# A. Introduction and framing

The Working Group III (WG III) contribution to the IPCC's Sixth Assessment Report (AR6) assesses literature on the scientific, technological, environmental, economic and social aspects of mitigation of climate change. It assesses the current state of knowledge[1] building on the WG III contribution to the IPCC's Fifth Assessment Report (AR5) and the three Special Reports in the Sixth Assessment cycle.[2]

The report reflects developments and changes in approaches in the literature on climate change mitigation published since the AR5:

- **A changed global landscape since AR5.** The development of the literature reflects the goals of the Paris Agreement {see Chapters 14, 15} and its novel governance structure, and the UN 2030 Agenda for Sustainable Development {1, 4, 17}. Literature further highlights the growing role of non-state actors such as cities, businesses, transnational initiatives, and public-private entities in the global effort to address climate change {8, 13}. It draws attention to the falling cost of low carbon technologies {2, 6} and the evolving role of international cooperation {14}, finance {15} and innovation {16}. An emerging literature addresses the global spread of climate policies and the growing number of developed countries with sustained reductions in greenhouse gas (GHG) emissions {2, 13}, and the mitigation challenges and opportunities posed by the COVID-19 pandemic {TS-Box 1, and Cross-Chapter Box 1 in Chapter 1}.
- **Close linkages between climate mitigation, development pathways and the pursuit of sustainable development goals.** The literature shows that the risks and co-benefits of mitigation action differ according to stages of development and national capabilities {1, 2, 4}. Choices of development pathways affect the portfolio of available mitigation options. The feasibility and cost of limiting emissions to any given level depend on both underlying development pathways and choices made about enabling conditions (Figure SPM.1) {1.4, 1.5, 4}. Climate change mitigation framed in the context of sustainable development, equity and poverty eradication, and rooted in the development aspirations of the economy and society within which they take place, is likely to be more acceptable, durable and effective {1, 4}.
- **Novel aspects of the assessment.** In addition to the well-established sectoral and systems chapters {6, 7, 8, 9, 10, 11, 12}, the report includes, for the first time, chapters dedicated to demand, services and social aspects of mitigation {5}, and innovation, technology development and transfer {16}. The assessment of future pathways combines a near- to medium- future perspective up to 2050, including ways of shifting development pathways towards sustainability {4}, and a long-term global perspective up to 2100 {3}. Collaboration between Working Groups is reflected in Cross-Working Group boxes which address topics such as the economic benefits from avoided impacts along long-term mitigation pathways {Cross-WG Box 1 in Chapter 3}, cities and climate change {Cross-WG Box 2 in Chapter 8}, and mitigation and adaptation via the bioeconomy {Cross-WG Box 3 in Chapter 12}. This assessment

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FOOTNOTE [1] The draft covers literature submitted for publication by 14 December 2020.
FOOTNOTE [2] The three Special reports are: *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; 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; IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.*

gives greater attention than AR5 to social, economic and environmental dimensions of mitigation actions, including from land-based actions {7, 12, 17}, and institutional, legal and financial aspects {13, 14, 15}.

- **Broader and more diverse analytic frameworks and multiple disciplines.** This report identifies multiple analytic frameworks relevant to assessing the drivers and barriers to, and options for, mitigation action. These include: economic and environmental efficiency; ethics and equity; innovation and transition dynamics {16}; and psychology, sociology, and political science {1.6, 5}. These help to identify and explain synergies and trade-offs, challenges and windows of opportunity, including for just transitions at national and global levels. {1, 5, 13, 14, 16}.
- **Accelerating the response.** The climate risks assessed by Working Groups I and II have increased since AR5, contributed to by rising global GHG emissions up to 2018. Limiting global warming cost effectively to 1.5ºC above pre-industrial levels, or to *likely* below 2ºC, implies that global carbon dioxide ($CO_2$) emissions peak before 2025 and reach net zero in the third quarter of this century. This would imply greater near-and medium-term ambition, accelerated action and effective implementation. {1, 3, 4, 14}.

This Summary for Policymakers (SPM) is structured as follows. Section *B*: *Where are we now and where are we headed,* addresses recent emission trends and drivers including recent sectoral, financial, technological and policy developments. Section *C: System transformations to limit global warming* identifies emission pathways consistent with limiting global warming to different levels, along with possible mitigation portfolios. It assesses individual mitigation options at the sectoral level, along with costs and feasibility. Section *D: Mitigation, adaptation, and sustainable development* addresses links between mitigation, adaptation, and sustainable development, including the risks and trade-offs associated with specific mitigation actions. Section *E: Strengthening the response* summarises our knowledge of how institutional design, policy, finance and governance arrangements can deliver climate mitigation while minimising risks and maximising co-benefits.

References to the underlying report and the Technical Summary are given in {} brackets. Confidence in key findings is indicated using the IPCC calibrated language.[3]

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FOOTNOTE [3] Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typesets in italics, for example, *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100%, more unlikely than likely 0–<50%, extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, for example, *very likely*. This is consistent with IPCC AR5.

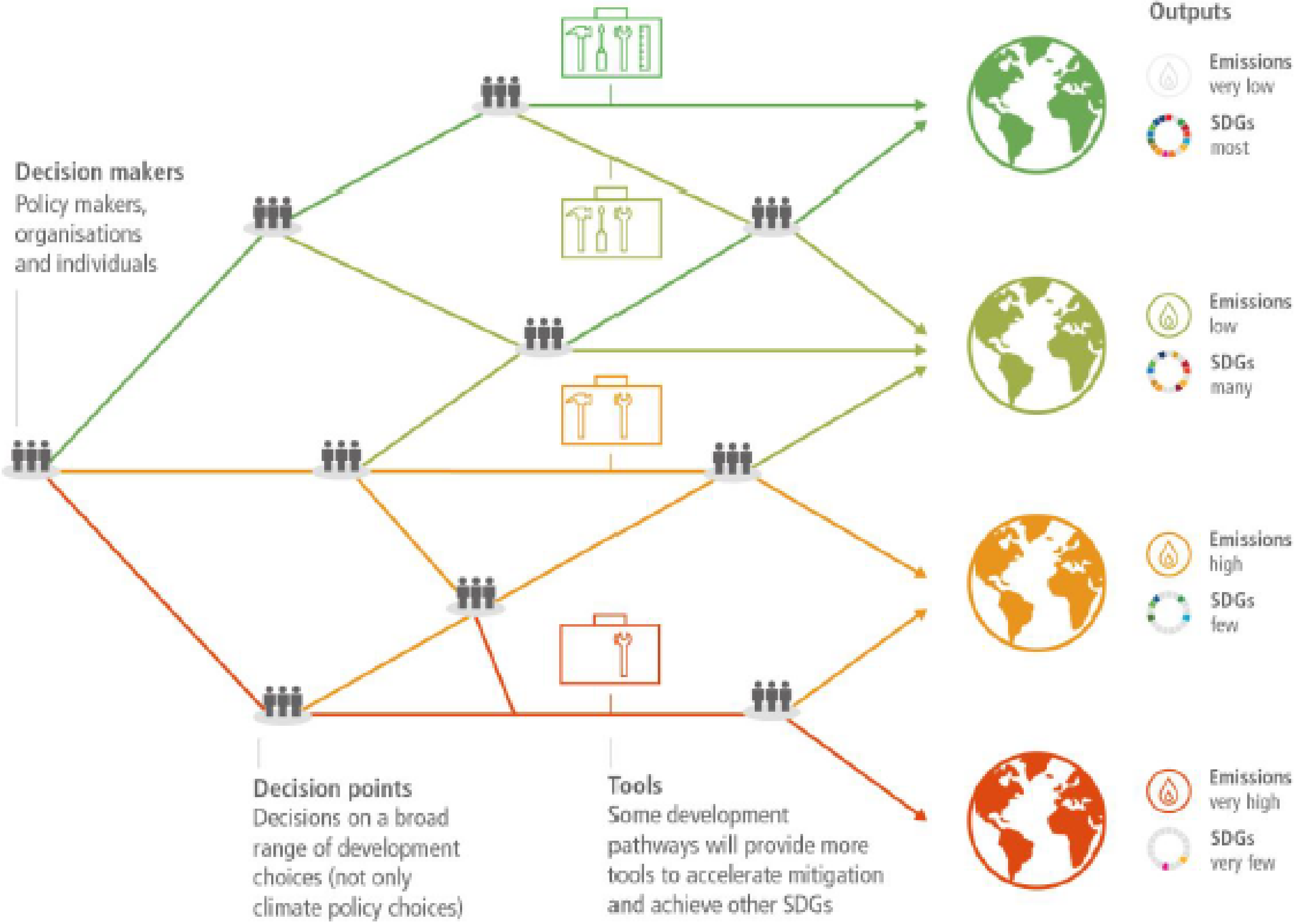



**Figure SPM.1 | Shifting development pathways to accelerate mitigation and increase sustainability**: Choices by a wide range of actors at key decision points along development pathways influence emissions and the availability of options for climate mitigation and system transformation.

# B. Where are we now and where are we headed?

**B1. Annual global GHG emissions have continued to rise since 2010 reaching 59±5.9 $GtCO_2$-eq in 2018. Although the rate of growth has fallen compared to the previous decade *(high confidence)*, 2018 GHG emissions were higher than at any previous time in human history (*medium confidence*). Emission growth has been varied, but persistent across different gases *(high confidence*). (Figure SPM.2) {2.2, Cross-Chapter Box 1 in Chapter 1}**

B1.1. Global anthropogenic GHG emissions were 59±5.9 $GtCO_2$-eq in 2018[4]: 11% (5.9 $GtCO_2$-eq) higher than in 2010, 51% (20 $GtCO_2$-eq) higher than 1990, and higher than at any previous time in human history *(medium confidence)*. Average annual GHG emissions for 2009–2018 were 56±5.6 $GtCO_2$-eq compared to 47±4.7 and 40±4.0 $GtCO_2$-eq for 2000–2009 and 1990–1999, respectively (*high confidence*). GHG emissions growth slowed since 2010: while average annual GHG emissions growth was 2.3% between 2000 and 2010, it was 1.3% for 2010–2018. {2.2}

B1.2. Emission growth has been varied, but persistent across different gases (*high confidence*). In 2018, $CO_2$ emissions from fossil fuel and industry (FFI) were 38±3.0 Gt, $CO_2$ from agriculture, forestry and other land-use change (AFOLU) 5.4±2.7 Gt, methane ($CH_4$) 12±2.3 $GtCO_2$-eq, nitrous oxide ($N_2O$) 2.5±1.5 $GtCO_2$-eq and fluorinated gases (F-gases) 1.8±0.35 $GtCO_2$-eq. While F-gas levels and $CO_2$ emissions from FFI have grown by 430% and 66% between 1990 and 2018, emissions increased by 25% and 28% for $CH_4$ and $N_2O$. The group of fluorinated gases have jointly grown much faster than other GHGs and makes a non-negligible contribution to global warming today. $CO_2$ remains the major driver of warming. (Figure SPM.2) {2.2}

B1.3. Net cumulative emissions of $CO_2$ remain the dominant driver of global warming from human activities. Between 1850 and 2018 total cumulative $CO_2$ emissions from FFI and AFOLU were 2400±390 $GtCO_2$. About 980±98 $GtCO_2$ has been added to the atmosphere since 1990, with about 330±31 $GtCO_2$ added since AR5 (2010). {2.2}

B1.4. The global COVID-19 pandemic has led to a historic drop in $CO_2$ emissions from fossil fuel and industry (*medium confidence*). Preliminary data for 2020 suggest a decrease in FFI $CO_2$ emissions relative to 2019 of about 7% (2.7–13%) or about 3 $GtCO_2$, but emission growth has picked up with economic activity again since April 2020. {Cross-Chapter Box 1 in Chapter 1, 2.2}

FOOTNOTE [4] Emissions of GHGs are weighed by Global Warming Potentials with a 100-year time horizon (GWP-100) from the Sixth Assessment Report. GWP-100 is commonly used in wide parts of the literature on climate change mitigation and is required for aggregate UNFCCC GHG emissions reporting by the Paris rule book. All metrics have limitations and uncertainties. For further details, see Box 2.2 and Annex B Section A.B.10.

