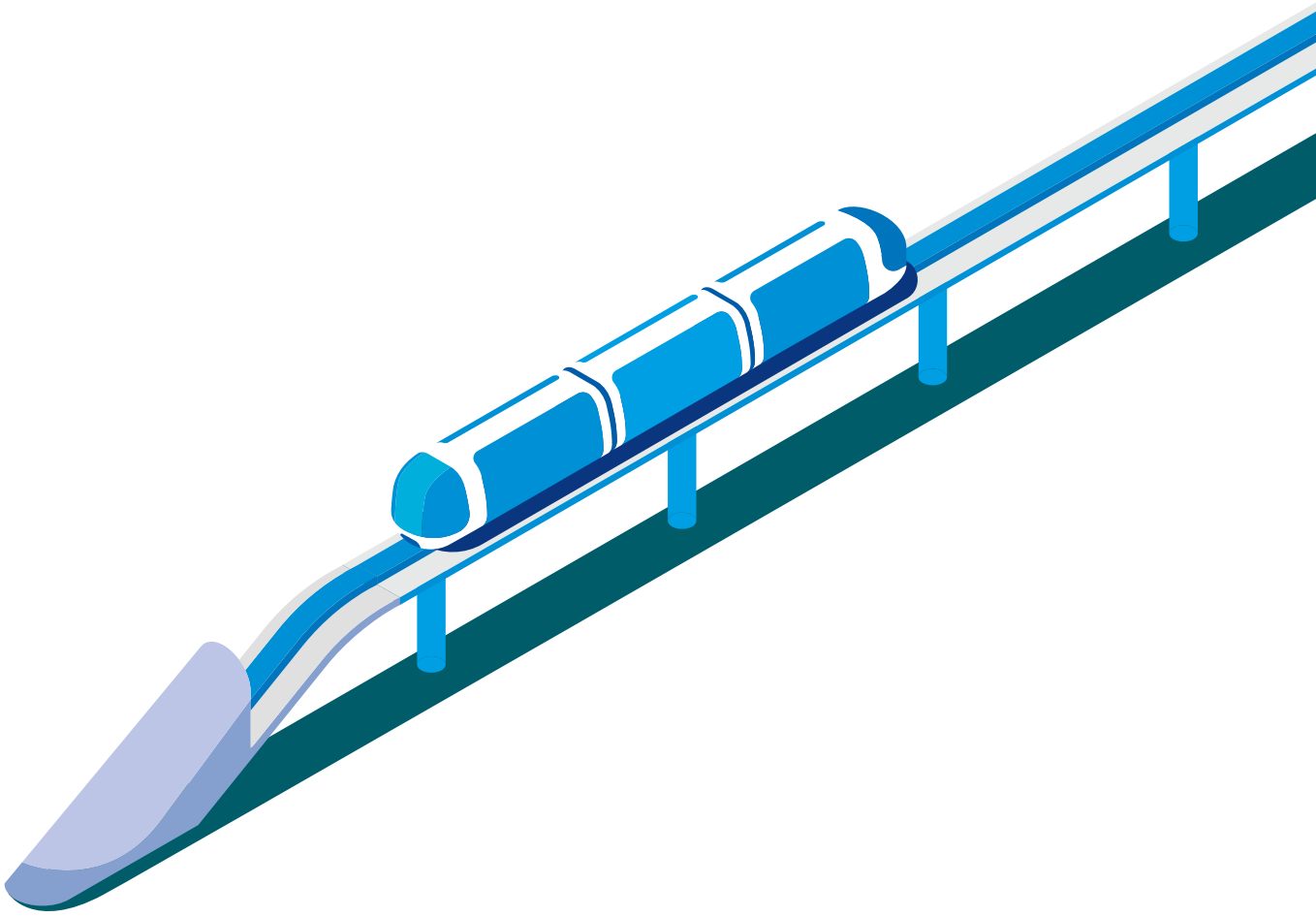
There is a qualitative difference between past energy transitions and the necessary future transition. For one thing, previous transitions were not constrained by time as a key factor for rapid change. More concretely, historical transitions were more "opportunity-driven", whereas low-carbon transitions are more "problem-driven" – the problem being the collective good (i.e. the climate) (Sovacool and Geels 2016). Furthermore, historically, energy "transitions" have occurred only in percentage terms (firstly, coal displacing biomass, then oil displacing coal and now natural gas and renewables displacing oil and coal). In terms of total energy use, the trends have more accurately reflected energy "additions" as all forms of energy rise to meet growing energy demand. Today we consume more coal, gas, oil, nuclear and renewables than ever before. Reducing emissions, however, requires that total hydrocarbon use decline with great expansion of renewable energy (along with technologies to capture or remove their emissions) (University of Columbia Center on Global Energy Policy 2019).

The depth of technological and institutional lock-in of the incumbent energy system is so profound it creates major obstacles or inertia, holding back much needed structural change (Jackson 2016). The rapid and systemic changes needed are radically different from what institutions are accustomed to withstanding. For example, switching to EVs requires multiple changes in the socio-technical system, which involve multi-actor processes of interactions across and between energy and transport regimes. Given the need for these complex and systemic changes, a sector-focused or silo approach will need to give way to decisions and policies that reach across sectoral, geographical and political boundaries. One way to do this is through mission-oriented policies, defined as systemic public policies that draw on frontier knowledge to attain specific goals, often to address "big problems" such as climate change that demand radical innovations and a multi-actor coordination (Mazzucato 2018). This also recognizes the catalytic role that governments can play in creating policies that can shape markets and direct them to meet major societal goals.

Given that energy is an enabler, and thus cuts across sectoral boundaries, low-carbon energy transitions can be well served by being directly linked to opportunities in other sectors such as electrifying transport and heating (including cooking) and decarbonizing energy-intensive industries. Equally important will be linking transitions with their associated co-benefits and costs and how these can be evaluated to provide supplementary information to serve as additional impetus for policymakers, decision makers and civil society to co-own and build consensus around the options (table 6.2).

The sheer scale of investment needed for accelerating energy transitions is very large. Global renewable energy investment in 2018, excluding large hydroelectric projects, exceeded the US$250 billion for a fifth successive year Frankfurt School-UNEP Collaborating Centre and BNEF 2019). However, climate policies that are consistent with the 1.5°C target require upscaling of energy system supply-side investments (resource extraction, power generation, fuel conversion, pipelines/transmission and energy storage), reaching levels of between US$1.6–3.8 trillion per year globally on average over the 2016–2050 time frame (McCollum *et al.* 2018).

The call to redirect investment to low-carbon energy systems raises a number of issues. Firstly, the high upfront capital outlay and low operating costs of



renewables is a new terrain in finance where further innovation is required. Secondly, while the historically low interest rates over the past 10 years have provided a very conducive environment for investment in renewable energy technologies (RETs), energy investment was mostly concentrated in high and upper-middle income countries (IEA 2019d). Thirdly, the high investment requirement in developing countries is being hampered by the high perception of risk, little opportunity for patient capital, and unstable political and regulatory regimes. To this end, multilateral, regional and national development banks could play a major role in leveraging larger finance by helping to de-risk investments. However, this would need to be co-developed where country policymakers play a deeper role by creating stable policy and regulatory conditions to encourage investment. This would also mean appealing to the immediate concerns of decision and policymakers, for example, integrating transport policy with air quality and climate policy and with vehicle emissions regulation. Policies should be harmonized wherever possible to take advantage of interdependencies and prevent undesirable outcomes such as CO_2 "leakage" from one sector to another.

7 Bridging the gap: Enhancing material efficiency in residential buildings and cars

Lead authors:

Edgar Hertwich (Norwegian University of Science and Technology), Reid Lifset (Yale School of Forestry & Environmental Studies, USA), Stefan Pauliuk (Faculty of Environment and Natural Resources, University of Freiburg, Germany), Niko Heeren (Yale School of Forestry & Environmental Studies, USA)

Contributing authors:

Saleem Ali (University of Delaware, USA), Peter Berrill (Yale School of Forestry & Environmental Studies USA), Tomer Fishman (Interdisciplinary Center Herzliya, Israel), Qingshi Tu (Yale School of Forestry & Environmental Studies USA), Paul Wolfram (Yale School of Forestry & Environmental Studies, USA)

7.1 Introduction

The production of materials is a significant source of greenhouse gas (GHG) emissions (figure 7.1). In 2015, materials production caused GHG emissions of 11 $GtCO_2e$, up from 5 $GtCO_2e$ in 1995, with the contribution of such production increasing from 15 per cent to 23 per cent of total global emissions over this period (Hertwich 2019). The largest contribution stems from bulk materials production, such as iron and steel, cement, lime and plaster, other minerals mostly used as construction products, as well as plastics and rubber (figure 7.1). Two thirds of the materials are used to make capital goods, with buildings and vehicles among the most important (figure 7.1). While the production of materials consumed in industrialized countries remained within the range of 2–3 $GtCO_2e$ in the 1995-2015 period, there was rapid growth in material-related emissions among developing and emerging economies (Hertwich 2019). Growth in investments is associated with a strong growth in metal consumption. Developing countries have stronger growth in metal consumption with gross domestic product (GDP) than industrialized countries, as a higher share of their GDP comprises investments (Zheng *et al.* 2018).

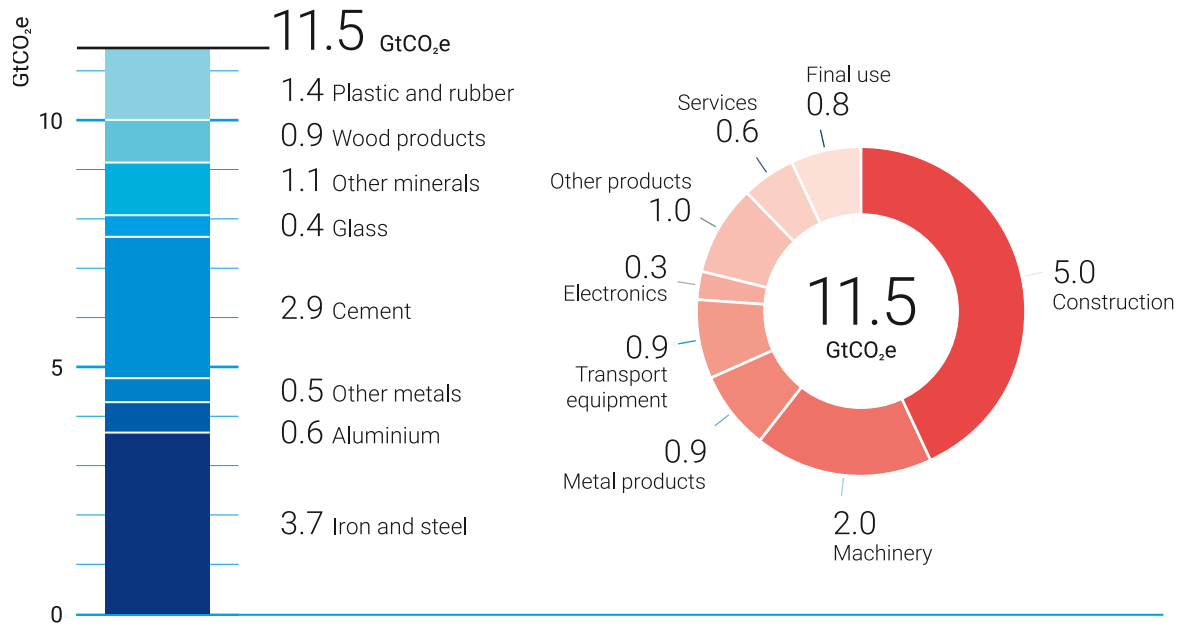
Options to mitigate emissions from materials production include supply-side measures, such as improved energy efficiency in production processes, the use of alternative production routes and raw materials with lower embodied GHG emissions, a shift towards cleaner energy sources and reductants, and CO_2 capture. Reducing the demand for materials is also an option to mitigate emissions and can be achieved through improving their efficiency (International Energy Agency [IEA] 2019a; Worrell *et al.* 2016).

Recent efforts have been made to evaluate the potential contribution of material efficiency to meet climate targets more broadly. In the Clean Technology Scenario of the International Energy Agency (IEA), compared with the baseline, steel demand is reduced by 24 per cent, cement by 15 per cent and aluminium by 17 per cent, which in total comprises around 30 per cent of the combined emission reductions for these materials. Other emission reductions were due to energy efficiency, innovative processes, cleaner energy and CO_2 capture and storage (IEA 2019a). Despite their effectiveness, material efficiency strategies have been systematically overlooked in climate policies (Hernandez *et al.* 2018).

Research on and development of demand-side material efficiency and substitution strategies has progressed substantially in the past decade (Allwood *et al.* 2017; Worrell *et al.* 2016; Zhang *et al.* 2018). Such research addresses the specific technical application of materials in buildings and other structures (Serrenho *et al.* 2019; Dunant *et al.* 2018), machinery (Milford *et al.* 2013) and vehicles (Løvik *et al.* 2014). Recent research combining insights from several bottom-up studies across different applications has identified that material efficiency could reduce emissions from steel production by half (Milford *et al.* 2013).

Material efficiency and substitution strategies affect not only energy demand and emissions during material production, but also potentially the operational energy use of the material products. Analysis of such strategies therefore requires a systems or life cycle perspective. Several investigations into material efficiency have focused on strategies that have little impact on operations, meaning that trade-offs and synergies have been ignored. Many energy efficiency

Figure 7.1. GHG emissions in $GtCO_2e$ associated with materials production by material (left) and by the first use of materials in subsequent production processes or final consumption (right)



Note: The data excludes emissions from land-use change and credits for carbon storage.
Source: Based on Hertwich *et al.* (2019).

strategies have implications for the materials used, such as increased insulation demand for buildings or a shift to more energy-intensive materials in the lightweighting of vehicles. While these additional, material-related emissions are well understood from technology studies, they are often not fully captured in the integrated assessment models that produce scenario results, such as those discussed in this report (Pauliuk *et al.* 2017).

In this chapter, focus is placed on residential buildings and cars, which are the most important individual products in terms of materials and energy use. Material efficiency strategies are reviewed with quantitative results presented of a recent modelling exercise for the implementation of such strategies in the G7 members (Canada, France, Germany, Italy, Japan, the United Kingdom and the United States of America), China and India, based on findings from an International Resource Panel study (International Resource Panel forthcoming). These countries were selected because they represent individually significant economies with varied development levels.
The following demand-side strategies for increased material efficiency in product design and manufacturing, use and end of life are considered for both residential buildings and cars (Allwood *et al.* 2011)

1) **Product lightweighting and material substitution** of high-carbon materials with low-carbon materials to reduce material-related GHG emissions associated with product production, as well as operational energy consumption of vehicles.

2) **Improvements in the yield of material production and product manufacture,** thus reducing the share of material that becomes waste in the production process.

3) **More intensive use, lifetime extension,** component reuse, remanufacturing and repair as strategies to obtain more service from material-based products.

4) **Enhanced recycling and reuse** so that secondary materials reduce the need to produce more emission-intensive primary materials.