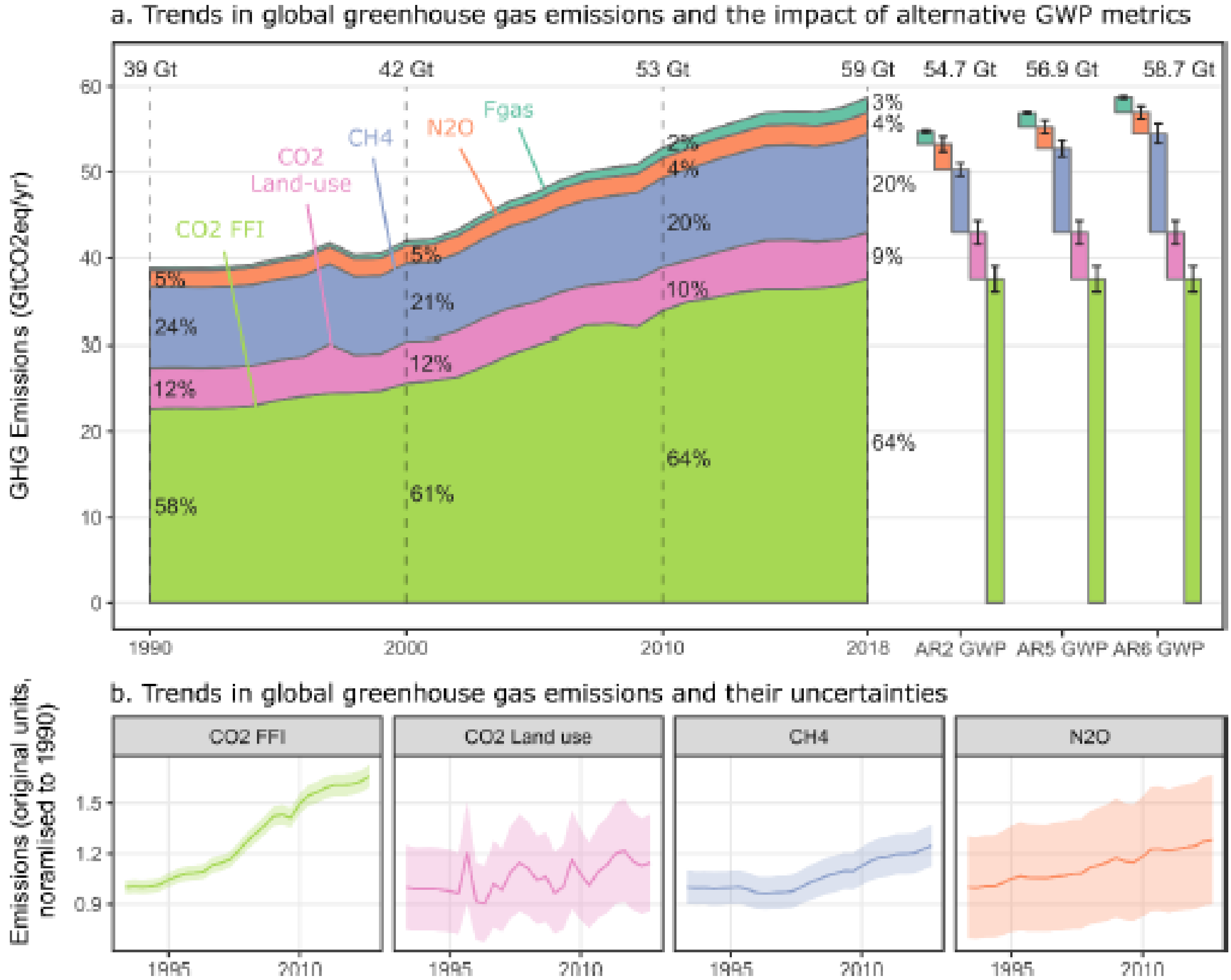



**Figure SPM.2 | Total anthropogenic GHG emissions ($GtCO_2$-eq $yr^{-1}$) 1990-2018:** $CO_2$ from fossil fuel combustion and industrial processes (FFI); $CO_2$ from Forestry and Other Land use (FOLU); methane ($CH_4$); nitrous oxide ($N_2O$); fluorinated gases (F-gases). Panel a: Aggregate GHG emission trends by groups of gases reported in $GtCO_2$-eq converted based on global warming potentials with a 100-year time horizon (GWP-100) from the IPCC Sixth Assessment Report. Waterfall diagrams juxtaposes GHG emissions for the most recent year 2018 in $CO_2$ equivalent units using GWP-100 values from the IPCC's Second, Fifth and Sixth Assessment Report, respectively. Error bars show the associated uncertainties at a 90% confidence interval. Panel b: Individual trends in $CO_2$-FFI, $CO_2$-FOLU, $CH_4$ and $N_2O$ emissions in (original) mass units (Gt $yr^{-1}$) for the period 1990–2018, normalised to 1 in 1990.

**B2. Growth in global per capita GDP and population has outpaced a fall in the global average use of energy per unit of GDP. However, a growing number of countries have entered a period of sustained GHG emission reductions in the absence of economic crises *(high confidence)*. (Figure SPM.3) {2.2, 2.3, 5.2, 9.3}**

B2.1. Materials and energy consumption associated with rising incomes have been the strongest driver of $CO_2$ emissions growth from fossil fuel combustion, with a smaller contribution from population growth. Continued growth in per capita GDP and population between 2010 and 2018 increased FFI $CO_2$ emissions by 2.3% and 1% per year, respectively. This growth continuously outpaced a reduction in the use of energy per unit of GDP (-2.2% per year, globally) (*high confidence*). Technological change driving energy efficiency improvements and a switch to lower carbon energy sources have led to a decoupling of economic growth and emissions in many countries, but fewer countries have experienced absolute emissions reductions. *(high confidence)*. {2.3}.

B2.2. Expansion in GHG intensive economic activities includes aviation (+28.5% from 2010 to 2020), SUVs (+17% from 2010 to 2020) and meat consumption (12% from 2010 to 2020) *(high confidence)*. However, there was a slight but significant shift from high carbon beef consumption to medium carbon intensive poultry consumption. Global energy demand for cooling in the residential sector increased by 40% from 2010 to 2018 *(high confidence)*. {5.2, 9.3}

B2.3. Energy demand has only decoupled from economic growth in relative terms, not in absolute amounts. A substantial decarbonisation of the energy system was only noticeable in North America, Europe and Eurasia, whereas globally the amount of $CO_2$ per unit of energy has practically remained unchanged over the last three decades *(high confidence)*. {2.2}

B2.4. There are at least 36 countries that have sustained territorial-based $CO_2$ and GHG emissions reductions for longer than 10 years. While total cumulative GHG reductions of these countries are small compared to recent global emissions growth, individual countries have cut their emissions by 50% from peak levels. Similarly, national GHG reduction rates in some years are in line with scenario pathways that limit warming well below 2°C at 66% probability (e.g., -4% average annual reductions), even outside of periods of economic decline *(high confidence)*. (Figure SPM.3) {2.2}

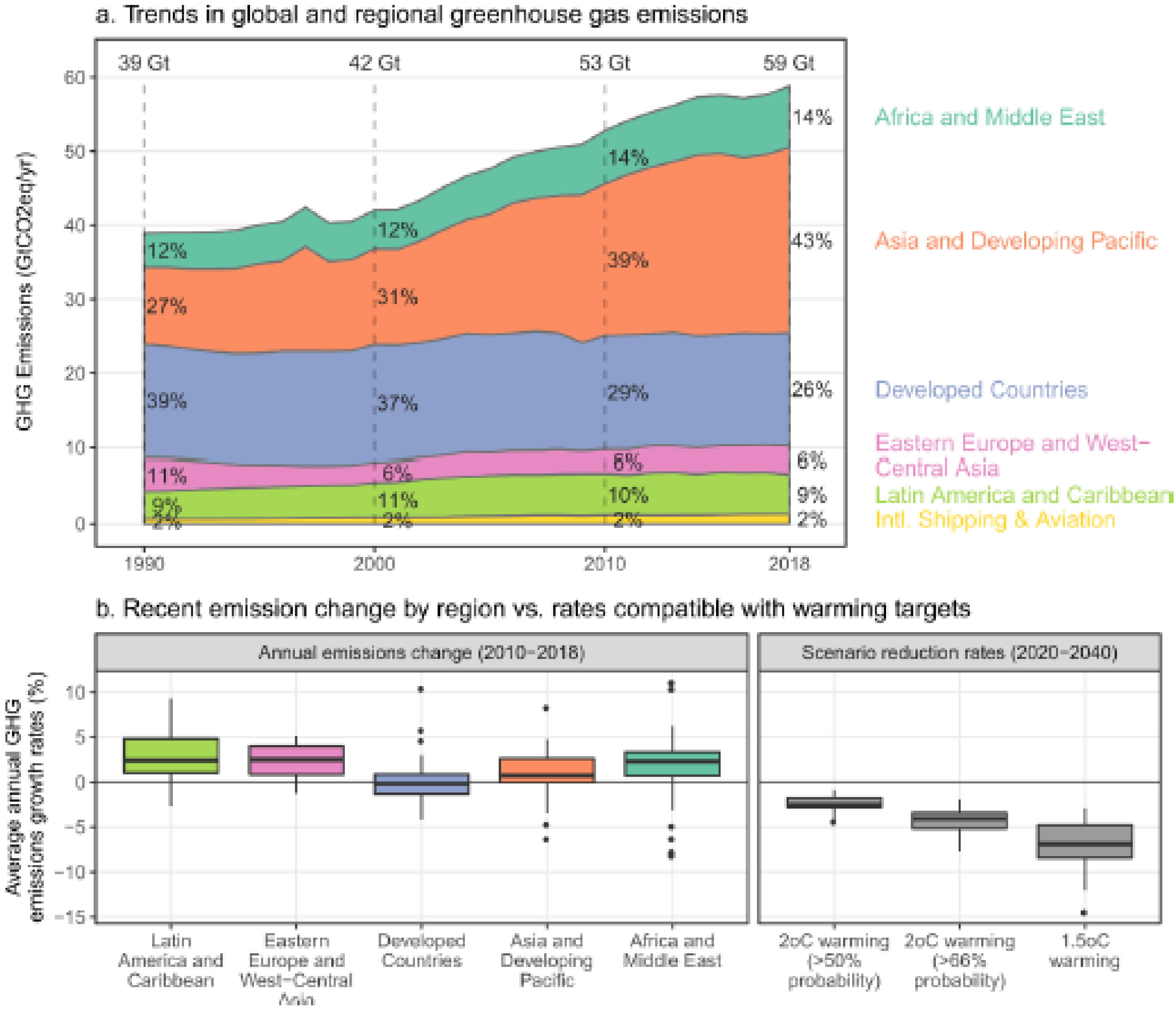



**Figure SPM.3 | Change in regional GHG emissions and rates of change compatible with warming targets.** Panel a: Regional GHG emission trends (in $GtCO_2$-eq $yr^{-1}$ (GWP100 AR6)) for the time period 1990–2018. GHG emissions from international aviation (AIR) and shipping (SEA) are not assigned to individual countries and shown separately. Panel b: Historical GHG emissions change by region (1990–2018), compared to rates of reduction compatible with 1.5°C and 2°C warming targets, assessed via reduction rates in AR6 IAM scenarios over the period 2020-2040.

**B3. GHG emissions differ significantly between nations, and between rich and poor people within nations, mirroring global income inequalities (*high confidence*). The top 10% emitters (the global wealthiest 10% on a per capita basis) contribute ten times as much to global emissions as the poorest 10% (*high confidence*). Providing universal access to modern energy globally will have negligible emission impacts (*medium confidence*). {2.2, 2.3, 2.4, 2.5, 2.6}**

B3.1. Average per capita GHG emissions in 2018 were 13.1 $tCO_2$-eq/cap in developed countries, 14.7 $tCO_2$-eq/cap in Eastern Europe and West Central Asia, 5.8 $tCO_2$-eq/cap in Latin America and Caribbean, 5.7 $tCO_2$-eq/cap in Asia and Developing Pacific, and 4.2 $tCO_2$-eq/cap in Africa and Middle East. Inequality in GHG emissions between countries has decreased over the last decades in correspondence with steady global economic growth and a decline in the global carbon GINI (*high confidence*). {2.2, 2.4}

B3.2. 35% of global cumulative GHG emissions between 2010 and 2018 were from developed countries and 3% from least developed countries; developed countries account for 17% and least developed countries 13% of the world's population. Consumption-based $CO_2$ emissions from the production of goods and services finally consumed in developed countries peaked in 2007 at about 17 $GtCO_2$ and declined subsequently. 46% of developing country $CO_2$ emissions in 2010 and 41% in 2015 were from export production to developed countries (*medium confidence*). {2.2, 2.3}

B3.3. Within countries, inequalities increased for both income and GHG emissions between 1980 and 2016, with the top 1% accounting for 27% of income growth. The global richest 10% contribute about 36–45% of global GHG emissions, while the world's poorest 10% contribute around 3–5% (*high confidence*). The richest 10% live on all continents, with two thirds in high-income regions and one third in emerging economies. Most of the lowest 10% emitters live in sub-Saharan Africa, South East Asia, Central Asia and Latin America. These regions are home to the almost 20% of global population lacking access to electricity and the 37% lacking access to clean cooking. Eradicating extreme poverty would increase global $CO_2$ emissions only slightly (*high confidence*). {2.5}

B3.4. The consumption patterns of higher income consumers are associated with large carbon footprints. Top emitters dominate emissions in key sectors, for example the top 1% account for 50% of GHG emissions from aviation (*high confidence*). Growing within country inequality in GHG emissions creates distributional and social cohesion dilemmas, compromises social trust, and affects the willingness of both rich and poor to accept mitigation and other policies to protect the environment (*medium confidence*). {2.5}

**B4. Changes in sectoral emission patterns since AR5 can be attributed to developments in technology, policies, investment patterns, and behaviour (*high confidence*). The cost, performance and adoption of many individual technologies have progressed, but deployment rates, deployment patterns, and the global reach of technological change is currently insufficient to achieve climate and sustainable development goals (*high confidence*). Many technological advances have not benefitted developing countries to the same extent as developed countries, nor have they necessarily led to the enhancement of technological capabilities, with the least-developed countries particularly disadvantaged (*medium confidence*). (Figure SPM.4, Figure SPM.5) {2.2, 6.3, 6.4, 7.2, 12.2, 16.2, 16.5, 16.6, Cross-Chapter Box 8 in Chapter 16}**

B4.1. In 2018, 34% (20 $GtCO_2$-eq) of global GHG emissions came from the energy sector, 23% (13 $GtCO_2$-eq) from industry, 23% (13 $GtCO_2$-eq) from AFOLU, 14% (8.3 $GtCO_2$-eq) from transport and 6% (3.4 $GtCO_2$-eq) from buildings. Once indirect emissions from energy use are considered, the relative shares of industry and buildings emissions are 33% and 17%, respectively. While average annual GHG emissions growth between 2010 and 2018 slowed significantly compared to the previous decade in the energy (from 3.2% to 1.4%) and the industry (from 5.0% to 1.7%) sectors, average annual growth in the transport sector has remained roughly constant at about 2% per year (*high confidence*). (Figure SPM.4) {2.2}

B4.2. Since 2010, the rapid cost decreases of solar (87%), wind (38%), and batteries (85%), and the capacity installed has exceeded previous expectations. Solar and wind energy now provide 7% of total electricity supply. In the last 12 years the AFOLU sector has achieved mitigation of ~0.7 $GtCO_2\ yr^{-1}$ (*medium confidence*) with biomass contributing two-thirds of modern renewable heating and cooling in buildings and industrial processes, and biofuels contributing 90% of renewable energy use in the transport sector (*high confidence*). Policy instruments have been a key driver for change in several countries (*medium confidence*), though recent reversals of past gains illustrate the difficulty of sustaining policies. (Figure SPM.5) {1.3, 1.5, 2.5, 6.3, 6.4, 7.2, 12.2}

B4.3. The scale-up, diffusion and global spread of carbon capture and storage (CCS), nuclear energy and carbon dioxide removal (CDR) technologies have not progressed as rapidly. Economic barriers, institutional challenges and public concerns about safety and sustainability are amongst the reasons inhibiting their diffusion *(high confidence)*. {2.5, 6.3, 11.3, 12.7, 16.3, 16.4}

B4.4. General Purpose Technologies (GPTs), such as digital, artificial intelligence or biotechnology, have already found applications across sectors, and have led to both synergies and trade-offs between mitigation and Sustainable Development Goals (SDGs) (*medium evidence, high agreement*). Digitalisation is fundamentally changing all economies and societies. Digital technologies, and associated innovation, can contribute to more efficient industrial processes and power, but they may also increase energy demand and demand for goods and services (*medium confidence*). {Cross Chapter Box 8 in Chapter 16, 5.3, 10, 12.6, 16.3}

B4.5. Some governments have strengthened innovation systems and policies by adopting a holistic approach. Such policies have accelerated deployment and diffusion of existing and new low-emission technologies, increased cooperation, and strengthened domestic innovation capabilities (*high confidence*). Systemic approaches are still not widespread and international technology cooperation as envisaged under international climate agreements is still limited in scope and size (*medium evidence, high agreement*). {16.6}

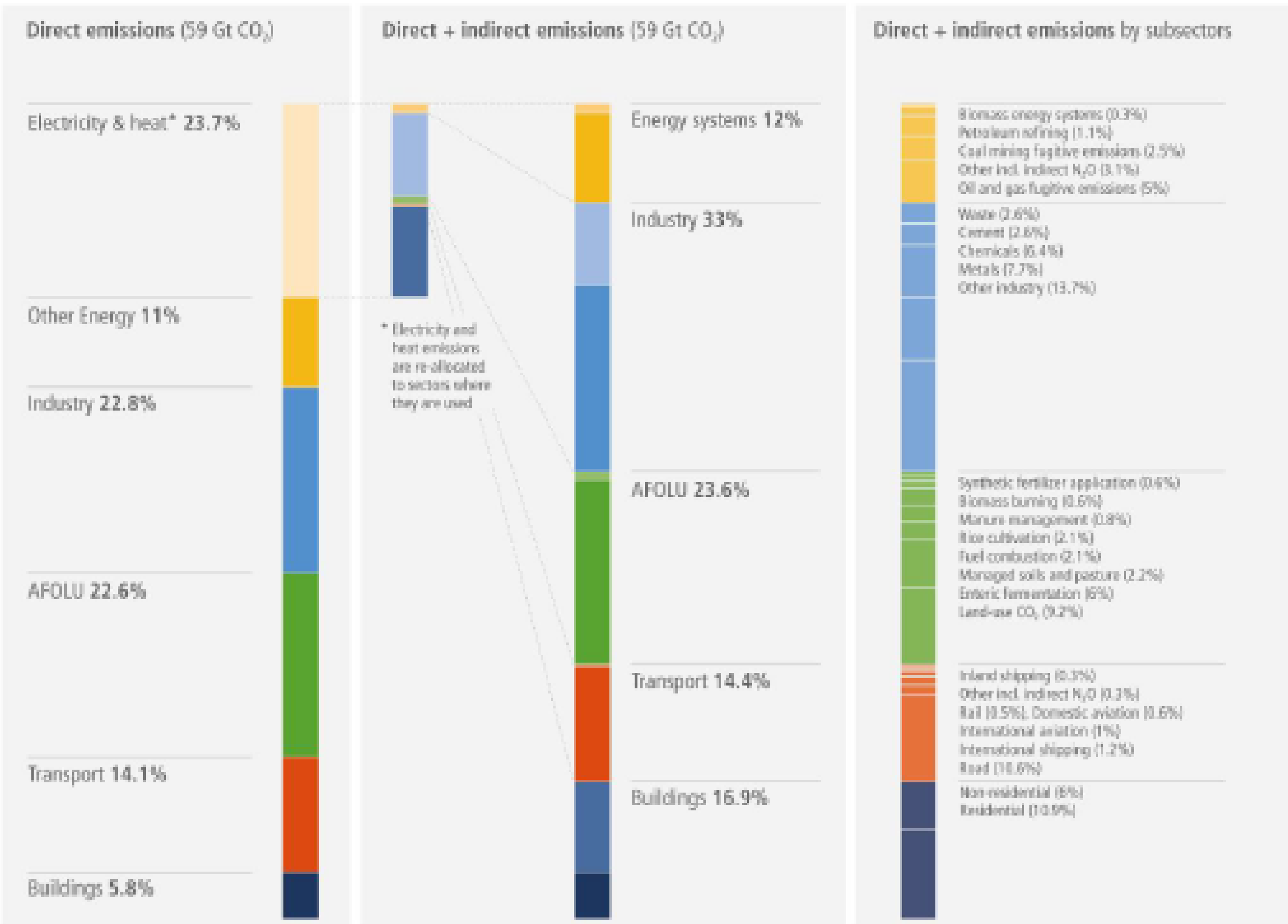



**Figure SPM.4 | Direct versus indirect emissions.** The stacked bar on the left indicates total global greenhouse gas emissions in 2018, split by sectors based on direct (scope 1) emissions accounting. The pull-out section for Electricity & heat depicts the reallocation of these emissions to final sectors as indirect (scope 2) emissions. This increases the contribution to global emissions from the industry and buildings sectors (central stacked bar). The stacked bar on the far right indicates the shares of subsectors in global emissions when indirect emissions are included.