7.2 Material-efficient housing

Global construction of buildings and infrastructure and the associated material supply caused 7 $GtCO_2e$ of GHG emissions in 2015, of which 4 $GtCO_2e$ were associated with the use of materials in construction (Hertwich 2019). In comparison, direct CO_2 emissions from fuel combustion in buildings were 3 $GtCO_2$, while emissions associated with the production of electricity consumed in buildings were 6.5 $GtCO_2$ (IEA 2019b). Although current statistics do not disaggregate construction-related emissions into residential and commercial buildings or consider infrastructure at a global scale, country-level results and material-use data suggest that residential buildings contribute 50–65 per cent of such emissions (Hertwich *et al.* 2019). In 2015, about 70 per cent of construction-related emissions were from developing countries (Hertwich 2019).

Despite this, studies of material efficiency options almost exclusively focus on industrialized countries, with just a few studies addressing China. Housing demand, construction style and building lifetimes are important drivers for material-related emissions of residential buildings. Research provides insight on the scope of various material efficiency strategies for residential buildings.

7.2.1 Product lightweighting and material substitution

Buildings often contain more energy-intensive materials such as concrete, steel and glass than technically required. There is a documented tendency for overdesign in larger steel-frame structures of around 20–30 per cent (Dunant *et al.* 2018). Cement, a major building material, is often used more than necessary in various applications, including concrete mixing, where fillers and other cementitious materials can substitute part of the cement with fewer emissions (John *et al.* 2018; Shanks *et al.* 2019). Finally, instead of using reinforced cement, masonry or steel frames, timber, bamboo and other plant fibres can be used as building materials, which has the potential to significantly reduce lifecycle GHG emissions in materials production and carbon storage, even when considering a potential trade-off with operational energy use (Heeren *et al.* 2015). New technology allows for a wider use of timber, even for tall structures. In some regions, building codes are being adapted to recognize these advances and facilitate the increased use of wood in buildings (Mahapatra *et al.* 2012). Large-scale use of wood as construction material necessitates that the forests from which the timber is obtained are managed sustainably (Kane and Yee 2017; Oliver *et al.* 2014). The International Resource Panel (forthcoming) estimates that through lightweighting structures, 8–10 per cent of GHG emissions related to materials in residential building construction in the G7 and China can be saved, with an even larger share in India (figure 7.2). An increased market penetration of wood could also reduce emissions or sequester carbon, corresponding to 10 per cent of GHG emissions from residential building materials, with savings reaching up to 30 per cent in India. At present, the country hardly uses timber in construction and lacks local resources and expertise.

Building codes, which have long been used to improve energy efficiency, present a potential model and platform for developing policies that support lighter-weight structures, the reuse of components and timber-based construction.

The rapid growth of certification systems for construction and building, such as Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM), and their adoption into building codes by governments worldwide has been an important policy driver for changes in construction practices (de Wilde 2014; Doan *et al.* 2017; Menezes *et al.* 2012). At present, certification is more widely applied to commercial buildings than to residential dwellings. However, the spread of certification systems and their use in building codes presents an opportunity to introduce or enhance material efficiency policies for homes that might not otherwise be politically feasible. The details of such certification systems therefore need to be monitored and evaluated and explicit attention should be given to the use of building codes as a policy instrument for material efficiency.

At the residential level and particularly for single family homes, minimum standards for energy efficiency, such as the International Energy Conservation Code (IECC) in the United States of America (International Code Council [ICC] 2012), have great potential to reduce operational energy consumption at the cost of increased material use. However, increased energy efficiency in buildings is achieved by adding additional or better insulation material and additional building technology, such as heat exchangers in ventilation systems. Compared with conventional buildings, energy-efficient buildings have lower lifecycle emissions, as energy demand is typically the main driver (Karimpour *et al.* 2014; Kristjansdottir *et al.* 2018). Some suggestions have been made to include embodied carbon in codes for new construction, with a focus on cement in concrete in California as one example (King 2018). Although it is unclear how quickly such stipulations will be adopted globally, they could significantly enhance reduced material use and the utilization of low-carbon materials.

7.2.2 Improvements in the yield of material production and product manufacturing

The use of building information systems and of prefabrication can reduce waste in the construction process, thus reducing the amount of primary materials required (Hertwich *et al.* 2019).

7.2.3 More intensive use and lifetime extension

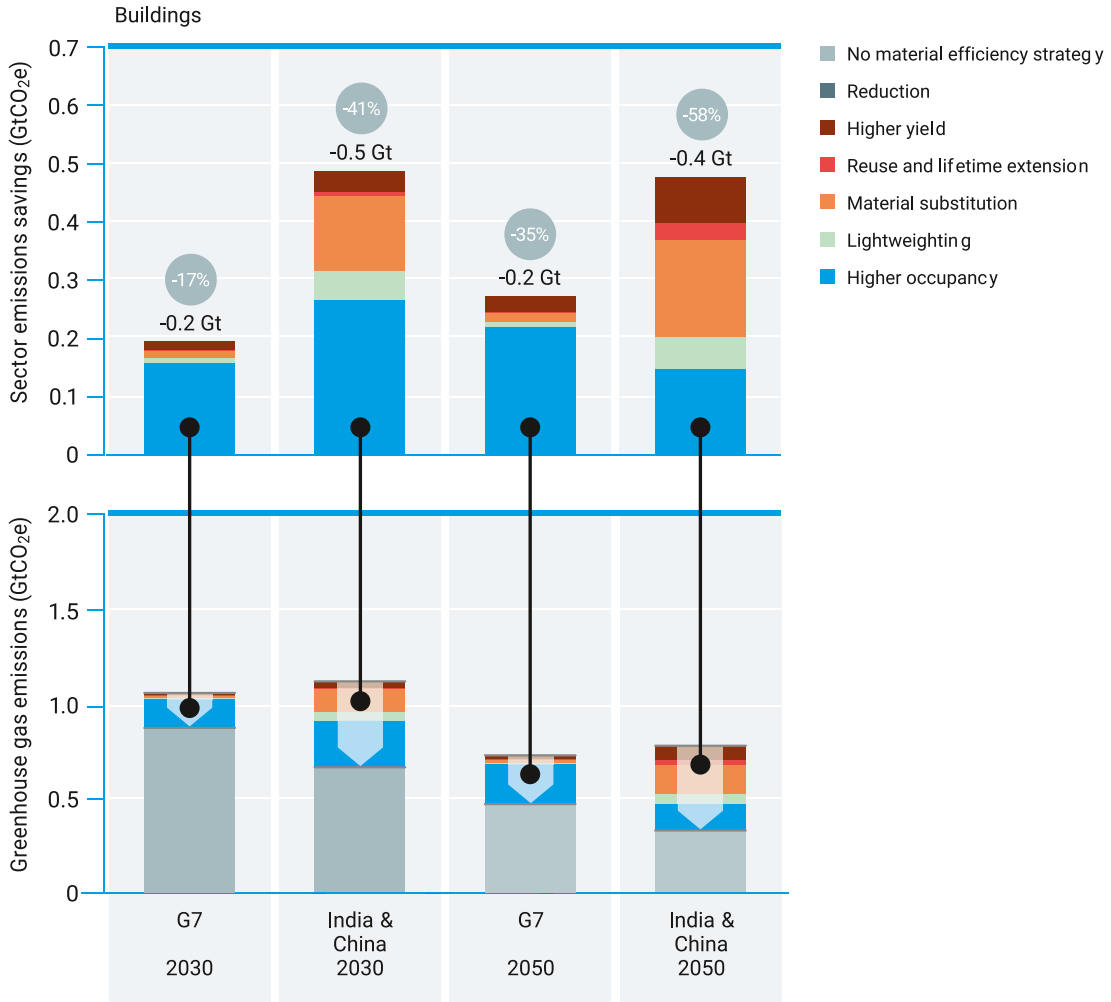
Housing demand tends to increase with a growing income, but varies widely across similar GDP/capita levels, from 34 m² per person in the United Kingdom to 68 m² in the United States. Such demand is influenced by tradition, planning rules, tax laws and available space. Multifamily and urban residences tend to be smaller than single family, suburban and rural residences. In most countries, the trend is shifting towards a smaller household size, which is leading to an increase in required space as facilities are shared between fewer people. Several studies show that future floor area demand is a crucial variable for GHG emissions and that more intensive use can result in significant reductions of both material and energy related emissions (Serrenho *et al.* 2019; Cao *et al.* 2018; Pauliuk *et al.* 2013). Such a reduction might be the result of urbanization (Güneralp *et al.* 2017), with populations moving from single family rural and suburban residences to multifamily houses in denser urban areas, increases in household size or cohabitation, the smarter design of buildings that allow resizing and tax or other incentives that encourage residents to downsize their residence after changes in family size (Lorek and Spangenberg 2018). The International Resource Panel (forthcoming) suggests that reducing per capita floor space by 20 per cent compared with a scenario that converges an industrialized-country's

floor space could reduce the emissions associated with the production of building materials for homes in G7 members by 50–60 per cent by 2050, given the already existing building stock. It would also reduce heating and cooling demand by up to 20 per cent, pending the retrofitting of existing buildings.

Policies that support homeownership may have the undesirable effect of subsidizing large residences through tax breaks and other measures. In some locations, spatial planning prevents the construction of multifamily residences and locks in suburban forms at high social and environmental costs. A reform of planning rules could bring about multiple benefits in this regard (Jones *et al.* 2018). One mechanism to increase the intensity of use is to strengthen incentives for older residents to downsize when children move out. Property taxes as well as an elimination of taxes on property transactions, such as the stamp duty in the United Kingdom, can have such an effect.

There is a wide variation in building lifetimes, from less than 25 years in some East Asian countries to more than 100 years in Europe. Extending building lifetimes can therefore have widely different effect. In China, extending the lifespan of buildings to 50 years could reduce CO_2 emissions by 400 Mt per year or about 20 per cent of construction-related emissions (Cai *et al.* 2015). In Europe, new buildings have lower energy use due to improvements in building standards and technology, with lifetime extensions resulting in higher total emissions compared with replacement buildings, unless the building are retrofit to a high energy standard (Serrenho *et al.* 2019). If only new, efficient buildings have

Figure 7.2. Annual emissions from the construction and operations of buildings in the G7 and in China and India, in a scenario that follows Shared Socioeconomic Pathway SSP1 to mitigate emissions to below 2°C



Source: International Resource Panel (forthcoming).

their lifetime extended, more modest savings will be had (figure 7.2) (International Resource Panel forthcoming). Policies requiring energy retrofit during building renovations, such as those of the European Union, could alleviate the trade-off between emissions savings from lifetime extension and operational energy use (International Energy Agency 2019b), though optimal strategies can only be identified on a case-by-case basis (Itard and Klunder 2007).

7.2.4 Enhanced recycling and reuse

Recycling of valuable materials is already widespread; reuse of building components is less common. When I-beams are reused, GHG savings can be significant, though there is the substantial logistical challenge of matching supply and demand, with reuse practices currently in decline (Densley Tingley *et al.* 2017). The recycling of construction and demolition waste from residential buildings offsets about 13–19 per cent of GHG emissions from building-material production in the G7. Metals are widely recycled and there is some recycling of timber and plastics. The use of concrete and other minerals as aggregates can still be improved, but emission savings are less.

Some policy levers are both well-studied and subject to overt policy worldwide. As is the case for recycling of construction and demolition waste (Brantwood Consulting 2016; Deloitte 2017), many are regulated to achieve other social or environmental goals (for example, limits on short-term lodging in residences), though some are still largely at the exploratory stage (disassembly of buildings).

7.3 Material-efficient cars

In 2015, light-duty vehicles (LDVs) contributed around 14 per cent or 7.5 $GtCO_2e$ to global GHG emissions. Of the emissions, 4.7 $GtCO_2e$ occurred during the operation of the vehicles (International Transport Forum 2019), 1.4 $GtCO_2e$ was associated with the production of fuels and another 1.4 $GtCO_2e$ was associated with the production of the vehicles (Hertwich 2019). Only about half of new vehicles replaced retired vehicles, with the remainder reflecting a growth in vehicle stock. G7 members were responsible for close to 40 per cent of the LDV-related GHG emissions, with the United States of America representing one quarter of global LDV emissions.

7.3.1 Product lightweighting and material substitution

Under a business-as-usual scenario, lightweighting vehicles with materials such as high-strength steel, aluminium or carbon fibre offers significant emission reductions of 3–6 per cent, if proper recycling of these materials can be instituted (Løvik *et al.* 2014; Milovanoff *et al.* 2019). The relative emission reductions from lightweighting are smaller for electric vehicles due to their lower operational emissions. Fuel-efficiency standards, fuel taxes and registration fees tied to the fuel economy are policy instruments that support vehicle lightweighting.

Downsizing the average size of vehicles is another important opportunity. In recent years, there has been a trend towards larger, heavier vehicles, such as sports-utility vehicles (SUVs) and pick-up trucks, which require more materials and higher operational energy use. Reversing that trend would reduce emissions substantially. Reducing the share of SUVs and light trucks in the United States of America from the current 53 per cent to 32 per cent by 2050 would reduce emissions from the production and operation of cars by 10 per cent. Registration fees tied to CO_2 emissions in some European countries have successfully reduced the CO_2 emissions rating of the average new vehicle, in part through shifting demand to smaller vehicles (D'Haultfœuille *et al.* 2016; Yan and Eskeland 2018). Fleets of shared vehicles tend to be smaller, but still provide users with transport capacity when it is needed. Encouraging collective rather than individual vehicle ownership could therefore help reduce vehicle mass and with this both material-related and operational emissions.

7.3.2 Improvements in the yield of material production and car manufacturing

Improvements in the yield of material production and car manufacturing can contribute modest reductions in material use and associated emissions (Milford *et al.* 2013).

7.3.3 More intensive use and lifetime extension

Car sharing, ride sharing and other measures to reduce individual automobility in favour of shared and collective transport can substantially reduce material use (Shaheen and Cohen 2019). Early evidence suggests that car sharing reduces household vehicle ownership and the average vehicle size (Chan and Shaheen 2012; Nijland and van Meerkerk 2017), though it also attracts users of public transport (Becker *et al.* 2018). There is also evidence to suggest that ride-hailing services, such as Uber and Lyft, can have an adverse effect and lead to increased traffic and vehicle size (Schaller 2017; Yin *et al.* 2018). Policies that discourage low-occupancy shared vehicles or penalize the increased congestion resulting from ride hailing, such as priority lanes for cars with three or more occupants or congestion pricing, can improve their environmental impact and material efficiency (Schaller 2018).

The International Resource Panel (forthcoming) estimates that having 25 per cent of drivers shift to car sharing would reduce emissions by 10 per cent, while shifting 25 per cent of trips to shared rides would reduce emissions by 20 per cent (figure 7.3). In some rich countries, car ownership is already starting to reduce, especially among younger urban populations, a trend that can be furthered by tax policies, parking fees and regulatory and institutional support for shared mobility. Most policies on shared mobility, however, currently focus on regulating drivers and services, rather than on environmental impacts and use of resources.