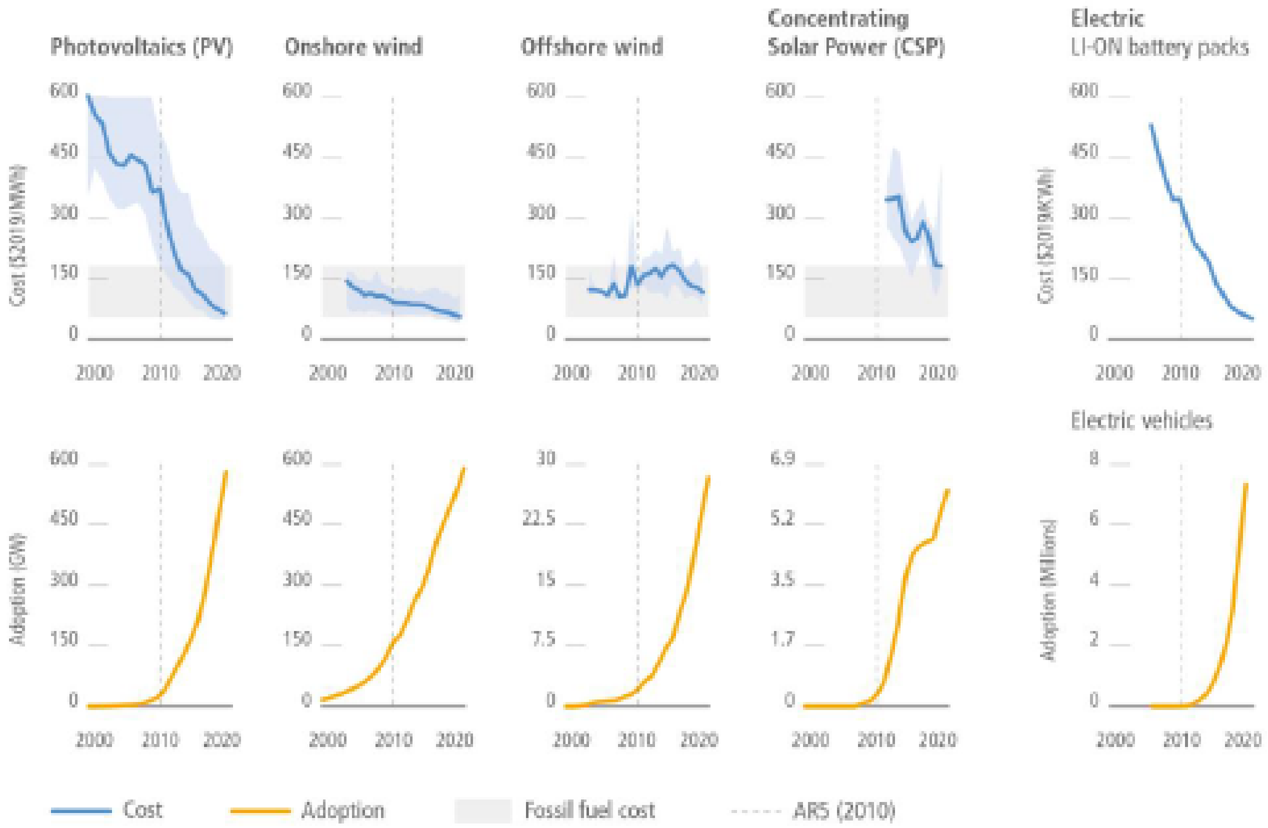



**Figure SPM.5 | Cost reductions and adoption in dynamic energy technologies.** Upper panel shows levelised costs of electricity (LCOE) for renewable energy technologies and battery storage. Blue areas show the range between the 5th and 95th percentiles in each year. Lines indicate average cost in each year. Range of fossil fuel (coal and gas) LCOE indicated as grey area $50-177 per MWh. Lower panel shows cumulative worldwide adoption for each technology, in GW of capacity for renewable energy and in vehicles for electric vehicles. Vertical dashed line placed at 2010 to indicate change since AR5.

**B5. Since AR5, there has been a substantial growth in climate policy and corresponding institutional arrangements at national and sub-national levels (*high confidence*). Many countries have developed cross-sectoral frameworks with multiple objectives that have climate mitigation as a co-benefit. Gaps remain in terms of the extent of coverage and the ambition of climate commitments and effective enabling conditions for implementation, such as sufficient policies, their stringency and suitable institutions (*medium evidence, high agreement*). {5.6, 13.2, 13.4, 13.5, 13.6, 14.3, 14.4, 14.5, 15.3, 15.5}**

B5.1. Little new climate legislation and few additional national strategies were added between 2012 and 2017, but climate targets have become more prevalent (*high confidence*). The share of global GHG emissions subject to mitigation policies has increased (*high confidence*). However, $CH_4$, $N_2O$, and $CO_2$ from the production of industrial materials and feedstocks, as well as fossil fuel combustion in many developing and some developed countries, are not yet covered by mitigation policies (*robust evidence, medium agreement*). {13.2, 13.6}

B5.2. Sub-national jurisdictions and cities, businesses and investors, international organisations, legal institutions, indigenous peoples and civil society groups, are engaged in climate mitigation. Climate actions, including partnerships, voluntary initiatives and the collective action of citizens, are taking place across multiple scales. These are having impact through: framing and shaping targets; knowledge generation; emissions disclosure; climate litigation; role models, local decision-making; and fostering experimentation (*high confidence*). {5.6, 13.3, 13.4, 13.5, 14.5}

B5.3. The Kyoto Protocol was instrumental in building institutional capacity to support international carbon markets and voluntary cooperation. The Paris Agreement has shifted international cooperation towards encouraging and supporting rising levels of ambition and the ability of Parties to achieve their mitigation objectives within the framework of sustainable development. The effectiveness of the Paris Agreement, on which views differ, depends on the success of its facilitative approach to mitigation ambition built on procedural commitments, normative expectations, transparency, and peer pressure (*high confidence*). {14.3, 14.4, 14.6}

B5.4. Recognition of the need to align financial flows with climate goals has created significant momentum in the financial industry. However, financial flows, for both adaptation and mitigation, have increased only modestly, from USD 343-385 billion annually in 2010-2012 to approximately USD 546 billion in 2018 (*medium confidence*). Financial flows linked to mitigation are a factor of five below the average levels needed to limit warming to 2ºC (*medium confidence*). Flows are unevenly distributed across regions and sectors and stakeholders (*high confidence*). {Figure 15.3, 15.3}

B5.5. The balance of public and private financial flows has been relatively stable over the past five years, at 40% and 60% respectively. The private sector has driven increased financial flows towards the renewable energy sector. In other sectors, where financially viable business models and appropriate risk assessments are less well established, there are barriers to the mobilisation of private sector finance (*high confidence*). Markets for green bonds and sustainable finance products have expanded significantly since AR5, reflecting investor preferences for scalable and highly standardised investment opportunities. {15.5}

**B6. Global emissions in 2030 as projected on a continuation of current policies exceed current national pledges. In turn, current pledges are not consistent with long-term emission pathways that would *likely* limit global warming to 2°C during the 21st century (*high confidence*). Existing and planned infrastructure and investments, institutional inertia and a social bias towards the status quo are leading to a risk of locking in future GHG emissions that may be costly or difficult to abate, due to early decommissioning, underutilisation and devaluation of stranded assets. (Figure SPM.6) {2.7, 3.3, 3.5, 4.2, Cross-Chapter Box 3 in Chapter 4}**

B6.1. Current policies lead to median projected global GHG emissions of 63 (57–70) $GtCO_2$-eq $yr^{-1}$ by 2030. Unconditional and conditional NDCs lead to projected emissions of 59 (55–65) and 56 (52–61) $GtCO_2$-eq $yr^{-1}$ respectively (*medium evidence, high agreement*). The emissions gap in 2030 between unconditional NDCs and cost-effective long-term mitigation pathways is 25-34 $GtCO_2$-eq (22-31 $GtCO_2$-eq) for limiting warming to 1.5°C with no or low (<0.1°C) overshoot (50% chance) and 14-23 $GtCO_2$-eq (11-20 $GtCO_2$-eq) for limiting warming to 2°C (66% chance). The comparable gaps for conditional NDCs are 23-29 $GtCO_2$-eq and 6-10 $GtCO_2$-eq respectively. (*medium evidence, high agreement*) (Figure SPM.6) {3.5, 4.2, Cross-Chapter Box 3 in Chapter 4}

B6.2. Estimates of committed $CO_2$ emissions from *current* fossil energy infrastructures are 658 (455-892) $GtCO_2$ depending on assumed decommissioning rates and capacity utilisations. Estimated committed $CO_2$ emissions from *current* and *planned* fossil energy infrastructures are 846 (597-1126) $GtCO_2$. Estimates for committed emissions from fossil energy infrastructure are nearly double the remaining carbon budget for limiting warming to 1.5°C with 50% probability (390 $GtCO_2$) (*medium evidence, high agreement*). These estimates do not cover planned infrastructure from industry, buildings and transportation for which there is no data. {2.7, 6.7, WGI SOD Chapter 5}

B6.3. Current average lifetimes for coal and gas power plants are 39 and 36 years respectively. To limit warming to 1.5°C, it is estimated that, without reducing utilisation rates, or large-scale retrofitting enabling biomass use and/or CCS, and assuming that no plants proposed or under construction come online, the average lifetime of coal and gas power infrastructure would need to be limited to 9 (5-20) and 12 (9-14) years respectively. To limit warming to 2°C with 66% probability, the comparable estimates are 16 (6-28) and 17 (10-25) years. These estimates are further reduced if it is assumed that plants proposed or under construction come online *(medium confidence)*. {2.7}

B6.4. Factors limiting ambitious transformation include structural barriers, an incremental rather than systemic approach, lack of coordination, inertia, lock-in to infrastructure and assets, and lock-in as a consequence of vested interests, regulatory inertia, and lack of technological capabilities and human resources. *(high confidence)* {1.5, 2.8, 5.5, 6.7, 13.8}