Extending the life of materials, through repair, reuse and remanufacturing, may reduce material-related emissions, but could also increase operational emissions when a

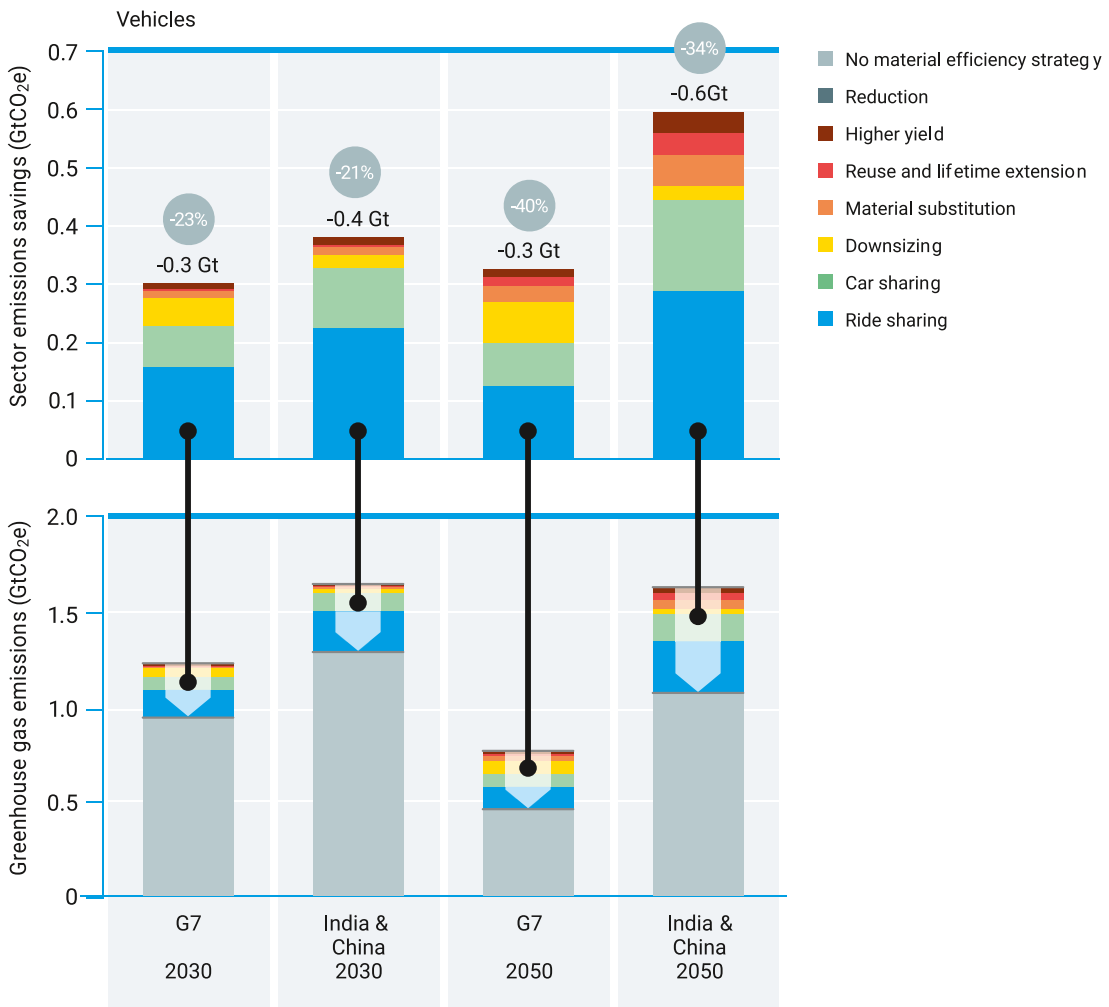
newer car may be more efficient or use a cleaner fuel (Kagawa *et al.* 2013; Lenski *et al.* 2013). Much vehicle reuse is connected to the export of vehicles from wealthier to poorer countries, where vehicle recycling is not as well established or sophisticated. In such cases, reuse may meet unmet needs but at the expense of increasing material-related emissions.

In the future, it is anticipated that individual car ownership may be replaced by fleets of self-driving vehicles (Greenblatt and Saxena 2015; Jones and Leibowicz 2019), which could result in a decrease in the number of vehicles needed and an increase in the use of such vehicles. If unregulated, such a trend will also likely increase driving distances which would impact emissions and may move people away from using more efficient public transport. With a policy that discourages individual ownership and enhances interoperability among public transport systems, self-driving cars could offer more ride-sharing services and be used as last-mile solutions in public transport systems (Hertwich *et al.* 2019).

7.3.4 Enhanced recycling and reuse

Current recycling of metals from end-of-life vehicles (ELV) is well established. The International Resource Panel (forthcoming) estimates that recycling of ELV offsets about half of the emissions in the primary production of the materials used to make the vehicle. Strengthening the reuse of components also offers significant savings (International Resource Panel forthcoming; Milford *et al.* 2013). Within policies, recycling is typically measured in terms of recycling rates and landfill diversion rather than GHG emissions (Sawyer-Beaulieu and Tam 2006). Adjusting ELV policies to incorporate considerations of embodied carbon warrants attention. The recovery of vehicle parts

Figure 7.3. Annual emissions from the manufacturing and use of passenger vehicles in the G7 and in China and India, in a scenario that follows the Shared Socioeconomic Pathway SSP1 to mitigate emissions to below 2°C



Source: International Resource Panel (forthcoming).

and the alloy-specific (closed-loop) recycling of metals may have a larger emissions pay-off than current shredding practices (Ohno *et al.* 2017; Sato *et al.* 2019). This could be achieved by developing reuse regulations and through more standardization across manufacturers. Some GHG reduction potential is missed because much of the steel in cars is downcycled to uses that are tolerant to copper contamination generated in the shredding of ELVs, such as, for example, reinforcing bar (Daehn *et al.* 2017). If the mixing of steel and copper in the recycling process were reduced, recycled steel could be used for higher value uses, such as car bodies, thereby reducing GHG emissions.

7.4 Summary and link to policy

Research has shown that demand-side material efficiency offers substantial GHG mitigation opportunities that are complementary to those obtained through an energy system transformation (see chapter 6). The potential of purely technical strategies is limited, but considered relatively easy to achieve, whereas the more intense use of housing and vehicles has larger potential, though it would impact social structures and lifestyles. Demand-side material efficiency widens the spectrum of emissions mitigation strategies and may therefore reduce the need for other risky, contested, unproven or expensive technologies.

Knowledge gaps regarding the link between material efficiency and climate change mitigation continue to exist, especially regarding the efficacy of policies where the focus of material efficiency has largely been confined to the end-of-life stage, such as targets for increased recycling. Socioeconomic transformations are crucial to harnessing the full potential of material efficiency, as, for example, greater intensity of use implies significant changes in use patterns or car ownership. The feasibility of and pathway towards such transformations in a carbon-constrained world requires further investigation. More intensive use is likely have a rebound effect, with money saved on car ownership being used for vacation travels or other high-emission activities (Makov and Font Vivanco 2018; Underwood and Fremstad 2018). Carbon pricing is a policy tool that can help minimize a rebound effect. It is important to gain a better understanding of other products and the coupling of sectors and cascading of materials, including implications to material quality resulting from increased reuse and recycling. Furthermore, the influence of the urban form, land-use planning and policies on service demand and consumption patterns need to be better understood.

Demand-side material efficiency and related reductions in energy consumption and GHG emissions could be achieved through a number of policies, including carbon taxation on bulk materials (Neuhoff *et al.* 2016), eco-design laws (Official Journal of the European Union 2009), green public procurement (Organisation for Economic Co-operation and Economic Development [OECD] 2015) or circular economy strategies (Material Economics 2018), as well as sector-specific approaches, such as changes in building codes (ICC 2018). However, not all policies aimed at resource efficiency or circular economy automatically have co-benefits with climate change mitigation. For example, a prolonged product lifetime as a result of policies may under certain circumstances actually delay the introduction of more efficient products, thus leading to higher system-wide emissions. Use of life cycle assessments and related forms of systems measurement, as well as careful and integrative policy design and evaluation are necessary for the more efficient use of resources, which will also lead to reduced emissions.

References

Chapter 1

C

Christensen, J. and Olhoff, A. (2019). Lessons from a decade of emissions gap assessments. Nairobi: United Nations Environment Programme (UNEP). https://wedocs.unep.org/bitstream/handle/20.500.11822/30022/EGR10.pdf?sequence=1&isAllowed=y. Accessed 29 October 2019.

Chapter 2

A

Al-Ghabban, A. (2013). Saudi Arabia's Renewable Energy Strategy and Solar Energy Deployment Roadmap, King Abdullah City for Atomic and Renewable Energy, p. 60. https://www.irena.org/DocumentDownloads/masdar/Abdulrahman Al Ghabban Presentation.pdf.

Al-Sarihi, A. (2019). *Climate Change and Economic Diversification in Saudi Arabia: Integrity, Challenges, and Opportunities*. Washington D.C.: Arab Gulf States Institute in Washington (AGSIW).

Ángel Gurría (2019). Presentation of the OECD "Financing Climate Futures" report. https://www.oecd.org/about/secretary-general/financing-climate-futures-rethinking-infrastructure-mexico-may-2019.htm. Accessed 5 November 2019.

Argentina, Boletín Oficial de la República Argentina (2019). *Resolución* 276/2019. https://www.boletinoficial.gob.ar/detalleAviso/primera/207713/20190517. Accessed 10 September 2019.

Argentina, Gabinete National de Cambio Climático (2019). Planes de Acción Nacionales Sectoriales de Cambio Climático [National Sectoral Climate Change Plans]. https://www.argentina.gob.ar/ambiente/sustentabilidad/planes-sectoriales.

Argentina, Ministerio de Ambiente y Desarrollo Sustentable (2018). *Monitoreo de la superficie de bosque nativo de la República Argentina* [Monitoring the area of Argentina's native forest]. https://www.argentina.gob.ar/sites/default/files/1.informe_monitoreo_2017_tomo_i1_3_0.pdf.

Australia, Department of the Environment and Energy (2018). *Australia's emissions projections 2018*. https://www.environment.gov.au/climate-change/publications/emissions-projections-2018.

Australia, Department of the Environment and Energy (2019). Climate Solutions Fund - Emissions Reduction Fund. https://www.environment.gov.au/climate-change/government/emissions-reduction-fund.

B

Baruj, G. and Drucaroff, S. (2018). *Estimaciones del potencial económico del océano en la Argentina* [Estimations of the ocean's economic potential in Argentina]. Buenos Aires: Centro Interdisciplinario de Estudios en Ciencia, Tecnologíá e Innovación. http://www.ciecti.org.ar/wp-content/uploads/2018/04/IT10-Pampa-azul_vDigital_16-abril-2018.pdf.

Bellini, E. (2019). Saudi Arabia plans new long-term RE targets, will resume tenders, 3 January. https://www.pv-magazine.com/2019/01/03/saudi-arabia-plans-to-set-new-long-term-re-targets-and-to-resume-tenders/. Accessed 10 September 2019.

BP (2019). *BP Statistical Review of World Energy 2019. 68th edition*. London. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf.

Brazil, Electricity Regulatory Agency (2019). *Resumo dos resultados dos Leilões de Geração no ACR de 2005 a 2019* [Summary of generation auctions in the Regulated Contracting Environment 2005 –2019]. Brasilia. https://www.aneel.gov.br/resultados-de-leiloes. Accessed 16 October 2019.

Brazil, Ministry of Science, Technology, Innovation and Communications (2019). *Brazil's third biennial update report to the United Nations Framework Convention on Climate Change*. https://unfccc.int/sites/default/files/resource/2018-02-28_BRA-BUR3_ENG_FINAL.pdf.

Buckley, T. and Garg, V. (2019). IEEFA briefing note: India's electricity sector transition still on track despite a weak FY2018/19, 25 April. http://ieefa.org/ieefa-briefing-note-indias-electricity-sector-transition-still-on-track-despite-a-weak-fy2018-19/. Accessed 13 September 2019.

Buckley, T. and Shah, K. (2019). IEEFA India: New record with renewable energy installations 40 times higher than thermal, 29 January. http://ieefa.org/ieefa-india-new-record-with-renewable-energy-installations-40-times-higher-than-thermal/. Accessed 13 September 2019.

C

Canada, Alberta Queen's Printer (2019). *An Act to Repeal the Carbon* Tax. http://www.qp.alberta.ca/1266.cfm?page=2019ch01.cfm&leg_type=Acts&isbncln=9780779810574.

Chosunilbo (2019). South Chungcheong Governor Resists Gov't's Coal Power Plans, 25 Janaury. http://english.chosun.com/site/data/html_dir/2019/01/25/2019012501708.html. Accessed 10 September 2019.

Chung, J. (2019). South Korea fires up on renewables, to close more coal plants, 18 June. https://www.reuters.com/article/us-southkorea-energy-renewable-analysis/south-korea-fires-up-on-renewables-to-close-more-coal-plants-idUSKCN1TJ0JK. Accessed 10 September 2019.

Clean Energy Regulator (2017). Energy Reduction Fund Project Map, 3 August. http://www.cleanenergyregulator.gov.au/ERF/project-and-contracts-registers/interactive-map. Accessed 10 September 2019.

Clean Energy Regulator (2018). When does the Renewable Energy Target end?, 25 May. http://www.cleanenergyregulator.gov.au/RET/Pages/About the Renewable Energy Target/When-does-the-Renewable-Energy-Target-end.aspx. Accessed 10 September 2019.

Climate Action Tracker (2017). F*oot off the gas: increased reliance on natural gas in the power sector risks an emissions lock-in*. https://climateactiontracker.org/documents/55/CAT_2017-06-16_DecarbNaturalGas_CATAnalysis.pdf.

Climate Action Tracker (2019a). Australia, 17 June. https://climateactiontracker.org/countries/australia/. Accessed 5 November 2019.

Climate Action Tracker (2019b). Brazil, 17 June. https://climateactiontracker.org/countries/brazil/. Accessed 5 August 2019.

Climate Action Tracker (2019c). Canada, 17 June. https://climateactiontracker.org/countries/canada/. Accessed 23 September 2019.

Climate Action Tracker (2019d). Countries. https://climateactiontracker.org/countries/. Accessed 13 August 2019.

Climate Action Tracker (2019e). Indonesia, 17 June. https://climateactiontracker.org/countries/indonesia/.

Climate Change Authority (2017). *Review of the emissions reduction fund. December 2017.* http://climatechangeauthority.gov.au/review-emissions-reduction-fund.

Compañía Administradora del Mercado Mayorista Eléctrico S.A. (CAMMESA) (2019). Renovables Hoy [Renewables Today]. https://despachorenovables.cammesa.com/renovables/. Accessed 13 September 2019.

D

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.

E

Energy & Climate Intelligence Unit (2019). Net Zero Tracker. https://eciu.net/netzerotracker. Accessed 10 September 2019.

Europe Beyond Coal (2019). Overview: *National coal phase-out announcements in Europe. Status March 2019.*

European Commission (2018a). *A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy.* Brussels. COM(2018) 773 final.

European Commission (2018b). In-*depth analysis in support of the Commission Communication COM(2018) 773: A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy.* Brussels. https://ec.europa.eu/knowledge4policy/publication/depth-analysis-support-com²018-773-clean-planet-all-european-strategic-long-term-vision_en.

European Commission (2018c). New Renewables, Energy Efficiency and Governance legislation comes into force on 24 December 2018, 21 December. https://ec.europa.eu/info/news/new-renewables-energy-efficiency-and-governance-legislation-comes-force-24-december-2018-2018-dec-21_en. Accessed 16 October 2019.

European Commission (2019a). *Clean mobility: Putting an end to polluting trucks. Commission welcomes first-ever EU standards to reduce pollution from trucks.* 18 February. http://europa.eu/rapid/press-release_IP-19-1071_en.htm.

European Commission (2019b). *Energy Union: Commission calls on Member States to step up ambition in plans to implement Paris agreement.* 18 June. https://ec.europa.eu/clima/news/energy-union-commission-calls-member-states-step-ambition-plans-implement-paris-agreement_en.

European Commission (2019c). *Clean mobility: New CO_2 emission standards for cars and vans adopted.* 15 April. https://ec.europa.eu/clima/news/clean-mobility-new-co2-emission-standards-cars-and-vans-adopted_en.

European Environment Agency (2018) *Trends and projections in Europe 2018. Tracking progress towards Europe's climate and energy targets.* Copenhagen. https://www.eea.europa.eu//publications/trends-and-projections-in-europe-2018.

F

Food and Agriculture Organization Corporate Statistical Database (2019). Land Use Total. http://www.fao.org/faostat/en/#data/GL. Accessed 19 September 2019.

Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Hauck, J., Peters, G. P., Peters, W. et al. (2019). Global Carbon Budget 2019. *Earth System Science Data* 11, 1783-1838. https://doi.org/10.5194/essd-11-1783-2019

G

Germany, Federal Ministry for Economic Affairs and Energy (2019). *Commission on Growth, Structural Change and Employment. Final Report.* Berlin. https://www.bmwi.de/Redaktion/EN/Publikationen/commission-on-growth-structural-change-and-employment.pdf?__blob=publicationFile&v=3https://www.bmwi.de/Redaktion/EN/Publikationen/commission-on-growth-structural-change-and-employment.pdf?__blob=publicationFile&v=3.

Global Forest Watch (2018). 2017 Was the Second-Worst Year on Record for Tropical Tree Cover Loss, 27 June. https://blog.globalforestwatch.org/data-and-research/2017-was-the-second-worst-year-on-record-for-tropical-tree-cover-loss. Accessed 10 September 2019.

Government of Brazil (2019). Programa de Parcerias de Investimentos [Investment Partnership Program]. https://www.ppi.gov.br/.

Government of Canada (2018a).*Regulations Amending the Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations: SOR/2018-263.* Canada Gazette, Part II 152(25).

Government of Canada (2018b). R*egulations Limiting Carbon Dioxide Emissions from Natural Gas-fired Generation of Electricity.* Canada Gazette, Part II 152(25). http://www.gazette.gc.ca/rp-pr/p2/2018/2018-12-12/html/sor-dors261-eng.html.

Government of Canada, Transport Canada (2019). Zero-emission vehicles. https://www.tc.gc.ca/en/services/road/innovative-technologies/zero-emission-vehicles.html. Accessed on 5 November 2019.

Government of Mexico (2019). *Tren Maya* [Maya Train]. http://www.trenmaya.gob.mx/.

Grassi, G., House, J., Dentener, F., Federici, S., den Elzen, M., & Penman, J. (2017). The key role of forests in meeting climate targets requires science for credible mitigation, Nature Climate Change, 7, pp. 220–226. doi: 10.1038/nclimate3227.

Gubinelli, G. (2018). *Plazos y tasas del RenovAr: la mirada de entidades bancarias a la hora de financiar proyectos de energías renovables* [RenovAr terms and rates: a look at banking institutions in financing renewable energy projects]. http://www.energiaestrategica.com/plazos-y-tasas-del-renovar-la-mirada-de-entidades-bancarias-a-la-hora-de-financiar-proyectos-de-energias-renovables/. Accessed 13 September 2019.

H

Hang, A. (2019). Is China Ready for Subsidy-Free Renewables, 31 May. https://www.greentechmedia.com/articles/read/is-china-ready-for-subsidy-free-renewables#gs.qmlij0. Accessed 13 September 2019.

He, H. and Cui, H. (2019). China announced 2019 subsidies for new energy vehicles. International Council on Clean Transportation, 18 June. https://theicct.org/publications/china-announced-2019-subsidies-new-energy-vehicles. Accessed 10 September 2019.

Hill, J. S. (2019). China Approves 21 Gigawatts Of Grid-Parity Wind & Solar Projects, 23 May. https://cleantechnica.com/2019/05/23/china-approves-21-gigawatts-of-grid-parity-wind-solar-projects/. Accessed 13 September 2019.

Houghton, R.A. and Nassikas, A.A. (2017). Global and regional fluxes of carbon from land use and land cover change 1850–2015. *Global Biogeochemical Cycles* 31(3), 456–472. https://doi.org/10.1002/2016GB005546.

I

India, Cabinet Committee on Economic Affairs (2018). 100% Electrification of Broad Gauge Routes of Indian Railways. https://pib.gov.in/newsite/PrintRelease.aspx?relid=183399. Accessed 5 November 2019.

India, Cabinet Committee on Economic Affairs (2019). Cabinet approves launch Kisan Urja Suraksha evam Utthaan Mahabhiyan, 19 February. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1565274.

India, Ministry of Environment, Forest and Climate Change (2019a). *India Cooling Action Plan.* New Delhi.

India, Ministry of Environment, Forest and Climate Change (2019b). NCAP: *National Clean Air Programme.* New Delhi.

India, Ministry of Power (2019). Saubhagya Dashboard. http://saubhagya.gov.in/dashboard. Accessed 22 June 2017.

India, Parliamentary Standing Committee on Energy (2018). T*hirty-seventh Report. Stressed/Non-performing Assets in Electricity Sector.* New Delhi. http://164.100.47.193/lsscommittee/Energy/16_Energy_37.pdf.

India, Press Information Bureau (2019). Cabinet approves Scheme for FAME India Phase II. New Delhi. https://pib.gov.in/newsite/PrintRelease.aspx?relid=189081.

Iguacel, J. (2018). Pasado, presente y futuro de la energía en Argentina [Past, present and future of energy in Argentina]. Neuquén, August. https://www.argentina.gob.ar/sites/default/files/2018-08-10_ppt_ji_neuquen_v4.5_f.pdf.

Instituto National de Tecnología Agropecuaria (n.d.). *Programa Nacional de los Suelos* [National Soils Programme]. https://inta.gob.ar/pnsuelos. Accessed 13 September 2019.

Intergovernmental Panel on Climate Change (2018). *Summary for Policymakers. Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.*

Intergovernmental Panel on Climate Change (2019). *Summary for Policymakers. Climate Change and Land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.*

International Energy Agency (2019). *Global Energy & CO_2 Status Report: The latest trends in energy and emissions in 2018*. https://www.iea.org/geco/. Accessed 10 September 2019.

J

Japan, Ministry of Economy, Trade and Industry (2018). *Long-Term Goal and Strategy of Japan's Automotive Industry for Tackling Global Climate Change.*

Japan, Ministry of Economy, Trade and Industry (2019a). *Kaiyo saisei kano enerugi hatsuden setsubi no seibi ni kakaru kaiiki no riyo no sokushin ni kansuru hōritsu-an' ga kakugi kettei sa remashita* [Act for promoting the utilization of sea areas in the development of power generation facilities using maritime renewables]. Tokyo.

Japan, Ministry of Economy, Trade and Industry (2019b). T*aiyohikarihatsuden jigyo ni kansuru kankyo eikyo hyoka ni tsuite* [About environmental impact assessments for solar power generation projects]. Tokyo.

Japan, Ministry of Economy, Trade and Industry (2019c). *Third interim report by the Committee on Energy Efficiency and Renewable Energy and the Subcommittee on Mass Introduction of Renewable Energy and Next-Generation Electricity Networks of the Electricity and Gas Industry Committee* [in Japanese]. Tokyo.

Japan, Ministry of the Environment (2019). Denryoku bunya no teitansoka ni mukete – *Arata na 3tsu no action* [Three new actions for a low-carbon power sector]. http://www.env.go.jp/press/files/jp/111265.pdf.

Jong, H.N. (2019). Indonesia forest-clearing ban is made permanent, but labeled 'propaganda', 14 August. https://news.mongabay.com/2019/08/indonesia-forest-clearing-ban-is-made-permanent-but-labeled-propaganda/. Accessed 10 September 2019.

K

KBS (2019). 앵커의 눈/단독〕'탈석탄·전기요금' 서민 직결 정책 깜깜이 논의 [Anchor's Eye/Exclusive] 'De-coal and Electricity Bill' Direct Policy, 8 June. https://mn.kbs.co.kr/news/view.do?ncd=4217276. Accessed 10 September 2019.

Keesler, D., Orifici, L. and Blanco, G. (2019). *Situación actual y proyección de emisiones de gases de efecto invernadero en la Argentina* [Current situation and projection of greenhouse gas emissions in Argentina]. Buenos Aires: Universidad Nacional del Centro de la Provincia de Buenos Aires. https://www.fio.unicen.edu.ar/images/pdf/2019/Informe_GREENPEACE_-_CTAE-FIO-UNICEN.pdf.

Keramidas, K., Tchung-Ming, S., Diaz-Vazquez, A.R., Weitzel, M., Vandyck, T., Després, J. et al. (2018). Global Energy and Climate Outlook 2018: *Sectoral mitigation options towards a low-emissions economy – Global context to the EU strategy for long-term greenhouse gas emissions reduction.* Luxembourg: Publications Office of the European Union. https://doi.org/10.2760/67475.

Kingdom of Saudi Arabia (2016). *Vision 2030.* http://vision2030.gov.sa/en/media-center.

KPMG (2019). *Carbon Tax: A Burning Issue.* https://home.kpmg/content/dam/kpmg/xx/pdf/2019/02/tnf-south-africa-feb25-2019.pdf. Accessed 25 April 2019.

Kuramochi, T., Fekete, H., Luna, L., de Villafranca Casa, M.J., Nascimento, L., Hans, F. et al. (2018). *Greenhouse gas mitigation scenarios for major emitting countries. Analysis of current climate policies and mitigation commitments: 2018 update.* NewClimate Institute, PBL Netherlands Environmental Assessment Agency and International Institute for Applied Systems Analysis.

L

Larsen, K., Houser, T. and Mohan, S. (2019). Sizing Up a Potential Fuel Economy Standards Freeze, 3 May. htpps://rhg.com/research/sizing-up-a-potential-fuel-economy-standards-freeze/. Accessed 16 September 2019.

Le Quéré, C., Andrew, R.M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A.C. et al. (2018). Global Carbon Budget 2017, *Earth System Science Data* 10, 405–448. https://doi.org/10.5194/essd-10-405-2018.

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(3), 213–217. https://doi.org/10.1038/s41558-019-0419-7.

M

Marsden Jacob Associates (2018). *Modelling Snowy 2.0* in the NEM. Public Report. https://www.snowyhydro.com.au/wp-content/uploads/2018/12/MJA-NEM-Study-Public-Report-3Dec2018.pdf.

Mercado Eléctrico (2019). Se licitarán líneas de transporte junto con las Energías Renovables Ronda Renovar IV [Transport lines will be tendered together with Renewable Energy Round IV], 4 April. http://www.melectrico.com.ar/web/index.php?option=com_content&view=article&id=2362:se-licitaran-lineas-de-transporte-junto-con-las-energias-renovables-ronda-renovar-iv&catid=1:latest-news. Accessed 13 September 2019.

Mexico, Cámara de Diputados del H. Congreso de la Unión (2012). *Ley General de Cambio Climático.* Diario Oficial de la Federación. http://www.diputados.gob.mx/LeyesBiblio/ref/lgcc.htm.

Mexico, Cámara de Diputados del H. Congreso de la Unión (2015). *Ley de Transición Energética.* Diario Oficial de la Federacion. http://www.diputados.gob.mx/LeyesBiblio/pdf/LTE.pdf.

Mexico, Centro Nacional de Control de Energía (2018). Acuerdo de suspensión de la SLP No. 1 2018 [Suspension Agreement for SLP No. 1 2018]. Mexico City.

Mexico, Diario Oficial de la Federación (2019). *Plan Nacional de Desarrollo* 2019-2024. https://www.dof.gob.mx/nota_detalle.php?codigo=5565599&fecha=12/07/2019.

Mexico, Ministry of Energy (2019). *Programa de Desarrollo del Sistema Eléctrico Nacional 2019-2033* [National Electricity System Development Programme 2019–2033]. Mexico City. https://www.gob.mx/sener/documentos/prodesen-2019-2033. Accessed 6 October 2019.

Mongabay (2018). Indonesian president signs 3-year freeze on new oil palm licenses, 20 September. https://news.mongabay.com/2018/09/indonesian-president-signs-3-year-freeze-on-new-oil-palm-licenses/. Accessed 18 April 2019.

N

National Development and Reform Commission of China (2019a). Notice of the NDRC on improving the mechanism for grid-connected prices for solar PV power projects.

National Development and Reform Commission of China (2019b). Notice of the NDRC on improving the policy for grid-connected prices for wind power projects.

National Energy Administration of China (2019). *Notice on coal power planning and construction risks warning for 2022.*

National Energy Administration, National Development and Reform Commission and Ministry of Finance of China (2019). Notice of the NDRC, MOF and NEA on solar PV project generation issues of 2018.

Natural Resources Defense Council (2018). C*omments of the Natural Resources Defense Council on EPA's Proposed Emission Guidelines for Greenhouse Gas Emissions From Existing Electric Utility Generating Units; Revisions to Emission Guideline Implementing Regulations; Revisions to New Source Review.* https://www.nrdc.org/sites/default/files/nrdc-ace-comments-20181031.pdf. Accessed 16 September 2019.

Nereim, V. (2017). Saudi Arabia Slows Pace of Energy Subsidy Cuts to Boost Economy, 19 December. https://www.bloomberg.com/news/articles/2017-12-19/saudi-arabia-slows-pace-of-energy-subsidy-cuts-to-boost-economy. Accessed 15 April 2018.

Nereim, V. and Cunningham, S. (2018). Saudis, SoftBank Plan World's Largest Solar Project, 28 March. https://www.bloomberg.com/news/articles/2018-03-28/saudi-arabia-softbank-ink-deal-on-200-billion-solar-project?utm_source=CP+Daily&utm_campaign=6344d9f796-CPdaily28032018&utm_medium=email&utm_term=0_a9d8834f72-6344d9f796-110247033. Accessed 7 November 2018.