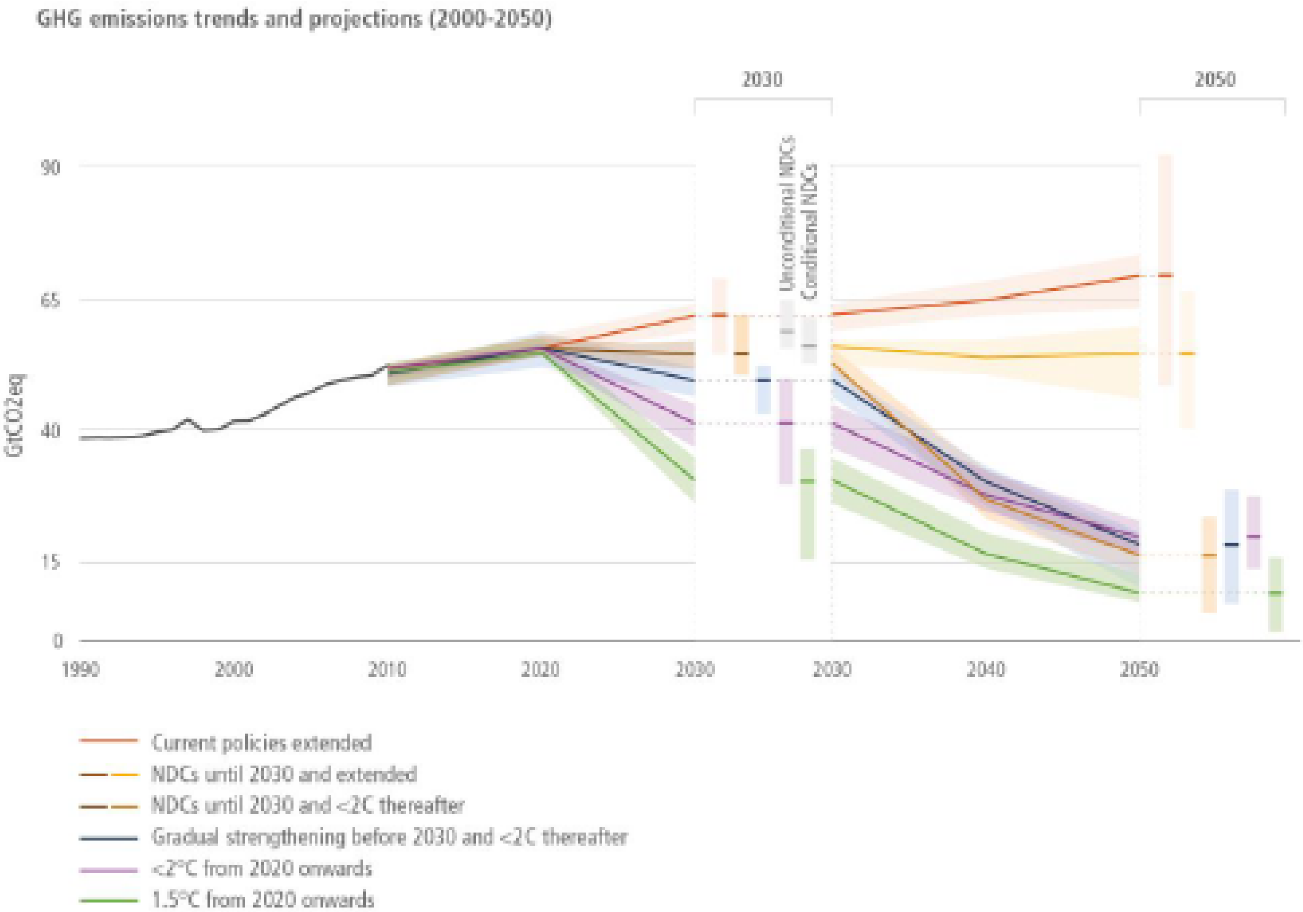



**Figure SPM.6 | Aggregate GHG emission outcomes of NDCs and long-term mitigation pathways consistent with global temperature limits.** Shown are emission ranges that would emerge from the implementation of current unconditional and conditional NDCs (grey bars) and global pathways from the AR6 scenario database that can be grouped into six types:

- Pathways with near-term emissions developments in line with (1) current policies and (2) NDCs, respectively, and extended with comparable ambition levels beyond 2030,
- Pathways holding warming below 2°C (66% chance) with near term emissions developments reflecting (3) ambition levels in current NDCs and (4) a gradual strengthening of mitigation action beyond NDCs, respectively, and
- Mitigation pathways undertaking immediate action from 2020 onwards towards (5) holding warming below 2°C (66% chance) and (6) limiting warming to 1.5°C by 2100 with low (<0.1°C) overshoot (50% chance), respectively.

The figure shows the emission pathways until 2050 (median and 25th-75th percentiles) with their emissions ranges in 2030 and 2050 broken out in full (median and 5th-95th percentiles). Projected emissions for the NDCs from Section 4.2.2 (Table 4.1) show median and full range.

[Notes: GHG emissions are expressed in $CO_2$-equivalent based on 100-year GWPs from AR6. The NDC estimates are based on the first round of submission to the UNFCCC and do not include recent updates most notably those submitted since November 2020.]

## C. System transformations to limit global warming

**C1. Global warming associated with published emissions pathways ranges from less than 1.5°C at peak to greater than 5°C by 2100 compared to pre-industrial levels. Baseline scenarios without any new climate policies lead to a median global warming of 3.3°C-5.4°C by 2100 (*medium confidence*). Limiting warming to below 1.5°C or 2°C compared to preindustrial levels requires rapid GHG emissions reductions and fundamental structural changes at global scale (*high confidence*). Weaker near-term action would place limiting warming to these levels out of reach as it would entail assumptions about subsequent accelerated policy development, and technology development and deployment, inconsistent with evidence and projections in the assessed literature (*high confidence*). (Table SPM.1) {3.3, 3.8}**

C1.1. In the absence of new climate policies and without the implementation of current pledges, annual GHG emissions in baseline scenarios increase from 58 to 59-80 $GtCO_2$-eq $yr^{-1}$ by 2030 and to 63-110 $GtCO_2$-eq $yr^{-1}$ by 2050, resulting in global warming of 3.3°C to 5.4°C by 2100 (*medium confidence*). The highest emissions scenarios in the literature combine assumptions about rapid long-term economic growth and pervasive climate policy failures, leading to a reversal of some recent trends and a fossil fuel dominated future. {3.3}

C1.2. In pathways that limit global warming to below 3.0°C by 2100, $CO_2$ emissions peak around 2035 (range: 2020-2060). In pathways that limit global warming to below 2.0°C by 2100 (50% or greater probability), $CO_2$ emissions peak immediately (range: 2020-2025). Many pathways in the literature limit global warming to 1.5°C by 2100 (50% probability) with a temperature overshoot of less than 0.1°C (low overshoot), but only a few limit global warming to 1.5°C by 2100 (50% probability) without overshoot during the course of the 21st century. (*high confidence*) (Table SPM.1) {3.3}

C1.3. Mitigation pathways *likely* to limit global warming to below 2°C by 2100 are associated with net global GHG emissions of 34–56 $GtCO_2$-eq $yr^{-1}$ by 2030 and 14–25 $GtCO_2$-eq $yr^{-1}$ in 2050. These correspond to GHG emissions reductions of 4–40% by 2030, and 55–74% by 2050 relative to modelled 2020 emission levels. Pathways that limit global warming to below 1.5°C by 2100 with 50% probability and with low overshoot require a further acceleration in the pace of the transformation, with GHG emissions reductions of 35–60% by 2030 and 73–94% in 2050 relative to modelled 2020 emission levels. (*medium confidence*) (Table SPM.1) {3.3}

**Table SPM.1 | Key characteristics of the global emissions pathways:** Summary of $CO_2$ and GHG emissions, net-zero timings and likely temperature outcomes. Scenarios are categorised by their climate outcome (rows), according to their likelihood of staying below threshold warming levels, according to both peak and 2100 temperature. Values shown are for the median (p50) and 10th-90th percentiles, noting that not all scenarios achieve net-zero $CO_2$ or GHGs. Baseline range corresponds to 10-90th percentile of baseline emissions across different socioeconomic pathways (SSPs).

| p50 (p10-p90) [0] | | Global Mean Temperature change | Emissions milestones [3,4] | | | GHG emissions Gt $CO_2$-eq/yr | | | GHG emissions reductions from 2020 % [5] | | | Cumulative $CO_2$ emissions Gt $CO_2$ [7,8] | | Cumulative net-negative $CO_2$ emissions Gt $CO_2$ | Temperature change 50% probability [9] °C | | Likelihood of staying below (%) [10] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Category [1, 2] | # scenarios | Category description | Peak $CO_2$ emissions | net-zero $CO_2$ | net-zero GHGs [6] | 2030 | 2040 | 2050 | 2030 | 2040 | 2050 | 2019 to netzero $CO_2$ | 2019-2100 | year of net-zero $CO_2$ to 2100 | at peak warming | 2100 | <1.5°C | <2.0°C | <3.0°C |
| C1 | 71 | <1.5°C with no or low overshoot (<0.1°C) | 2020 (2020-2020) | 2056 (2045-2070) | 2077 (2058-...) | 30 (21-35) | 16 (8-22) | 9 (3-14) | 44 (35-60) | 70 (60-84) | 83 (73-94) | 523 (347-680) | 336 (-30-569) | -200 (-477-0) | 1.56 (1.46-1.59) | 1.25 (1.09-1.46) | 38 (33-58) | 96 (94-99) | 100 (100-100) |
| C2 | 82 | <1.5°C with high overshoot (>0.1°C) | 2020 (2020-2025) | 2057 (2049-2067) | 2073 (2058-...) | 43 (34-56) | 24 (18-32) | 12 (6-20) | 23 (3-40) | 56 (44-67) | 77 (65-91) | 710 (542-901) | 348 (9-685) | -344 (-673--71) | 1.68 (1.61-1.8) | 1.4 (1.23-1.49) | 24 (14-31) | 88 (77-94) | 100 (100-100) |
| C3 | 285 | Likely below 2°C | 2020 (2020-2025) | 2071 (2060-...) | ... (2080-...) | 44 (34-56) | 28 (22-36) | 19 (14-25) | 21 (4-40) | 49 (37-60) | 66 (55-74) | 872 (701-1074) | 751 (531-1017) | -34 (-274-0) | 1.74 (1.64-1.84) | 1.62 (1.52-1.76) | 18 (10-28) | 80 (70-89) | 100 (100-100) |
| C4 | 85 | Below 2°C | 2020 (2020-2025) | 2088 (2069-...) | ... (2078-...) | 50 (43-58) | 37 (31-44) | 28 (23-34) | 7 (-1-24) | 33 (21-45) | 50 (37-60) | 1205 (1018-1497) | 1160 (752-1497) | -5 (-309-0) | 1.93 (1.88-1.99) | 1.87 (1.7-1.96) | 7 (4-11) | 58 (50-65) | 99 (98-100) |
| C5 | 156 | Below 2.5°C | 2020 (2020-2030) | ... (2080-...) | ... (2094-...) | 52 (45-58) | 46 (37-53) | 39 (31-47) | 6 (-2-18) | 17 (6-35) | 31 (15-45) | 1723 (1331-2179) | 1719 (1285-2179) | 0 (-138-0) | 2.16 (2.03-2.44) | 2.13 (1.99-2.41) | 1 (0-4) | 32 (14-45) | 97 (89-98) |
| C6 | 81 | Below 3°C | 2035 (2025-2060) | ... (...-...) | ... (...-...) | 56 (50-63) | 56 (47-62) | 52 (46-59) | -2 (-10-5) | 1 (-13-11) | 4 (-11-16) | 2686 (2345-3065) | 2686 (2345-3065) | 0 (0-0) | 2.71 (2.55-2.86) | 2.71 (2.53-2.86) | 0 (0-0) | 4 (1-8) | 72 (55-83) |
| C7 | 184 | Above 3°C | 2080 (2040-2100) | ... (...-...) | ... (...-...) | 64 (55-74) | 68 (57-82) | 72 (58-89) | -11 (-19--1) | -20 (-34--3) | -27 (-42--4) | 4502 (3478-5262) | 4502 (3478-5262) | 0 (0-0) | 3.66 (3.16-4.23) | 3.66 (3.16-4.23) | 0 (0-0) | 0 (0-0) | 8 (1-30) |
| Baseline | 104 | - | 2085 (2040-2100) | ... (...-...) | ... (...-...) | 68 (59-80) | 73 (62-94) | 77 (63-110) | -12 (-24--8) | -21 (-49--11) | -29 (-73--10) | 4792 (3066-7214) | 4792 (3066-7214) | 0 (0-0) | 3.88 (3.29-5.02) | 3.88 (3.29-5.02) | 0 (0-0) | 0 (0-0) | 3 (0-27) |

**Footnotes**

0 Values in the table refer to the 50th and (10th-90th) percentile values from the distribution of all the scenarios in that category and does not imply any likelihood statement.

1 Category definitions consider both at peak warming and warming at the end-of-century (2100).
C1: Below 1.5°C in 2100 with a 50% chance (and a peak warming <1.6°C with a 50% chance). C2: Below 1.5°C in 2100 with a 50% chance (and a peak warming >1.6°C but below 2°C with a 50% chance).

(2040-2100)

**Footnotes**

0 Values in the table refer to the 50th and (10th-90th) percentile values from the distribution of all the scenarios in that category and does not imply any likelihood statement.

1 Category definitions consider both at peak warming and warming at the end-of-century (2100).
C1: Below 1.5°C in 2100 with a 50% chance (and a peak warming <1.6°C with a 50% chance). C2: Below 1.5°C in 2100 with a 50% chance (and a peak warming >1.6°C but below 2°C with a 50% chance).
C3: Likely below 2°C throughout the century with at least 67% chance.
C4, C5, C6: Below 2.0°C, 2.5°C and 3.0°C throughout the century, respectively, with a 50% chance. C7: Above 3.0°C with a 50% chance. Baseline: Based on SSP family Baseline scenario set. This Baseline category includes scenarios within Categories C6 and C7.

2 All warming levels are relative to the pre-industrial temperatures from the 1850-1900 period

3 Milestones based on native model data for $CO_2$ & GHG emissions.

4 Categories with percentiles that do not reach net-zero before 2100 are denoted with "..."

5 For cases where models do not report all GHG species, missing GHG species are infilled and calculated as Kyoto basket with AR6 GWP-100 $CO_2$-equivalent factors. See Annex C for details.

6 There is a range of model estimates for GHG emissions in 2020, with a median on 57 Gt $CO_2$-eq/yr (52-61, p10-p90). Hence the percentage GHG reduction ranges shown here do not exactly match the percentile ranges shown in the three columns to the left. Negative values represent an increase in emissions.

7 Cumulative $CO_2$ budgets (the "carbon budget") are calculated based on emissions pathways that are harmonized to 2015 as used in the climate assessment for consistency. Reported GHG emissions from 2015-18 (EDGAR) are subtracted to give remaining budget from 2019 onwards.

8 Emissions rounded to nearest giga-tonne

9 Temperature change for category (at peak and in 2100), based on the median warming for each scenario assessed using the probabilistic climate model emulators.

10 Probability of staying below the temperature thresholds for the scenarios in each category, taking into consideration the range of uncertainty from the climate model emulators consistent with the WGI AR6 assessment. The probabilities refer to the probability at peak temperature. Note that in the case of temeprature overshoot (E.g., category C1 and C2), the probabilities at the end of the century are higher than the probability at peak temperature.

**C2. In most pathways, global average temperature peaks or stabilises roughly when global $CO_2$ emissions reach net zero. The timing of peak temperature also depends on non-$CO_2$ emissions. The level of peak warming is determined by the remaining carbon budget until the time when net zero $CO_2$ emissions are reached and the level of non-$CO_2$ emissions by that time. A more rapid transition towards net zero $CO_2$ emissions limits peak warming levels and avoids temperature overshoot and net negative $CO_2$ emissions. (*high confidence*) {3.3, 3.5}**

C2.1. The remaining carbon budget until global $CO_2$ emissions reach net zero is the key determinant of the level of peak warming, along with the level of non-$CO_2$ emissions at that time. The remaining carbon budget, from the year 2019, in pathways that limit warming to 1.5°C with 50% probability is around 525 (345-680) $GtCO_2$ in the case of low overshoot, and around 710 (540-900) $GtCO_2$ in the case of higher overshoot. Pathways *likely* to limit warming to below 2.0°C have a higher carbon budget of around 870 (700-1075) $GtCO_2$. Cumulative $CO_2$ emissions from 2019 to 2100 in pathways that limit median warming to below 3.0°C are around 2685 (2345-3065) $GtCO_2$. (Table SPM.1) (*high confidence*) {3.3}

C2.2. In most pathways, temperatures peak or are stabilised roughly at the time global $CO_2$ emissions reach net-zero. Lower peak temperatures are associated with earlier carbon neutrality. A warming level of 1.5°C with 50% probability and both low and high overshoot corresponds to reaching carbon neutrality around 2055 (2050-2065), while limiting warming to below 2.0°C with a *likely* chance corresponds to reaching carbon neutrality around 2070 (2060–2095). (*high confidence*) {3.3}

C2.3. Net-zero GHG emissions imply deeper emissions reductions than do net-zero $CO_2$, and result in a gradual decline of temperature over time (*high confidence*). The net-zero year for GHG emissions is around 15 (11-24) years later than for $CO_2$ in pathways that limit warming to below 2°C and 12 (5-26) years later for pathways that limit warming to below 1.5°C (*medium confidence*). {3.3}

C2.4. In pathways that employ $CO_2$ removal and reach net negative $CO_2$ emissions, the remaining carbon budgets up until the year of net zero-$CO_2$ are considerably higher than cumulative $CO_2$ emissions to 2100 (*high confidence*). This is due to the overshoot of the carbon budget and temperature in pathways with net negative $CO_2$ emissions. {3.3, 3.5}

C2.5. Early mitigation of short-lived non-$CO_2$ forcers which act as warming agents, such as $CH_4$ and black carbon, can contribute to limiting warming to a specified level. Reducing non-$CO_2$ emissions more rapidly does not avoid the need to reduce $CO_2$ emissions to net-zero but can expand the remaining carbon budget for a specific peak warming level. In deep mitigation pathways, non-$CO_2$ forcing prior to 2030 can be driven upwards by reductions in cooling aerosols, which override the effect of warming agents such as methane (*medium confidence*). {3.5}

**C3. This assessment draws on a set of illustrative pathways selected from those available in the literature. Comparison of these shows how different socio-economic conditions, levels of ambition, technology emphases, and policy choices can lead to distinctly different transformations. Pathways consistent with limiting global warming to below 2°C and 1.5°C entail rapid emissions reductions and a fundamental transformation of all sectors and all regions in order to reach net zero $CO_2$ emissions globally along with deep reductions in non-$CO_2$ emissions. In a global net zero $CO_2$ emissions system, different sectors and regions may act as either sources or sinks as part of an overall balance. (*high confidence*) (Figure SPM.7) {3.2, 3.3, 3.4, 6.6}**

C3.1. Pathways that avoid net negative $CO_2$ emissions ("2.0-NBZ" and "1.5-NBZ" in Figure SPM.7), thus limiting temperature overshoot, require more rapid near-term emissions reductions in order to reach net zero $CO_2$ emissions earlier than in other pathways. Such pathways include some $CO_2$ removal (e.g., afforestation) in order to compensate for remaining positive emissions in some sectors (e.g., industry). (*high confidence*) {3.4}

C3.2. In pathways that assume lower demand ("1.5-LD" in Figure SPM.7) or shift development pathways towards sustainability ("1.5-SP" in Figure SPM.7), mitigation challenges are significantly reduced. These pathways entail reduced dependence on $CO_2$ removal, reduced pressure on land, and lower carbon prices (*high confidence*). {3.4, 3.8, 4.3}

C3.3. A gradual strengthening of ambition ("2.0-GS" in Figure SPM.7) could reduce GHG emissions to 10 $GtCO_2$-eq below the level implied by current pledges by 2030. This would avoid some carbon lock-ins and reduce potential disruptive developments associated with the immediate near-term emissions reductions. Such gradual strengthening of ambition would keep options open to limit warming to below 2°C but would place limiting warming to below 1.5°C with low overshoot out of reach. (*medium confidence*) {3.4}

C3.4. In all illustrative pathways, the AFOLU and energy supply sectors reach net zero $CO_2$ emissions earlier than the buildings, industry and transport sectors. Emissions from the latter sectors remain positive throughout the century in several of the illustrative pathways and are thus compensated by $CO_2$ removal in the AFOLU and energy supply sectors (*high confidence*). (Figure SPM.7) {3.4}

C3.5. Different regions may reach net zero $CO_2$ emissions at different points in time. In modelled pathways, regions with higher potential for land-based mitigation tend to reach net zero $CO_2$ emissions earlier than other regions. In most scenarios that limit global warming to below 2°C or 1.5°C, all regions reach net zero $CO_2$ emissions before the 2080s. (*medium confidence*) (Figure SPM.7) {3.4}

C3.6. The growing number of published mitigation pathways aids understanding of the potential contribution of technological solutions to limiting global warming. Less literature is available on low-demand pathways, similar to "1.5-LD", that emphasise mitigation potential from behavioural and technological options on the demand side, and on systems-analytical studies that bring together supply- and demand-side solutions in an internally consistent way (*robust evidence, medium agreement*). {3.3, 4.4}