Norway, Ministry of Climate and Environment (2016). *Press release: - Indonesia's Peat Moratorium could benefit people, welfare and climate.* 5 December. https://www.regjeringen.no/en/aktuelt/indonesias-president-forbyr-a-odelegge-torvmyrer/id2522663/. Accessed 10 September 2019.

Notimex (2019). CCE pide a gobierno de AMLO continuar con subastas de energía limpia [CCE asks the AMLO Government to continue clean energy tenders], 31 January. https://www.eleconomista.com.mx/empresas/CCE-pide-a-gobierno-de-AMLO-continuar-con-subastas-de-energia-limpia-20190131-0077.html. Accessed 10 September 2019.

O

Olivier, J.G.J. and Peters, J.A.H.W. (2018). *Trends in global CO_2 and total greenhouse gas emissions:* 2018 report. The Hague: PBL Netherlands Environmental Assessment Agency. https://www.pbl.nl/sites/default/files/downloads/pbl-2018-trends-in-global-co2-and-total-greenhouse-gas-emissons-2018-report_3125_0.pdf.

Olivier, J.G.J. and Peters, J.A.H.W. (2019). *Trends in global CO_2 and total greenhouse gas emissions:* 2019 report. The Hague: PBL Netherlands Environmental Assessment Agency. https://www.pbl.nl/en/publications/trends-in-global-co2-and-total-greenhouse-gas-emissions-2019-report.

P

Pan, C., Peters, G.P., Andrew, R.M., Korsbakken, J.I., Li, S., Zhou, D. and Zhou, P. (2017). Emissions embodied in global trade have plateaued due to structural changes in China, *Earth's Future* 5(9), 934–946. https://doi.org/10.1002/2017EF000625.

Panigatti, J.L. (2010). *Argentina 200 Años 200 Suelos* [Argentina 200 years 200 soils]. https://inta.gob.ar/sites/default/files/script-tmp-inta-200-suelos.pdf.

Peters, G.P., Minx, J.C., Weber, C.L. and Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008, *Proceedings of the National Academy of Sciences* 108(21), 8903–8908. https://doi.org/10.1073/pnas.1006388108.

Powering Past Coal Alliance (2018). South Chungcheong Province, home to half of South Korea's coal power generation, joins PPCA, 2 October. https://poweringpastcoal.org/news/member-news/South-Chungcheong-Province-South-Korea-coal-Powering-Past-Coal-Alliance. Accessed 10 September 2019.

P

President of Indonesia (2018). *Instruksi presiden republik Indonesia nomor 8 tahun 2018 tentang penundaan dan evaluasi perizin* [Presidential Instruction no. 8 of 2018 on the postponement and evaluation of oil palm plantation licensing and improved productivity of oil palm plantations]. Jakarta. https://assets.documentcloud.org/documents/4910673/Inpres-Moratorium-Sawit.pdf.

President of Indonesia (2019). *Penghentian Pemberian Izin Baru dan Penyempurnaan Tata Kelola Hutan Alam Primer dan Laha* [Presidential instruction (Inpres) no. 5 of 2019: Termination of granting new permits and improving governance of primary natural forests and peatlands]. Jakarta. https://peraturan.bpk.go.id/Home/Download/107863/Inpres No. 5 Tahun 2019.pdf.

PRODES (2019). Monitoramento da Floresta Amazônica Brasileira por Satélite [Amazon forest monitoring by satellite]. http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes. Accessed 29 May 2019.

R

Republic of Indonesia (2019). *Rencana Usaha Penyediaan Tenaga Listrik* (RUPTL) 2019–2028 [General Power Supply Plan 2019–2028].

Republic of Indonesia, Ministry of Eenergy and Mineral Resources (2017). *2017 Handbook of Energy and Economic Statistics of Indonesia*. Jakarta. https://www.esdm.go.id/assets/media/content/content-handbook-of-energy-economic-statistics-of-indonesia-2017-.pdf.

Republic of Korea, Ministry of Environment (2018). National greenhouse gas reduction target by 2030: Amended baseline roadmap for achieving the target [in Korean]. Seoul. http://energytransitionkorea.org/sites/default/files/2018-11/18.072030-온실가스-감축로드맵-수정안관계부처-합동 %281%29.pdf.

Republic of South Africa, Department of Energy (2018). Draft Integrated Resource Plan 2018. Pletoria. http://www.energy.gov.za/IRP/irp-update-draft-report2018/IRP-Update-2018-Draft-for-Comments.pdf. Accessed 5 September 2019.

Republic of South Africa, Department of Environmental Affairs (2018). *Climate Change Bill, 2018*. Government Gazette. https://www.environment.gov.za/sites/default/files/legislations/climatechangebill2018_gn41689.pdf.

Reuters (2019). South African parliament approves long-delayed carbon tax bill, 19 February. https://www.reuters.com/article/us-safrica-carbontax/south-african-parliament-approves-long-delayed-carbon-tax-bill-idUSKCN1Q81U8. Accessed 25 April 2019.

Rochedo, P.R.R., Soares-Filho, B., Schaeffer, R., Viola, E., Szklo, A., Lucena, A.F.P. et al. (2018). The threat of political bargaining to climate mitigation in Brazil, *Nature Climate Change* 8, 695–698. https://doi.org/10.1038/s41558-018-0213-y.

Rogelj, J., Nabel, J., Chen, C., Hare, W., Markmann, K., Meinshausen, M. et al. (2010). C*openhagen Accord pledges are paltry, Nature* 464, 1126–1128. https://doi.org/10.1038/4641126a.

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H. et al. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 °C, *Nature* 534, 631–639. https://doi.org/10.1038/nature18307.

S

Sauer, N. and Collett-White, R. (2019). Russia floats first law to regulate CO_2 emissions, 22 March. https://www.climatechangenews.com/2019/03/22/russia-floats-first-law-regulate-carbon-emissions/. Accessed 2 May 2019.

Singh, N. (2019). El PRODESEN 2019-2033 planea más de 50 proyectos de expansión de redes de transmisión y distribución para lograr una mejor integración de renovables, Energía Estratégica [PRODESEN 2019-2033 plans more than 50 projects to expand transmission and distribution networks to better integrate renewables], 3 June. https://www.energiaestrategica.com/el-prodesen-2019-2033-planea-mas-de-50-proyectos-de-expansion-de-redes-de-transmision-y-distribucion-para-lograr-una-mejor-integracion-de-renovables. Accessed 13 September 2019.

Solís, A. (2018a). AMLO apuesta por el carbón para producir más electricidad [AMLO bets on coal to produce more electricity], 24 December. https://www.forbes.com.mx/amlo-apuesta-por-el-carbon-para-producir-mas-electricidad/. Accessed 10 September 2019.

Solís, A. (2018b). CFE gastará más en plantas de carbón que en centrales renovables [CFE spends more on carbon plants than renewable plants], 18 December. https://www.forbes.com.mx/en-cfe-gastara-mas-en-plantas-de-carbon-que-en-centrales-renovables/. Accessed 5 November 2019.

T

Torchia, A., Kalin, S. and Rashad, M. (2018). Saudi's PIF invested in 50-60 firms via SoftBank fund: director, 23 October. https://www.reuters.com/article/us-saudi-investment-pif/saudis-pif-invested-in-50-60-firms-via-softbank-fund-director-idUSKCN1MX12X. Accessed 5 November 2019.

Tu, Q., Betz, R., Mo, J., Fan, Y. and Liu, Y (2019). Achieving grid parity of wind power in china – Present levelized cost of electricity and future evolution, *Applied Energy* 250, 1053–1064. https://doi.org/10.1016/j.apenergy.2019.05.039.

U

U.S. Climate Alliance (2019). Montana Governor Steve Bullock Becomes 25th Governor to Join U.S. Climate Alliance, 1 July. https://www.usclimatealliance.org/publications/2019/7/1/montana-governor-steve-bullock-becomes-25th-governor-to-join-us-climate-alliance. Accessed 10 September 2019.

U.S. Energy Information Administration (2018). Today in Energy: U.S. energy-related CO_2 emissions fell slightly in 2017, 5 September. https://www.eia.gov/todayinenergy/detail.php?id=36953. Accessed 10 September 2019.

United Nations (2019). Climate Action Summit Delivers Major Step-Up in National Ambition, Private Sector Initiatives on Pathway to Key 2020 Deadline, 23 September. https://www.un.org/press/en/2019/envdev1998.doc.htm. Accessed 5 November 2019.

United Nations, Department of Economic and Social Affairs, Population Division (2019). *World Population Prospects 2019*. https://population.un.org/wpp/Download/Standard/Population/. Accessed 13 August 2019.

United Nations Environment Programme (2018). *The Emissions Gap Report 2018*. Nairobi. https://www.unenvironment.org/resources/emissions-gap-report-2018.

United Nations Framework Convention on Climate Change (2018). NDC registry (interim). http://www4.unfccc.int/ndcregistry/Pages/All.aspx. Accessed 1 August 2018.

United Nations Framework Convention on Climate Change (2019a). Communication of long-term strategies. https://unfccc.int/process/the-paris-agreement/long-term-strategies. Accessed 9 May 2019.

United Nations Framework Convention on Climate Change (2019b). Highlights from Parties at the Multilateral Assessment session at SBI 50. Bonn, June. https://unfccc.int/sites/default/files/resource/SBI50_MA_key_messages_summary.pdf.

V

Van Sant, S. (2019). California Signs Deal With Automakers To Produce Fuel-Efficient Cars. 25 July. https://www.npr.org/2019/07/25/745389326/california-signs-deal-with-automakers-to-produce-fuel-efficient-cars?t=1569794744209. Accessed 10 September 2019.

Vembadi, S., Das, N. and Gambhir, A. (2018). 175 Pune: Prayas (Energy Group). http://www.prayaspune.org/peg/publications/item/405-175-gw-renewables-by-2022-a-september-2018-update.html.

Vigliotti, M. (2019). Federal carbon tax to be introduced in Alberta in January: McKenna, 13 June. https://ipolitics.ca/2019/06/13/federal-carbon-tax-to-be-introduced-in-alberta-in-january-mckenna/.

X

Xiao, M. (2019). What Impact Will China's 2019 New Energy Vehicle (NEV) Subsidy Policy Have?, 11 April. https://www.interactanalysis.com/what-impact-will-chinas-2019-new-energy-vehicle-nev-subsidy-policy-have/. Accessed 20 September 2019.

Chapter 3

A

Allen, M.R., Dube, O.P., Solecki, W., Aragón-Durand, F., Cramer, W., Humphreys, S., Kainuma, M. et al. (2018). Framing and context. I*n Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.). Geneva, Switzerland: Intergovernmental Panel on Climate Change/World Meteorological Organization. 47–92.

B

Bertoldi, P., den Elzen, M., Ford, J., Klein, R., Ley, D., Roberts, T., Rogelj, J., (2018). Cross-Chapter Box 11. Consistency Between Nationally Determined Contributions and 1.5°C Scenarios. *In Global warming of 1.5°CAn IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.). Geneva, Switzerland: Intergovernmental Panel on Climate Change/World Meteorological Organization. 47–92.

C

Climate Action Tracker (2019). Climate Action Tracker – CAT Emissions Gap (updated December, 2018). https://climateactiontracker.org/documents/508/CAT_2018-12-09_PublicData_EmissionsGaps_Dec2018update.xls. Accessed 5 July 2019.

Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., et al. (2014). Assessing transformation pathways. *In Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Edenhofer, O.R., Pichs-Madruga, Y.,

Sokona, E., Farahani, S., Kadner, K., Adler, S.A., Baum, I., Brunner, S. Eickemeier, P., Kriemann, B., Savolainen, S., Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. 413–510.

D

de Coninck, H., Revi, A., Babiker, M., Bertoldi, P., Buckeridge, M., Cartwright, A. et al. (2018). Strengthening and implementing the global response. *In Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.). Geneva, Switzerland: Intergovernmental Panel on Climate Change/World Meteorological Organization.

F

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.

H

Huppmann, D., Kriegler, E., Krey, V., Riahi, K., Rogelj, J., Rose, S.K. et al. (2018a). IAMC 1.5°C Scenario Explorer and Data Hosted by IIASA. https://data.ene.iiasa.ac.at/iamc-sr15-explorer. Accessed 7 November 2019.

Huppmann, D., Rogelj, J., Kriegler, E., Krey, V. and Riahi, K. (2018b). A new scenario resource for integrated 1.5 °C research. *Nature Climate Change* 8(12), 1027–1030.

I

International Energy Agency (2018). *World Energy Outlook 2018*. Paris, France.

Intergovernmental Panel on Climate Change (2014). C*limate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Geneva, Switzerland.

Intergovernmental Panel on Climate Change (2018). Summary for policymakers. In Global Warming of 1.5°C. *An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.). Geneva, Switzerland: Intergovernmental Panel on Climate Change/World Meteorological Organization. 32.

J

Jeffery, M.L., Gütschow, J., Rocha, M.R. and Gieseke, R. (2018). Measuring success: improving assessments of aggregate greenhouse gas emissions reduction goals. *Earth's Future* 6(9), 1260–1274.

Joos, F., Roth, R., Fuglestvedt, J.S., Peters, G. P., Enting, I.G., von Bloh, W. et al. (2013). Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmospheric Chemistry and Physics* 13(5), 2793–2825.

L

Le Quéré, C., Andrew, R.M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A.C., Korsbakken, J.I. et al. (2018). Global Carbon Budget 2017. *Earth System Science Data* 10, 405–448.

M

McCollum, D.L., Zhou, W., Bertram, C., de Boer, H.-S., Bosetti, V., Busch, S., Després, J. et al. (2018). Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy* 3(7), 589–599.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., Knutti, R. et al. (2009). Greenhouse-gas emission targets for limiting global warming to 2°C. Nature 458(7242), 1158–1162.

Meinshausen, M., Raper, S.C.B. and Wigley, T.M.L. (2011). Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – part 1: model description and calibration. *Atmospheric Chemistry and Physics* 11(4), 1417–1456.

R

Ricke, K.L. and Caldeira, K. (2014). Maximum warming occurs about one decade after a carbon dioxide emission. *Environmental Research Letters* 9(12), 124002.

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H. et al. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature* 534(7609), 631–639.

Rogelj, J., Forster, P.M., Kriegler, E., Smith, C.J. and Séférian, R. (2019). Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature* 571(7765), 335–342.

Rogelj, J., Meinshausen, M., Sedláček, J. and Knutti, R. (2014). Implications of potentially lower climate sensitivity on climate projections and policy. *Environmental Research Letters* 9(3), 031003.

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V. et al. (2018). Mitigation pathways compatible with 1.5°C in the context of sustainable development. *In Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.). Geneva, Switzerland: Intergovernmental Panel on Climate Change/World Meteorological Organization. 93–174.