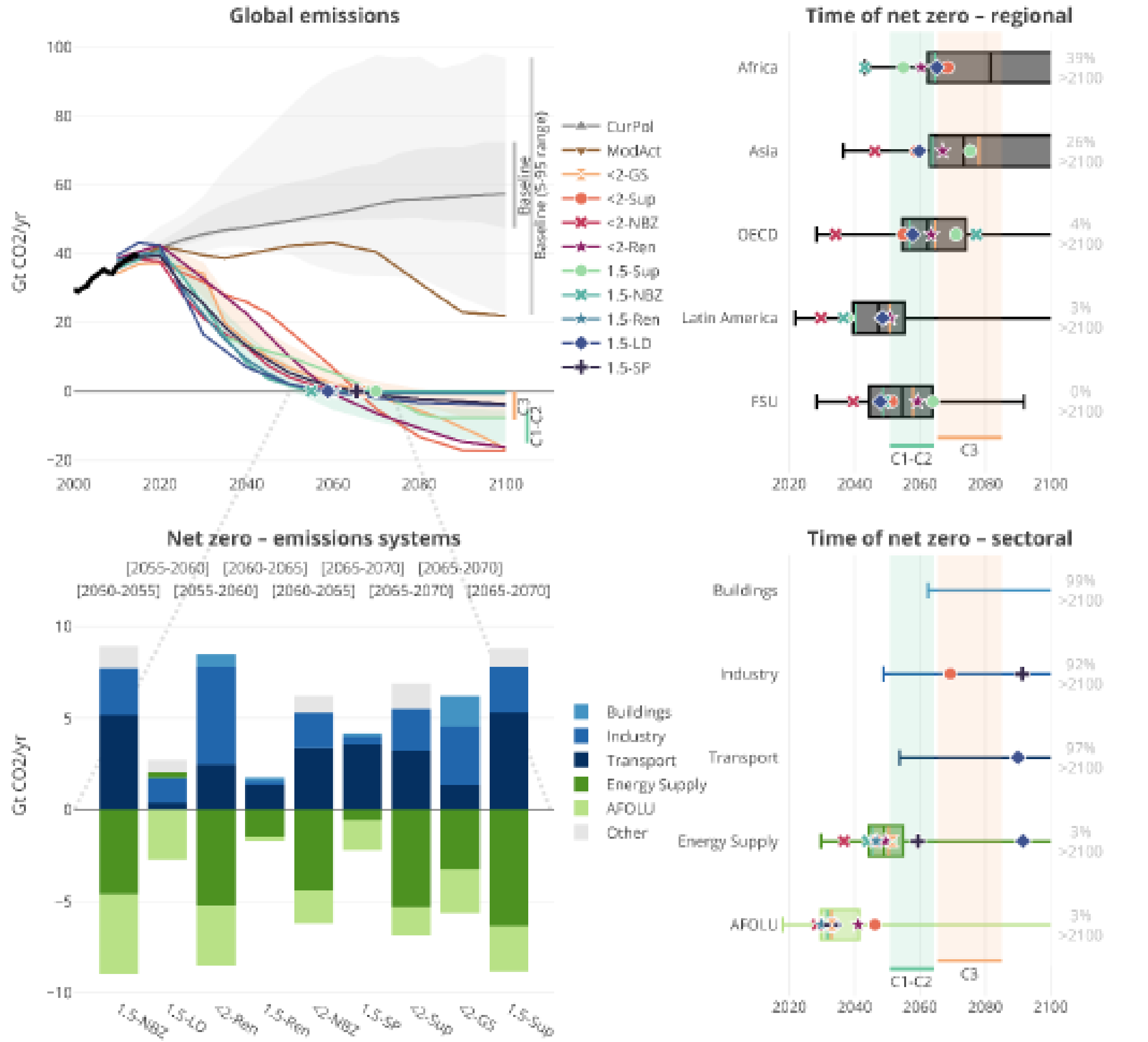



**Figure SPM.7 | Alternative net-zero $CO_2$ emissions strategies.** a. Global $CO_2$ emissions ranges (p10-p90) under baseline, <1.5°C and <2°C pathways (C1-2, C3 categories respectively), with the 11 Illustrative Pathways (IPs) marked by their year of global net-zero CO2 emissions (2050-2070). b. The IPs differ with respect to the net-zero $CO_2$ emissions systems and the respective sectoral composition of $CO_2$ emissions sources and sinks. c. Timing of when individual regions reach net-zero $CO_2$ emissions can differ considerably. d. Sectoral timing also differs, with AFOLU and Energy Supply sectors decarbonising relatively earlier, balancing out residual emissions in Buildings, Industry and Transport sectors (many of which may not reach net-zero by 2100). #scenarios: C1: 71, C2: 82, C3: 285, Baseline: 104. Shaded ranges and boxplot whiskers show 10-90th percentiles. The percentages to the right represent the proportion of assessed pathways which do not attain net-zero $CO_2$ for the region or sector in question before 2100.

**C4. The potential for demand-side mitigation and new ways of providing services exist within, and cut across, the socio-behavioural, infrastructural and technological domains. The GHG emissions reduction potential in end-use sectors is as high as 50-80% in 2050. Providing basic services and meeting decent living standards everywhere requires transformations in infrastructure (*high confidence*). (Figure SPM.8) {5.3, 8.2, 9.4, 10.2, 12.4}**

C4.1. Demand-side options in end-use sectors can reduce 50-80% of global GHG emissions by 2050 compared to emissions under a scenario based on stated policies. Energy end-use technologies contribute most to mitigation in the transport, building and industry sectors. Physical infrastructures, such as compact cities, co-location of jobs and housing, and the reallocation of street space, can contribute a third of GHG emission reductions in the transport sector. In the building sector adopting zero energy/carbon buildings standards, and reducing overheating and overcooling, and hot water, and fitting buildings with renewable energy can all reduce GHG emissions. (*high confidence*) (Figure SPM.8) {5.3, 8.2, 9.4, 10.2, 12.4}

C4.2. Lifestyle options such as heating and cooling set-point adjustments, reduced appliance use, shifts to human-centred mobility and public transit, reduced air travel, and improved recycling, which form part of the demand-side potential, can deliver an additional 2 $GtCO_2$-eq savings in 2030 and 3 $GtCO_2$-eq savings 2050 beyond the savings achieved in conventional technology-centric mitigation scenarios (*medium confidence*). {5.3, Table 5.5}

C4.3. Smaller scale modular technologies in energy end-use and energy supply diffuse more rapidly into markets, improve in cost and performance faster through technological learning, offer efficiency benefits, escape technological lock-in more easily, and create more employment than centralised larger scale technologies (*high confidence*). {5.3, 5.5, 9.8}

C4.4. A shift to diets with a higher share of plant-based protein in regions with excess consumption of calories and animal-source food can lead to substantial reductions in GHG emissions, while also providing health benefits *(high confidence)*. Diets low in meat and dairy are already prevalent in many countries and cultures and their take-up is increasing from current low levels elsewhere. Plant-based diets can reduce GHG emissions by up to 50% compared to the average emission intensive Western diet. {5.3, 12.4}

C4.5. Providing better services with less energy and resource input is possible and consistent with providing wellbeing for all *(medium confidence)*. The impacts of improved service provision on the constituents of wellbeing has many more positive than negative impacts. In low-energy demand scenarios, final energy demand is 40% lower in 2050 than in 2018, while wellbeing is maintained or improved. {5.1, 5.2, 5.3}

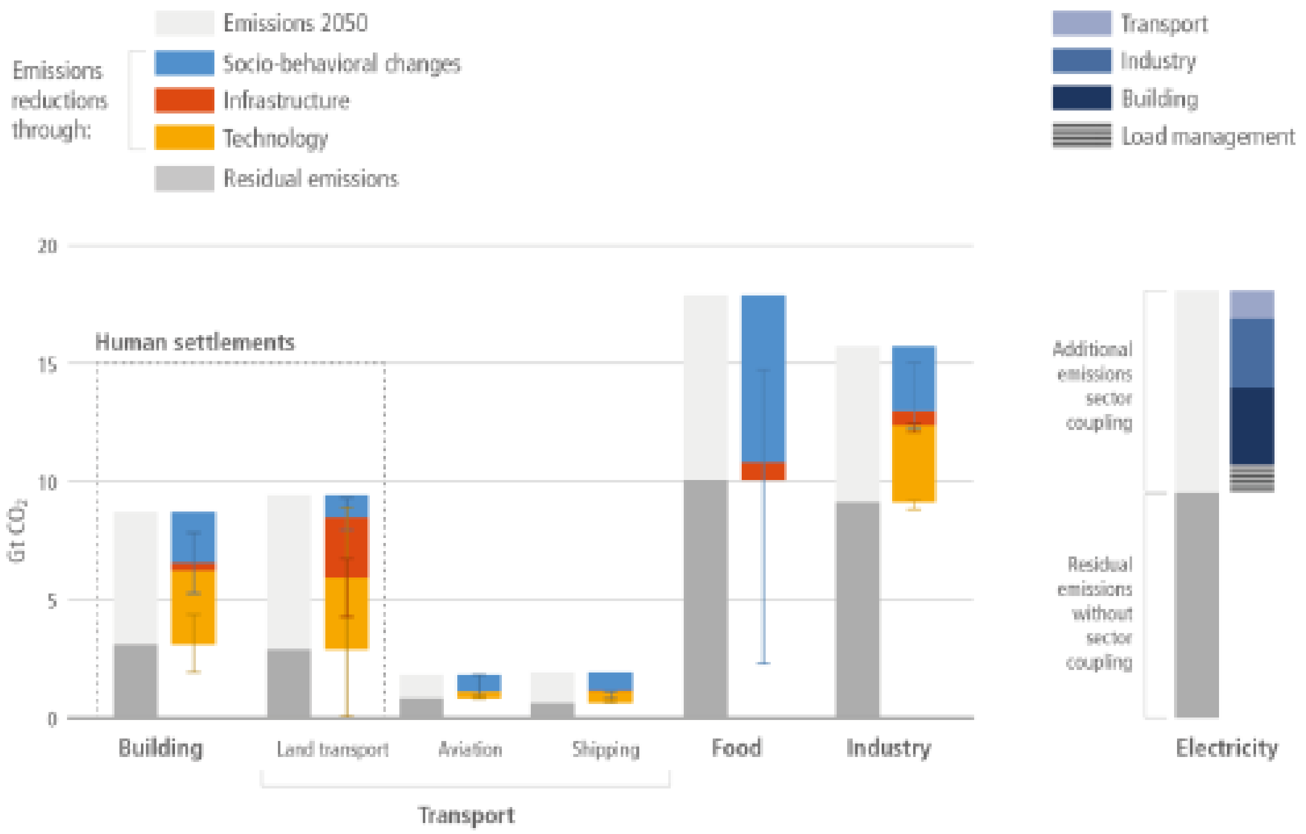



**Figure SPM.8 | Climate change mitigation potentials classified in socio-behavioural, infrastructural, and technological options can reduce GHG emissions by 50-80% in end-use sectors by 2050.** Drawing on the full potential requires changes in social norms, the provision in low-carbon infrastructures, and wide-range adoption of granular efficient end-use technologies. Electrification of transport, building and industry sector increases the demand on the electricity sector and associated indirect emissions, while demand side measures and load management compensate for this increased load. Based on review of studies estimating demand-side potentials associated with demand-side GHG emission reduction strategies. Reported are median values and full ranges (minimal to maximal potential). To be able to give approximation for the full potential across sectors, interaction effects between the three categories are ignored. Potentials are estimated against 2050 values of IEA's stated policy scenario. Data sources and explanations: see Chapter 5, Section 5.3

**C5. Scenarios that limit warming to 2°C and 1.5°C imply energy system transformations over the coming decades. These involve substantial reductions in fossil fuel use, major investments in low-carbon energy forms, switching to low-carbon energy carriers, and energy efficiency and conservation efforts. Institutional and technological 'lock-in' to emitting infrastructure and energy system management approaches is a major risk arising from delaying mitigation action beyond the 2020–2030 timeframe.** (*high confidence*) {6.6, 6.7, 16.4}

C5.1. Global energy sector emissions need to decline at about 2.2–3.3% per year through to 2050 to limit warming to 1.5ºC and about 1.2–1.8% to limit warming to 2ºC (*high confidence*). {6.7}