Roy, J., Tschakert, P., Waisman, H., Abdul Halim, S., Antwi-Agyei, P., Dasgupta, P. et al. (2018). Sustainable development, poverty eradication and reducing inequalities. *In Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.). Geneva, Switzerland: Intergovernmental Panel on Climate Change/World Meteorological Organization.

S

Schleussner, C.-F., Rogelj, J., Schaeffer, M., Lissner, T., Licker, R., Fischer, E.M. et al. (2016). Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change* 6(9), 827–835.

Stocker, T.F., Qin, D., Plattner, G.-K., Alexander, L.V., Allen, S.K., Bindoff, N.L. et al. (2013). Technical Summary. In Climate Change 2013: *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M. Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.). Cambridge, United Kingdom and New York, USA: Cambridge University Press, 33–115.

T

Tchung-Ming, S., Diaz-Vazquez, A.R., Keramidas, K. and Kitous, A. (2018). *Global Energy and Climate Outlook 2018: greenhouse gas emissions and energy balances. Supplementary material to "Global Energy and Climate Outlook 2018: sectoral mitigation options towards a low-emissions economy.* Luxembourg: Publications Office of the European Union. http://ec.europa.eu/jrc/en/geco

Tokarska, K.B. and Zickfeld, K. (2015). The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. *Environmental Research Letters* 10(9), 094013.

U

United Nations Environment Programme (2010). The Emissions Gap Report - Are the Copenhagen Accord Pledges Sufficient to *Limit Global Warming to 2°C or 1.5°C?.* Nairobi.

United Nations Environment Programme (2015). The Emissions Gap Report 2015: A UNEP Synthesis Report. http://www.unep.org/emissionsgapreport2015/. Accessed 7 November 2019.

United Nations Environment Programme (2018). The Emissions Gap Report 2018. https://www.unenvironment.org/resources/emissions-gap-report-2018. Accessed 7 November 2019.

United Nations Framework Convention on Climate Change (2015). *Adoption of the Paris Agreement.* Paris. FCCC/CP/2015/L.9/Rev.1. 1-32.

Z

Zickfeld, K. and Herrington, T. (2015). The time lag between a carbon dioxide emission and maximum warming increases with the size of the emission. *Environmental Research Letters* 10(3), 031001.

Zickfeld, K., MacDougall, A.H. and Matthews, H.D. (2016). On the proportionality between global temperature change and cumulative CO_2 emissions during periods of net negative CO_2 emissions. *Environmental Research Letters 11*(5), 055006.

Chapter 4

B

Bloomberg NEF (2018). Electric Vehicle Outlook 2018. https://about.bnef.com/electric-vehicle-outlook/. Accessed 7 October 2018.

C

Christensen, J. and Olhoff, A. (2019). *Lessons from a decade of emissions gap assessments.* Nairobi: United Nations Environment Programme.

F

Food and Agriculture Organization Corporate Statistical Database (2018). Land Use Total – (Emissions – Land Use). Accessed 7 November 2019.

Farand, C. (2019). What is the UN climate action summit?, 16 September. https://www.climatechangenews.com/2019/09/16/un-climate-action-summit/.

I

International Energy Agency (2019). Tracking Clean Energy Progress 2019. https://www.iea.org/tcep/. Accessed 13 September 2019.

International Energy Agency (2018). *World energy balances* (2018 edition). Paris.

Intergovernmental Panel on Climate Change (2018). Summary for policymakers. In *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.). Geneva, Switzerland: Intergovernmental Panel on Climate Change/World Meteorological Organization.

International Renewable Energy Agency (2019). *Renewable power generation costs in 2018.* Abu Dhabi.

J

Jewell, J., Vinichenko, V., Nacke, L. and Cherp, A. (2019). Prospects for powering past coal. *Nature Climate Change 9,* 592–597. https://doi.org/10.1038/s41558-019-0509-6

K

Kuramochi, T., Höhne, N., Schaeffer, M., Cantzler, J., Hare, B., Deng, Y. et al. (2018). Ten key short-term sectoral benchmarks to limit warming to 1.5°C. *Climate Policy* 18, 287–305. https://doi.org/10.1080/14693062.2017.1397495

N

New Development Bank (2018). The MDBs' alignment approach to the objectives of the Paris Agreement: working together to catalyse low-emissions and climate-resilient development, 3 December. https://www.ndb.int/press_release/mdbs-alignment-approach-objectives-paris-agreement-working-together-catalyse-low-emissions-climate-resilient-development/

O

Olivier, J.G.J. and Peters, J.A.H.W. (2018). *Trends in global CO_2 and total greenhouse gas emissions: 2018 report* (PBL Report No. 3599). Bilthoven: PBL Netherlands Environmental Assessment Agency.

S

Smouse, S.M., Jones, A., Fapohunda, B.O., Render, M. and Hindman, J.W. (2018). Coal- and gas-fired power construction and cancellation trends in countries with the most new coal power capacity since 2003. In ASME 2018 *Power Conference.* Lake Buena Vista: American Society of Mechanical Engineers. https://doi.org/doi:10.1115/POWER2018-7466

T

The New Climate Economy (2018). *Unlocking the inclusive growth story of the 21st Century: accelerating climate action in urgent times.* Washington, D.C.

U

United Nations Environment Programme (2017). *The Emissions Gap Report 2017*. Nairobi. https://doi.org/ISBN 978-92-9253-062-4

United Nations Environment Programme (2018). *The Emissions Gap Report 2018.* Nairobi.

United Nations Framework Convention on Climate Change (2015). *Paris Agreement - Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015 Addendum Part two: Action taken by the Conference of the Parties at its twenty-first session.* Bonn. Decision 1/CP.21.

United Nations Framework Convention on Climate Change (2019). Communication of long-term strategies. https://unfccc.int/process/the-paris-agreement/long-term-strategies. Accessed 5 September 2019.

W

World Bank (2019). Carbon Pricing Dashboard: up-to-date overview of carbon pricing initiatives. https://carbonpricingdashboard.worldbank.org/map_data. Accessed 7 November 2019.

World Resources Institute (2019). Case studies on existing long-term strategies. https://www.wri.org/climate/case-studies. Accessed 17 September 2019.

Chapter 5

B

Bastin, J.-F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D. et al (2019). The global tree restoration potential. *Science* 365(6448), 76–79. https://doi.org/10.1126/science.aax0848.

Bertram, C., Luderer, G., Popp, A., Minx, J.C., Lamb, W.F., Stevanović, M. et al. (2018). Targeted policies can compensate most of the increased sustainability risks in 1.5 °C mitigation scenarios. E*nvironmental Research Letters* 13(6), 064038. https://doi.org/10.1088/1748-9326/aac3ec.

Bryan, B. A., Gao, L., Ye, Y., Sun, X., Connor, J.D., Crossman, N.D., et al. (2018). China's response to a national land-system sustainability emergency. *Nature* 559(7713), 193–204. https://doi.org/10.1038/s41586-018-0280-2.

C

Creutzig, F., Agoston, P., Minx, J.C., Canadell, J.G., Andrew, R.M., Le Quéré, C. et al. (2016). Urban infrastructure choices structure climate solutions. *Nature Climate Change* 6, 1054–1056. https://doi.org/10.1038/nclimate3169.

Creutzig, F., Baiocchi, G., Bierkandt, R., Pichler, P.-P. and Seto, K.C. (2015). Global typology of urban energy use and potentials for an urbanization mitigation wedge. *Proceedings of the National Academy of Sciences* 112(20), 6283–6288. https://doi.org/10.1073/pnas.1315545112.

F

Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, United Nations Childrens' Fund, World Food Programme and World Health Organization (2018). *The State of Food Security and Nutrition in the World 2018. Building climate resilience for food security and nutrition.* Rome: FAO.

G

Global Energy Assessment (2012). *Global Energy Assessment – Toward a Sustainable Future.* Cambridge and New York: Cambridge University Press; Laxenburg: International Institute for Applied Systems Analysis.

Grubler, A., Bai, X., Buettner, T., Dhakal, S., Fisk, D.J., Ichinose, T. et al. (2012). Urban Energy Systems. In Global Energy Assessment – Toward a Sustainable Future. Johansson, T.B., Patwardhan, A., Nakićenović, N. and Gomez-Echevarri, L. (eds.). Cambridge and New York: Cambridge University Press; Laxenburg: International Institute for Applied Systems Analysis. Chapter 18. 1307–1400.

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D.L. et al. (2018). A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nature Energy 3(6), 515–527. https://doi.org/10.1038/s41560-018-0172-6.

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R. and Meybeck, A. (2011). Global food losses and food waste. Rome: Food and Agriculture Organization of the United Nations (FAO). http://www.fao.org/fileadmin/user_upload/suistainability/pdf/Global_Food_Losses_and_Food_Waste.pdf.

I

International Energy Agency (2018). *World Energy Outlook 2018*. Paris.

Intergovernmental Panel on Climate Change (2014). *Climate Change 2014: Mitigation of Climate Change.* Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, A. et al. (eds.). Cambridge and New York: Cambridge University Press.

Intergovernmental Panel on Climate Change (2018). Summary for Policymakers. *In Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., et al. (eds.). Geneva: World Meterological Organization.

L

Lelieveld, J., Klingmüller, K., Pozzer, A., Burnett, R.T., Haines, A. and Ramanathan, V. (2019). Effects of fossil fuel and total anthropogenic emission removal on public health and climate. Proceedings of the *National Academy of Sciences* 116(15), 7192–7197. https://doi.org/10.1073/pnas.1819989116.

Lucon O., Ürge-Vorsatz, D., Ahmed, A.Z., Akbari, H., Bertoldi, P., Cabeza, L.F. et al. (2014). Buildings. In Climate Change 2014: *Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Edenhofer, O., Pich-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, A. et al. (eds.). Cambridge and New York: Cambridge University Press. Chapter 9. 671–738.

M

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.

McCollum, D.L., Krey, V. and Riahi, K. (2011). An integrated approach to energy sustainability. *Nature Climate Change* 1(9), 428-429. https://doi.org/10.1038/nclimate1297.

N

Nakićenović, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S. et al. (2000). *Special report on Emissions Scenarios.* Cambridge: Cambridge University Press.

P

Preston, I., White, V., Thumim, J., Bridgeman, T. and Brand, C. (2013). *Distribution of carbon emissions in the UK: implications for domestic energy policy.* York: Joseph Rowntree Foundation.

R

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S. et al. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Rockström, J., Gaffney, O., Rogelj, J., Meinshausen, M., Nakićenović, N. and Schellnhuber, H.J. (2017). A roadmap for rapid decarbonization. Science 355(6331), 1269–1271. https://doi.org/10.1126/science.aah3443.

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V. et al. (2018). Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In Global Warming of 1.5°C. *An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J. Shukla, P.R. et al. (eds.) Geneva: World Meterological Organization. Chapter 2. 93–174.

S

Sachs, J.D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakićenović, N. and Rockström, J. (2019). Six Transformations to achieve the Sustainable Development Goals. *Nature Sustainability* 2(9), 805–814. https://doi.org/10.1038/s41893-019-0352-9.

Schumpeter, J.A. (1935). The analysis of economic change. *The Review of Economics and Statistics* 17(4), 2–10.

Seto, K.C., Dhakal, S., Bigio, A., Blanco, H., Delgado, G.C., Dewar, D. et al. (2014). Human Settlements, Infrastructure and Spatial Planning.

T

Tupy, M.L. (2012). Dematerialization (update), 12 July. https://www.cato.org/blog/dematerialization-update. Accessed 6 November 2019.

The World in 2050 (TWI2050) (2018). *Transformations to Achieve the Sustainable Development Goals. Report prepared by The World in 2050 initiative.* Laxenburg: International Institute for Applied Systems Analysis (IIASA).

The World in 2050 (TWI2050) (2019). *The Digital Revolution and Sustainable Development: Opportunities and Challenges. Report prepared by The World in 2050 initiative.* Laxenburg: International Institute for Applied Systems Analysis (IIASA).

U

United Nations, Department of Economic and Social Affairs, Population Division (2018). *World Urbanization Prospects: The 2018 Revision.* New York.

V

van Vuuren, D.P., Riahi, K., Calvin, K., Dellink, R., Emmerling, J., Fujimori, S. et al. (2017). The Shared Socio-economic Pathways: Trajectories for human development and global environmental change. *Global Environmental Change* 42, 148–152. https://doi.org/10.1016/j.gloenvcha.2016.10.009.

World Health Organization (2019). Air pollution. https://www.who.int/airpollution/en/.

World Health Organization and United Nations Childrens' Fund (2017). *Progress on Drinking Water, Sanitation and Hygiene. 2017 update and SDG baselines.* Geneva.

Wilson, E.O. (2016). Half-earth. Our Planet's Fight for Life. London: WW Norton & Company.

Z

Zimm, C. and Nakićenović, N. (2019). What are the implications of the Paris Agreement for inequality? *Climate Policy*, 1-10. https://doi.org/10.1080/14693062.2019.1581048.

Chapter 6

A

Agora Energiewende (2015). *The integration costs of wind and solar power. An overview of the debate on the effects of adding wind and solar photovoltaic into power systems.* https://www.agora-energiewende.de.

Anenberg, S., Miller, J., Henze, D. and Minjares, R. (2019). *Global snapshot of the air pollution-related health impacts of transportation sector emissions in 2010 and 2015.* Washington, D.C.: International Council on Clean Transportation and Climate & Clean Air Coalition. https://theicct.org/sites/default/files/Global_health_impacts_transport_emissions_2010-2015_20190226_1.pdf

B

Bailis, R., Drigo, R., Ghilardi, A. and Masera, O. (2015). The carbon footprint of traditional woodfuels. Nature Climate Change 5, 266–272.

Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L.J., Fischedick, M., Lechtenböhmer, S. et al. (2018). A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. *Journal of Cleaner Production* 187, 960–973. https://doi.org/10.1016/j.jclepro.2018.03.107

Batchelor, S., Brown, E., Scott, N. and Leary, J. (2019). Two birds, one stone — reframing cooking energy policies in Africa and Asia. *Energies* 12(9), 1591.

Bhamidipati, P.L., Haselip, J. and Hansen, U.E. (2019). How do energy policies accelerate sustainable transitions? Unpacking the policy transfer process in the case of GETFiT Uganda. *Energy Policy* 132, 1320–1332.

BloombergNEF (2019). *Clean energy investment trends 2018*. https://data.bloomberglp.com/professional/sites/24/BNEF-Clean-Energy-Investment-Trends-2018.pdf

Bogdanov, D., Farfan, J., Sadovskaia, K., Aghahosseini, A., Child, M., Gulagi, A. et al. (2019). Radical transformation pathways towards sustainable electricity via evolutionary steps. *Nature Communications* 10, 1077.

BP (2019). *Statistical review of world energy 2019*, 68th edition. London. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf

Byrne, R., Mbeva, K. and Ockwell, D. (2018). A political economy of niche-building: neoliberal-developmental encounters in photovoltaic electrification in Kenya. *Energy Research and Social Science* 44, 6–16.

C

Caldecott, B., Sartor, O. and Spencer, T. (2017). *Lessons from previous 'coal transitions.' High level summary for decision-makers*. Paris: Institute for Sustainable Development and International Relations and Climate Strategies. https://coaltransitions.files.wordpress.com/2016/09/coal_synthesisreport_v04.pdf.

Cardoso, A. and Turhan, E. (2018). Examining new geographies of coal: dissenting energyscapes in Colombia and Turkey. *Applied Energy* 224, 398–408. https://doi.org/10.1016/j.apenergy.2018.04.096

Climate Analytics (2016). I*mplications of the Paris Agreement for coal use in the power sector.* Berlin.

Climate Analytics (2017). *Synthesis of the Least Developed Countries' NDCs.* Berlin. https://climateanalytics.org/publications/2017/synthesis-of-the-least-developed-countries-ndcs/

D

Dagnachew, A.G., Lucas, P.L., Hof, A.F. and van Vuuren, D. (2018). Trade-offs and synergies between universal electricity access and climate change mitigation in Sub-Saharan Africa. *Energy Policy* 114, 355–366.

de Coninck, H., Revi, A., Babiker, M., Bertoldi, P., Buckeridge, M., Cartwright, A. et al. (2018). Strengthening and implementing the global response. I*n Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.). In Press.

Dhar, S., Pathak, M. and Shukla, P.R. (2017). Electric vehicles and India's low carbon passenger transport: A long-term co-benefits assessment. *Journal of Cleaner Production* 146, 139–148. https://doi.org/10.1016/j.jclepro.2016.05.111

Dhar, S., Pathak, M. and Shukla, P.R. (2018). Transformation of India's transport sector under global warming of 2°C and 1.5°C scenario. Journal of Cleaner Production 172, 417–427.

E

Edenhofer, O., Steckel, J.C., Jakob, M. and Bertram, C. (2018). Reports of coal's terminal decline may be exaggerated. *Environmental Research Letters* 13(2), 024019. https://doi.org/10.1088/1748-9326/aaa3a2.

Enerdata (2019). Global Energy Statistical Yearbook 2019. https://yearbook.enerdata.net/coal-lignite/coal-production-data.html. Accessed 25 October 2019.

Enerdata (2019). Global Energy and CO_2 Data. https://www.enerdata.net/research/energy-market-data-co2-emissions-database.html. Accessed 25 October 2019.

Energy Transitions Commission (2019). *Mission possible: reaching net-zero carbon emissions from harder-to-abate sectors by mid-century.* London, United Kingdom. http://www.energy-transitions.org/sites/default/files/ETC_MissionPossible_FullReport.pdf

F

Frankfurt School-United Nations Environment Programme Collaborating Centre and BloombergNEF (2019). *Global trends in renewable energy investment 2019.* Frankfurt am Main. https://fs-unep-centre.org/fileadmin/user_upload/GTR_2019.pdf

Fuso-Nerini, F.F., Tomei, J., To, L.S., Bisaga, I., Parikh, P., Black, M. et al. (2018). Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nature Energy* 3, 10–15. https://doi.org/10.1038/s41560-017-0035-5

G

Gambhir, A., Rogelj, J., Luderer, G., Few, S. and Napp, T. (2019). Energy system changes in 1.5 °C, well below 2 °C and 2 °C scenarios. *Energy Strategy Reviews* 23, 69–80.

Garg, A. and Steckel, J.C. (2017). Bridging the gap: phasing out coal. In *The Emissions Gap Report 2017* – A UN Environment Synthesis Report. United Nations Environment Programme. Nairobi. Chapter 5. https://wedocs.unep.org/bitstream/handle/20.500.11822/22106/EGR_2017_ch_5.pdf?isAllowed=y&sequence=1

Germany, Cabinet of Germany (2019). Climate Action Programme 2030. https://www.bundesregierung.de/bregen/issues/climate-action/klimaschutzprogramm-2030-1674080. Accessed 1 November 2019.

Germany, Federal Ministry for Economic Affairs and Energy Commission on Growth, Structural Change and Employment (2019). *Structural change and employment. Final report*, 2019. https://www.bmwi.de/Redaktion/EN/Publikationen/commission-on-growth-structural-change-and-employment.html

Germany, Federal Ministry of the Environment, Nature Conservation and Nuclear Safety (2018). Klimaschutzbericht 2018: *zum Aktionsprogramm Klimaschutz 2020 der Bundesregierung.* https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzbericht_2018_bf.pdf

Gouldson, A., Sudmant, A., Khreis, H. and Papargyropoulou, E. (2018). *The economic and social benefits of low-carbon cities: a systematic review of the evidence.* London and Washington, D.C.: Coalition for Urban Transitions. http://newclimateeconomy.net/content/cities-working-papers

I

International Energy Agency (2017a). *World energy outlook* 2017. Paris.

International Energy Agency (2017b). E*nergy technology perspectives 2017*: catalyzing energy technology transformations. Paris. https://webstore.iea.org/download/direct/1058?fileName=Energy_Technology_Perspectives_2017.pdf

International Energy Agency (2018a). *Key world energy statistics 2018.* Paris.

International Energy Agency (2018b). W*orld energy outlook 2018.* Paris.

International Energy Agency (2019a). *Global energy and CO_2 status report: the latest trends in energy and emissions 2018.* Paris. https://www.iea.org/geco/emissions/

International Energy Agency (2019b). *Material efficiency in clean energy transitions.* Paris. https://webstore.iea.org/download/direct/2454?fileName=Material_efficiency_in_clean_energy_transitions.pdf

International Energy Agency (2019c). *Status of power system transformation 2019 power system flexibility.* Paris. https://webstore.iea.org/download/direct/2782?fileName=Status_of_Power_System_Transformation_2019.pdf

International Energy Agency (2019d). *World energy investment 2017.* Paris. https://www.iea.org/publications/wei2017/

International Energy Agency (2019e). *Key world energy statistics 2018.* https://webstore.iea.org/download/direct/2831?fileName=Key_World_Energy_Statistics_2019.pdf

International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, World Bank and World Health Organization (2019). *Tracking SDG 7*: the energy progress report 2019. Washington, D.C. http://documents.worldbank.org/curated/en/517781558037625254/pdf/Main-Report.pdf

International Renewable Energy Agency (2019a). *Global energy transformation: a roadmap to 2050* (2019 edition). Abu Dhabi.

International Renewable Energy Agency (2019b). *Innovation landscape for a renewable-powered future.* Abu Dhabi.

International Renewable Energy Agency (2019c). *Renewable power generation costs in 2018.* Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf

J

Jackson, T. (2016). *Prosperity without Growth*, 2nd edition. London: Routledge.

Jordaan, S.M., Romo-Rabago, E., McLeary, R., Reidy, L., Nazari, J. and Herremans, I.M. (2017). The role of energy technology innovation in reducing greenhouse gas emissions: a case study of Canada. *Renewable and Sustainable Energy Reviews* 78, 1397–1409. https://doi.org/10.1016/j.rser.2017.05.162

L

Least Developed Countries Renewable Energy and Energy Efficiency Initiative for Sustainable Development (2019). LDC REEEI. https://www.reeeei.org. Accessed 1 November 2019.

Lema, R., Hanlin, R., Hansen, U.E. and Nzila, C. (2018). Renewable electrification and local capability formation: linkages and interactive learning. *Energy Policy* 117, 326–339.

M

Martinez Romera, B. (2016). The Paris Agreement and the regulation of international bunker fuels. *Review of European Community and International Environmental Law* 25(2), 215–227.

May-Tobin, C. (2011). Wood for fuel. In *The Root of the Problem. What's Driving Tropical Deforestation Today?* Cambridge, Massachusetts: Union of Concerned Scientists. https://www.ucsusa.org/sites/default/files/legacy/assets/documents/global_warming/UCS_DriversofDeforestation_Chap8_Woodfuel.pdf.

Mazzucato, M. (2018). Mission-oriented innovation policies: challenges and opportunities. *Industrial and Corporate Change* 27(5), 803–815. https://doi.org/10.1093/icc/dty034

McCollum, D.L., Zhou, W., Betram, C., de Boer, H-S, Bosetti, V. Busch, S. *et al.* (2018). Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy* 3(7), 589–599. https://doi.org/10.1038/s41560-018-0179-z

Mulugetta, Y., Ben Hagan, E. and Kammen, D. (2018). Energy access for sustainable development. *Environmental Research Letters* 14(2). https://doi.org/10.1088/1748-9326/aaf449

O

Ockwell, D., Byrne, R., Hansen, U.E., Haselip, J. and Nygaard, I. (2018). The uptake and diffusion of solar power in Africa: socio-cultural and political insights on a rapidly emerging socio-technical transition. *Energy Research and Social Science* 44, 122–129.

R

Raven, R. and Verbong, G. (2007). Multi-regime interactions in the Dutch energy sector: the case of combined heat and power technologies in the Netherlands 1970-2000. Technology Analysis and Strategic Management 19(4), 491–507.

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V. et al. (2018). Mitigation pathways compatible with 1.5°C in the context of sustainable development. In Global Warming of 1.5°C. *An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.). In Press.

Roy, J., Tschakert, P., Waisman, H., Abdul Halim, S., Antwi-Agyei, P., Dasgupta, P. et al. (2018). Sustainable development, poverty eradication and reducing inequalities. In Global Warming of 1.5°C. *An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.). In Press.

S

Scrivener, K.L., Vanderley M.J. and. Gartner, E.M. (2018). Eco-efficient cements: potential economically viable solutions for a low-CO_2 cement-based materials industry. *Cement and Concrete Research* 114, 2–26. https://doi.org/10.1016/j.cemconres.2018.03.015

Shearer, C., Neha, M-S., Myllyvirta, L., Yu, A. and Nace, T. (2019). Boom and bust 2018: *tracking the global coal plant pipeline.* CoalSwarm, Greenpeace USA, and Sierra Club.

Sovacool, B. and Geels, F. (2016). Further reflections on the temporality of energy transitions: a response to critics. E*nergy Research & Social Science* 22, 232–237. https://doi.org/10.1016/j.erss.2016.08.013

Spencer, T., Colombier, M., Sartor, O., Garg, A., Tiwari, V., Burton, J. et al. (2018). The 1.5°C target and coal sector transition: at the limits of societal feasibility. *Climate Policy*, 18(3), 335–331. https://doi.org/10.1080/14693062.2017.1386540

T

Truffer, B., Murphy, J.T. and Raven, R. (2015). The geography of sustainability transitions: contours of an emerging theme. *Environmental Innovation and Societal Transitions* 17, 63–72.

U

United Nations Conference on Trade and Development (2017). *The Least Developed Countries report 2017: transformational energy access.* Geneva. https://unctad.org/en/pages/PublicationWebflyer.aspx?publicationid=1902

United Nations Department of Economic and Social Affairs (2019). *World population prospects.* Geneva. https://www.un.org/en/development/desa/population/index.asp

University of Columbia Center on Global Energy Policy (2019). Energy transition fact sheet. https://energypolicy.columbia.edu/sites/default/files/file-uploads/Energy%20Transition%20Fact%20Sheet.pdf

V

Vieweg, M., Bongardt, D., Hochfeld, C., Jung, A, Scherer, E., Adib, R. et al. (2018). *Towards decarbonising transport - a 2018 stocktake on sectoral ambition in the G20.* Berlin: Agora Verkehrswende and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

Vogl, V., Åhman, M. and Nilsson, L.J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production* 203, 736–745. https://doi.org/10.1016/j.jclepro.2018.08.279

W

Watson, F (2019). December global electric vehicle sales set new record: S&P Global Platts, London, 11 Feb. https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/021119-december-global-electric-vehicle-sales-set-new-record-sampp-global-platts-data. Accessed 25 October 2019.

Wieczorek, A.J. (2017). Sustainability transitions in developing countries: major insights and their implications for research and policy. *Environmental Science & Policy,* 204–216.

Williams, D. (2019). For the first time ever, electric cars outsold gas and diesel vehicles in Norway, 4 April. https://edition.cnn.com/2019/04/04/world/norway-zero-emission-vehicles-trnd/index.html

World Steel Association (2018). *Steel statistical yearbook 2018.* Brussels.

Chapter 7

A

Allwood, J.M., Ashby, M.F., Gutowski, T.G. and Worrell, E. (2011). Material efficiency: A white paper. *Resources, Conservation and Recycling* 55(3), 362–381. https://doi.org/10.1016/j.resconrec.2010.11.002.

Allwood, J.M., Gutowski, T.G., Serrenho, A.C., Skelton, A.C.H. and Worrell, E. (2017). Industry 1.61803: The *transition to an industry with reduced material demand fit for a low carbon future. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 375(2095). https://doi.org/10.1098/rsta.2016.0361.

B

Becker, H., Ciari, F., Axhausen, K.W. (2018). Measuring the car ownership impact of free-floating car-sharing – A case study in Basel, Switzerland. *Transportation Research Part D: Transport and Environment* 65, 51–62. https://doi.org/10.1016/j.trd.2018.08.003.

Brantwood Consulting (2016). *Guide for Selecting Policies to Reduce and Divert Construction, Renovation, and Demolition Waste.*

C

Cai, W., Wan, L., Jiang, Y., Wang, C. and Lin, L. (2015). Short-lived buildings in China: impacts on water, energy, and carbon emissions. *Environmental Science & Technology* 49, 13921–13928. https://doi.org/10.1021/acs.est.5b02333.

Cao, Z., Shen, L., Zhong, S., Liu, L., Kong, H. and Sun, Y. (2018). A probabilistic dynamic material flow analysis model for Chinese urban housing stock. *Journal of Industrial Ecology* 22, 377–391. https://doi.org/10.1111/jiec.12579.

Chan, N.D. and Shaheen, S.A. (2012). Ridesharing in North America: past, present, and future. *Transport Reviews* 32, 93–112. https://doi.org/10.1080/01441647.2011.621557.

D

D'Haultfœuille, X., Durrmeyer, I., and Février, P. (2016). Disentangling sources of vehicle emissions reduction in France: 2003–2008. International Journal of Industrial Organization 47, 186–229. https://doi.org/10.1016/j.ijindorg.2016.05.002.

Daehn, K.E., Serrenho, A.C. and Allwood, J.M. (2017). *How will copper contamination constrain future global steel recycling? Environmental Science & Technology* 51, 6599–6606. https://doi.org/10.1021/acs.est.7b00997.

de Wilde, P. (2014). The gap between predicted and measured energy performance of buildings: a framework for investigation. *Automation in Construction* 41, 40–49. https://doi.org/10.1016/j.autcon.2014.02.009.

Deloitte (2017). *Resource Efficient Use of Mixed Wastes: Improving management of construction and demolition waste.* Final Report. Prepared for the European Commission, Directorate-General for Environment (DG ENV).

Densley Tingley, D., Cooper, S. and Cullen, J. (2017). Understanding and overcoming the barriers to structural steel reuse, a UK perspective. *Journal of Cleaner Production* 148, 642–652. https://doi.org/10.1016/j.jclepro.2017.02.006.

Doan, D.T., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Ghaffarianhoseini, A. and Tookey, J. (2017). A critical comparison of green building rating systems. *Building and Environment* 123, 243–260. https://doi.org/10.1016/j.buildenv.2017.07.007.

Dunant, C.F., Drewniok, M.P., Eleftheriadis, S., Cullen, J.M. and Allwood, J.M. (2018). Regularity and optimisation practice in steel structural frames in real design cases. *Resources, Conservation and Recycling* 134, 294–302. https://doi.org/10.1016/j.resconrec.2018.01.009.

G

Greenblatt, J.B. and Saxena, S. (2015). Autonomous taxis could greatly reduce greenhouse-gas emissions of US light-duty vehicles. *Nature Climate Change* 5, 860–863.

Güneralp, B., Zhou, Y., Ürge-Vorsatz, D., Gupta, M., Yu, S., Patel, P.L., Fragkias, M., Li, X. and Seto, K.C. (2017). Global scenarios of urban density and its impacts on building energy use through 2050. *Proceedings of the National Academy of Sciences* 114, 8945–8950. https://doi.org/10.1073/pnas.1606035114.

H

Heeren, N., Mutel, C.L., Steubing, B., Ostermeyer, Y., Wallbaum, H. and Hellweg, S. (2015). Environmental impact of buildings—what matters? *Environmental Science & Technology* 49, 9832–9841. https://doi.org/10.1021/acs.est.5b01735.

Hernandez, A.G., Cooper-Searle, S., Skelton, A.C.H. and Cullen, J.M. (2018). Leveraging material efficiency as an energy and climate instrument for heavy industries in the EU. *Energy Policy* 120, 533–549. https://doi.org/10.1016/j.enpol.2018.05.055.

Hertwich, E. (2019). The Carbon Footprint of Material Production Rises to 23 per cent of Global Greenhouse Gas Emissions. https://doi.org/10.31235/osf.io/n9ecw.

Hertwich, E.G., Ali, S., Ciacci, L., Fishman, T., Heeren, N., Masanet, E., Asghari, F.N., Olivetti, E., Pauliuk, S., Tu, Q. and Wolfram, P. (2019). Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. Environmental Research Letters 14, 043004. https://doi.org/10.1088/1748-9326/ab0fe3.

I

International Code Council (2012). International Energy Conservation Code.

International Code Council (2018). 2018 International Green Construction Code. https://www.iccsafe.org/products-and-services/i-codes/2018-i-codes/igcc/. Accessed 31 May 2019.

International Energy Agency (2019a). *Material Efficiency in Clean Energy Transitions*. Paris.

International Energy Agency (2019b). *Perspectives for the Clean Energy Transition.* The Critical Role of Buildings. Paris.

International Resource Panel (forthcoming). Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. Hertwich, E., Lifset, R., Ali, S., Pauliuk, S., Heeren, Tu, Q. A report of the International Resource Panel Nairobi: United Nations Environment Programme (UNEP). https://doi.org/10.5281/zenodo.3542681

International Transport Forum (2019). *ITF Transport Outlook 2019*. Paris: Organisation for Economic Co-operation and Development (OECD). https://doi.org/10.1787/transp_outlook-en-2019-en.

Itard, L. and Klunder, G. (2007). Comparing environmental impacts of renovated housing stock with new construction. *Building Research & Information* 35(3), 252–267. https://doi.org/10.1080/09613210601068161.

J

John, V.M., Damineli, B.L., Quattrone, M. and Pileggi, R.G. (2018). Fillers in cementitious materials — Experience, recent advances and future potential. *Cement and Concrete Research* 114, 65–78. https://doi.org/10.1016/j.cemconres.2017.09.013.

Jones, C.M., Wheeler, S.M., Kammen and D.M. (2018). Carbon footprint planning: Quantifying local and state mitigation opportunities for 700 California cities. *Urban Planning* 3(2), 35–51. https://doi.org/10.17645/up.v3i2.1218.

Jones, E.C. and Leibowicz, B.D. (2019). Contributions of shared autonomous vehicles to climate change mitigation. Transportation Research Part D: *Transport and Environment* 72, 279–298. https://doi.org/10.1016/j.trd.2019.05.005.

K

Kagawa, S., Hubacek, K., Nansai, K., Kataoka, M., Managi, S., Suh, S. and Kudoh, Y. (2013). Better cars or older cars? Assessing CO_2 emission reduction potential of passenger vehicle replacement programs. *Global Environmental Change* 23(6), 1807–1818. https://doi.org/10.1016/j.gloenvcha.2013.07.023.

Kane, M. and Yee, R. (2017). The Walworth alternative: Retaining and enhancing Britain's social housing estates utilising contemporary timber construction. *Journal of Green Building* 12(1), 11–35. https://doi.org/10.3992/1552-6100.12.1.11.

Karimpour, M., Belusko, M., Xing, K. and Bruno, F. (2014). Minimising the life cycle energy of buildings: Review and analysis. *Building and Environment* 73, 106–114. https://doi.org/10.1016/j.buildenv.2013.11.019.

King, B. (2018). *A Low Carbon Concrete Building Code.* Towards a carbon-sequestering built environment. https://www.ecobuildnetwork.org/images/pdfs/A-Low-Carbon-Concrete-Building-Code10-9.pdf. Accessed 5 November 2019.

Kristjansdottir, T.F., Heeren, N., Andresen, I. and Brattebø, H. (2018). Comparative emission analysis of low-energy and zero-emission buildings. *Building Research & Information* 46(4), 367–382. https://doi.org/10.1080/09613218.2017.1305690.

L

Lenski, S.M., Keoleian, G.A. and Moore, M.R. (2013). *An assessment of two environmental and economic benefits of 'Cash for Clunkers'. Ecological Economics* 96, 173–180. https://doi.org/10.1016/j.ecolecon.2013.10.011.

Lorek, S and Spangenberg, J.H. (2019). I*dentification of promising instruments and instrument mixes to promote energy sufficiency.* Deliverable 5.5. EUFORIE – European Futures for Energy Efficiency.

Løvik, A.N., Modaresi, R. and Müller, D.B. (2014). Long-term strategies for increased recycling of automotive aluminum and its alloying elements. *Environmental Science & Technology* 48(8), 4257–4265. https://doi.org/10.1021/es405604g.

M

Mahapatra, K., Gustavsson, L. and Hemström, K. (2012). Multi-storey wood-frame buildings in Germany, Sweden and the UK. *Construction Innovation* 12(1), 62–85. https://doi.org/10.1108/14714171211197508.

Makov, T. and Font Vivanco, D. (2018). Does the Circular Economy Grow the Pie? The Case of Rebound Effects From Smartphone Reuse. Frontiers in Energy Research 6. https://doi.org/10.3389/fenrg.2018.00039.

Material Economics (2018). *The Circular Economy – A Powerful Force for Climate Mitigation.*

Menezes, A.C., Cripps, A., Bouchlaghem, D. and Buswell, R. (2012). Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. *Applied Energy* 97, 355–364. https://doi.org/10.1016/j.apenergy.2011.11.075.

Milford, R.L., Pauliuk, S., Allwood, J.M. and Müller, D.B. (2013). The roles of energy and material efficiency in meeting steel industry CO_2 targets. *Environmental Science & Technology* 47(7), 3455–3462. https://doi.org/10.1021/es3031424.

Milovanoff, A., Kim, H.C., De Kleine, R., Wallington, T.J., Posen, I.D. and MacLean, H.L. (2019). A dynamic fleet model of U.S light-duty vehicle lightweighting and associated greenhouse gas emissions from 2016 to 2050. *Environmental Science & Technology* 53, 2199–2208. https://doi.org/10.1021/acs.est.8b04249.

N

Neuhoff, K., Ismer, R., Acworth, W., Ancygier, A., Fischer, C., Haussner, M. et al. (2016). *Inclusion of Consumption of carbon intensive materials in emissions trading – An option for carbon pricing post-2020.* Climate Strategies.

Nijland, H. and van Meerkerk, J. (2017). *Mobility and environmental impacts of car sharing in the Netherlands. Environmental Innovation and Societal Transitions* 23, 84–91. https://doi.org/10.1016/j.eist.2017.02.001.

O

Official Journal of the European Union (2009). Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products.

Ohno, H., Matsubae, K., Nakajima, K., Kondo, Y., Nakamura, S., Fukushima, Y. and Nagasaka, T. (2017). Optimal recycling of steel scrap and alloying elements: Input-output based linear programming method with its application to end-of-life vehicles in Japan. *Environmental Science & Technology* 51(22), 13086–13094. https://doi.org/10.1021/acs.est.7b04477.

Oliver, C.D., Nassar, N.T., Lippke, B.R. and McCarter, J.B. (2014). Carbon, fossil fuel, and biodiversity mitigation with wood and forests. Journal of Sustainable Forestry 33(3), 248–275. https://doi.org/10.1080/10549811.2013.839386.

Organisation for Economic Co-operation and Development (2015). *Going Green: Best Practices for Sustainable Procurement.* Paris.

P

Pauliuk, S., Sjöstrand, K. and Müller, D.B. (2013). Transforming the Norwegian dwelling stock to reach the 2 degrees Celsius climate target. *Journal of Industrial Ecology* 17, 542–554. https://doi.org/10.1111/j.1530-9290.2012.00571.x.

Pauliuk, S., Arvesen, A., Stadler, K. and Hertwich, E.G. (2017). Industrial ecology in integrated assessment models. *Nature Climate Change* 7, 13–20. https://doi.org/10.1038/nclimate3148.

S

Sato, F.E.K., Furubayashi, T. and Nakata, T. (2019). Application of energy and CO_2 reduction assessments for end-of-life vehicles recycling in Japan. *Applied Energy* 237, 779–794. https://doi.org/10.1016/j.apenergy.2019.01.002.

Sawyer Beaulieu, S.S. and Tam, E.K.L. (2006). Regulation of end of life vehicle (ELV) retirement in the US compared to Canada. *International Journal of Environmental Studies* 63(4), 473–486. https://doi.org/10.1080/00207230600802106.

Schaller, B. (2017). Unsustainable? *The Growth of App-Based Ride Services and Traffic, Travel and the Future of New York City.* New York: Schaller Consulting.

Schaller, B. (2018). The New Automobility: Lyft, Uber and the Future of American Cities. New York: Schaller Consulting.

Serrenho, C.A., Drewniok, M., Dunant, C. and Allwood, J.M. (2019). Testing the greenhouse gas emissions reduction potential of alternative strategies for the English housing stock. *Resources, Conservation and Recycling* 144, 267–275. https://doi.org/10.1016/j.resconrec.2019.02.001.

Shaheen, S. and Cohen, A. (2019). Shared ride services in North America: definitions, impacts, and the future of pooling. *Transport Reviews* 39(4), 427–442. https://doi.org/10.1080/01441647.2018.1497728.

Shanks, W., Dunant, C.F., Drewniok, M.P., Lupton, R.C., Serrenho, A. and Allwood, J.M. (2019). How much cement can we do without? Lessons from cement material flows in the UK. *Resources Conservation and Recycling* 141, 441–454. https://doi.org/10.1016/j.resconrec.2018.11.002.

Underwood, A. and Fremstad, A. (2018). Does sharing backfire? A decomposition of household and urban economies in CO_2 emissions. *Energy Policy* 123, 404–413. https://doi.org/10.1016/j.enpol.2018.09.012.

W

Worrell, E., Allwood, J., Gutowski, T. (2016). The role of material efficiency in environmental stewardship. *Annual Review of Environment and Resources* 41, 575–598. https://doi.org/10.1146/annurev-environ-110615-085737.

Y

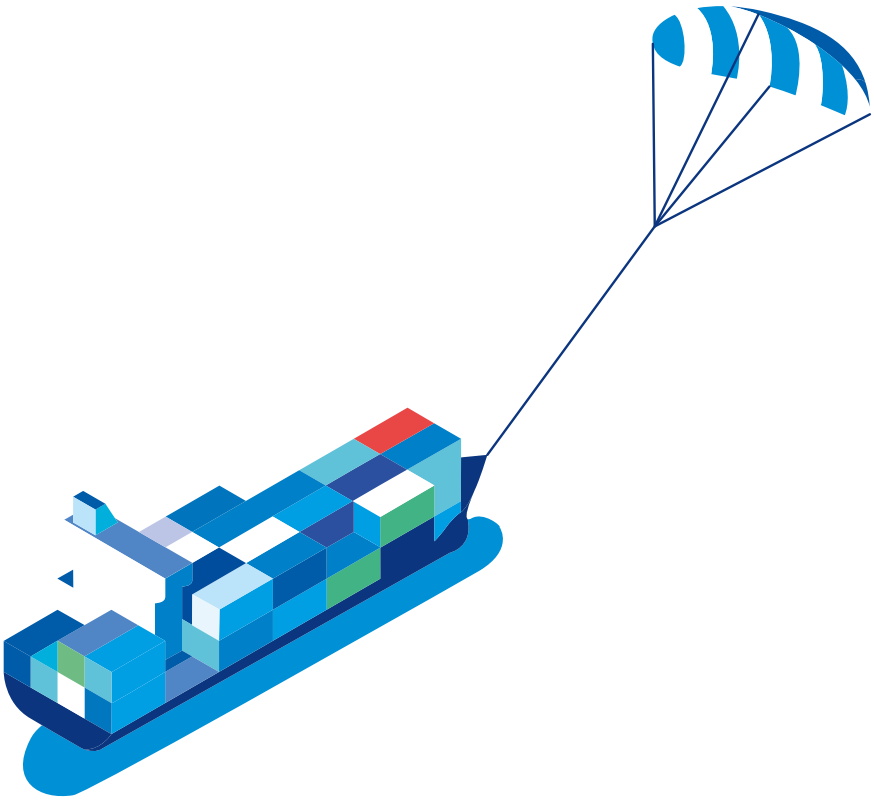
Yan, S. and Eskeland, G.S. (2018). Greening the vehicle fleet: Norway's CO_2-differentiated registration tax. *Journal of Environmental Economics and Management* 91, 247–262. https://doi.org/10.1016/j.jeem.2018.08.018.

Yin, B., Liu, L., Coulombel, N. and Viguie, V. (2018). Appraising the environmental benefits of ride-sharing: The Paris region case study. *Journal of Cleaner Production* 177, 888–898.

Z

Zhang, C., Chen, W.-Q., Ruth, M. (2018). *Measuring material efficiency:* A review of the historical evolution of indicators, methodologies and findings. Resources, *Conservation and Recycling* 132, 79–92. https://doi.org/10.1016/j.resconrec.2018.01.028.

Zheng, X., Wang, R., Wood, R., Wang, C. and Hertwich, E.G. (2018). High sensitivity of metal footprint to national GDP in part explained by capital formation. *Nature Geoscience* 11, 269–273. https://doi.org/10.1038/s41561-018-0091-y.



United Nations Avenue, Gigiri
P O Box 30552, 00100 Nairobi, Kenya
Tel +254 20 76 1234 |
publications@unenvironment.org
www.unenvironment.org