C5.2. Carbon-neutral energy systems can combine: zero- or negative carbon electricity systems; widespread electrification of end uses; targeted use of alternative fuels such as hydrogen, bioenergy, and ammonia in hard-to-decarbonise sectors; energy conservation and efficiency measures; greater integration across energy systems; and use of CDR to offset emissions from hard-to-decarbonise sectors. The approaches chosen would depend on national circumstances. The transformations needed for carbon-neutral energy systems will not occur without changes involving technologies and infrastructure, institutions, firms, and individuals. (*high confidence*) {6.6, 16.4}

C5.3. Since AR5, there have been rapid improvements in key energy system technologies, notably batteries, wind power, solar power, and digitalisation. Low-carbon electricity is now the cheapest option in many applications. Low-carbon transitions can be more economically attractive than carbon-intensive transitions in many circumstances. Nonetheless, deployment of energy system mitigation options significantly lags what would be needed to limit warming to 2ºC or 1.5ºC. *(high confidence)* {6.4}

C5.4. Low-carbon technologies will need to supply 90% or 100% of global electricity by 2050 to limit warming to 2ºC or 1.5ºC, compared with less than 40% today. At the same time, the proportion of electricity in final energy would need to increase to over 35% by 2050 to limit warming to 2°C, or by 40% by 2050 to limit warming to 1.5°C, compared with about 20% today. *(medium confidence)* {6.4}

C5.5. Investments in fossil infrastructure are at risk of being "stranded" if warming is limited to 2ºC or 1.5ºC. Investments in coal generation without carbon capture are particularly vulnerable. Natural gas without carbon capture is largely eliminated in scenarios with carbon-neutral energy systems. Petroleum refining investments may be stranded with a move to electro-mobility. Limiting warming to 2ºC or 1.5ºC will lead to substantial reductions in the value of fossil resources. The combined economic impacts of stranded fossil fuel resources and capital could amount to trillions of dollars. *(high confidence)* {6.7}

**C6. The majority of GHG emission reductions by 2050 in the transport sector are projected to come from the electrification of light-duty vehicles. These technologies are now commercially available. Further innovation in batteries, hydrogen fuel-cells, biofuels and synthetic fuels, along with vehicle design and efficiency, is occurring. Emission reductions in long-haul trucking, shipping and aviation will depend on substantial additional R&D and demonstration. Digital substitution and changes in logistics, urban form, pricing, and behaviour can help transform all transport modes. (*medium confidence*) {10.2, 10.3, 10.4, 10.5, 10.6}**

C6.1. In scenarios that limit warming to 1.5°C or likely below 2°C GHG emission reductions in the transport sector are in the range 20% to 80% (10th to 90th percentile) i.e., from 1.8 to 7.2 $GtCO_2\ yr^{-1}$. Greater reductions are possible in electrified cars, bikes, tuk-tuks, motorbikes, and buses where technology is already commercial. With expanded low-carbon electricity infrastructure, electro-mobility can allow leapfrogging in developing countries. Long-range heavy vehicles (trucks, ships, planes) will likely require substantial R&D breakthroughs and policy interventions. Technologies for this vehicle segment are not yet commercial. (*medium confidence*) {3.4, 10.3, 10.4}

C6.2. Alternatives to oil-based mobility since AR5 are due mostly to battery technology. Further improvements in material and energy efficiency in battery production and recycling will reduce critical mineral risks and the environmental footprint of electrification. Novel battery chemistries with higher energy density, along with hydrogen, biofuels, and synthetic fuels, are emerging as commercial options for all transport modes. *(medium confidence)* {6.3, 10.3}

C6.3. Demand reduction programs, energy efficiency, and infrastructure improvements continue to assist GHG mitigation in passenger and freight systems. Enabling transit, active transport, local shared mobility, and associated urban planning and land use, with digital communication replacing the need to travel, would help transformative change in all transport modes. (*medium confidence*) {5.3, 10.2}

C6.4. Technologies are not yet commercial for transformative reductions in shipping, aviation, and long-haul trucking GHG emissions. Substantially more R&D into alternative fuels, especially drop-in fuels, alongside policy interventions, could increase the options available. Reviewing governance arrangements for emissions from international transport would assist this process. (*medium confidence*) {10.4, 10.5, 10.6, 16}

**C7. There is a large emissions reduction potential associated with existing urban and rural settlements and scope to avoid emissions from settlements yet to be built, including the design, size and use of buildings. The scale and pace of urbanisation around the world risks carbon lock-in but also provides an opportunity to design and build low-carbon cities conducive to low-carbon lifestyles and technologies. (*high confidence*) {8.2, 9.3, 9.4, 9.5}**

C7.1. Building new cities could require 90 billion tonnes of raw materials per year by 2050 in a baseline scenario, up from 40 billion tonnes in 2010. Embodied emissions from construction materials represented 18% of total GHG emissions from the building sector in 2018. Embodied emissions can be reduced through extending the lifetime of buildings and their components and reducing waste. Using bio-based/wood-based materials and nature-based solutions are opportunities for temporary carbon storage in buildings (*medium confidence*). In scenarios likely to limit global warming to 2°C or below while meeting sustainable development goals, indirect emissions would be reduced by 91%, direct emissions reduced by 69%, and embodied emissions by 31%. This reflects the expected role of embodied emissions if the zero energy/carbon concept is applied. (*medium confidence*) {8.3, 9.3, 9.4, 9.5}

C7.2. Decarbonisation of the building sector requires: sufficiency measures, such as building design, size and use, to reduce the demand for energy and materials; efficiency measures to reduce energy consumption by providing access to the best available technologies; and on-site renewables to address remaining energy demand. Buildings are moving from a passive to an active role in the energy system, generating decarbonised power that can contribute to the flexibility of the energy system. Direct F-gas emissions from heating and cooling systems can, with policy support, be addressed through technological solutions. (*high confidence*) {9.4, 9.5, 9.10}

C7.3. Reducing urban per capita emissions through resource-efficient and compact urban growth would help offset increases in urban population (*high confidence*). Urban and land-use planning that prioritises resource-efficient infrastructure, promotes strategic densification, and creates compact, walkable neighbourhoods connected by transit, with associated price instruments can reduce urban energy use and GHG emissions by 36-54% in 2050, compared to a "business-as-usual" baseline (*medium confidence*). {8.2, 8.3, 8.4, 8.5, 8.6, 8.7}

C7.4. Nature-based solutions to mitigate climate change, such as urban forestry and green infrastructure can sequester carbon while achieving multiple co-benefits (*high confidence*). Green roofs and green facades, networks of parks and open spaces, protection of urban nature, urban agriculture, and water-sensitive design offer a wide range of adaptation co-benefits including flood mitigation, reduced pressure on urban sewer systems, reduced urban heat island effects, and public health (*high confidence*). {8.4}

**C8. Reaching zero GHG emissions from industry would require coordinated action throughout value chains and take-up of the full range of mitigation options. These include: end-use demand management; energy and materials efficiency; circular material flows; emission free electricity, fuel and feedstock; and carbon capture storage and utilisation. (*high confidence*) {11.2, 11.3, 11.4}**

C8.1. The basic materials industries account for 60-70% of industrial GHG and $CO_2$-emissions. Material intensity, defined as the stock of manufactured capital per unit of GDP, is increasing as demand for higher material living standards increases. Per capita material stocks in several developed countries have saturated. *(high confidence)* {11.2}

C8.2. Emissions from the production of primary materials could reach zero or become negative with combinations of direct and indirect electrification, biofuels, CCU and CCS. This could involve higher production costs but small increases in costs to final consumers. Many technology options are in pilot stages and require intensive commercialisation efforts. A transition of industry towards zero emissions requires substantial scaling up of electricity, gas, hydrogen, recycling, and other infrastructure. It also entails the phase-out of blast furnaces in steelmaking and conversion of chemical industries to low GHG feedstocks and fuels. *(high confidence)* {11.3}

C8.3. Some scenarios achieve close to net zero emissions from the most energy intensive industries (steel, chemicals, and cement) by 2050. Reduced materials demand, more recycling, and electrification can lower mitigation costs and the need for CCS, but these options are not well represented in published scenarios. Demand for plastics has been growing more than for any other material since 1970. Mitigation challenges include the more than 99% reliance on fossil feedstocks, very low recycling rates, and high petrochemical process emissions. At the same time, plastics can also help reduce emissions, for example, as an insulation material in power cables or for preserving food. There are no shared visions for fossil-free plastics. *(high confidence)* {11.4, Box 11.2}

C8.4. Demand management, materials efficiency and more circular material flows can substantially reduce the demand for virgin basic materials (e.g., steel, cement, aluminium, and plastics) and associated emissions, but are less explored and practically applied than other mitigation options *(high confidence)*. {11.3, 11.4}

C8.5. Reaching zero emissions may reshape where energy intensive industry is located, how value chains are organised, and what gets transported. Regions with bountiful solar and wind resources, or methane co-located with CCS geology, may become exporters of hydrogen, hydrogen carriers, and energy intensive basic materials. *(medium confidence)* {Box 11.1}

C8.6. Light industry and manufacturing can be largely decarbonised through switching to low GHG fuels (e.g., biofuels and hydrogen) and electricity (e.g., for electrothermal heating and heat pumps) (*high confidence*). {11.4, Table 11.4}

**C9. The Agriculture, Forestry and Other Land Use (AFOLU) sector can provide large-scale GHG emission reductions and land-based CDR at relatively low cost, but cannot compensate for slow mitigation in other sectors. The provision of renewable resources can facilitate mitigation in other sectors through substitution for fossil fuels and other GHG-intensive products (*high confidence*). Implementation is challenging and context specific. Achieving sustained results, under climate change pressures, while maximising co-benefits related to food and fibre security, social and biological diversity, ecosystem services and sustainable development, requires appropriate country specific policies and significant investment. {7.4, 7.6, 7.7, 12.5, 12.6}**

C9.1. The mitigation potential from AFOLU is approximately 9±3 $GtCO_2$-eq $yr^{-1}$ between 2020 and 2050 at a cost of up to 100 USD/$tCO_2$-eq (*medium confidence*). Reduced land conversion/increased land protection, enhanced management, and restoration of forests, wetlands, savannas and grasslands can reduce emissions and/or sequester carbon by 6.1±2.9 $GtCO_2$-eq $yr^{-1}$. The agriculture mitigation potential from soil carbon management in croplands and grasslands, agroforestry, biochar, rice cultivation, and livestock and nutrient management is 3.9±0.2 $GtCO_2$-eq $yr^{-1}$. Demand-side measures including shifting to plant-based diets and reducing food waste, can provide 1.9 $GtCO_2$-eq $yr^{-1}$ potential through diverted agricultural production (excluding land-use change). In scenarios published since SR1.5, the mitigation estimate from CCS (BECCS) has fallen and is now 0.8 median (0–6.3) $GtCO_2$ $yr^{-1}$ in 2050. Bioenergy (especially from side streams) can have substitution effects in the energy and transport sectors of 2.8–7.0 $GtCO_2$ $yr^{-1}$ (*medium confidence*). {7.4}

C9.2. In scenarios that limit warming to 1.5ºC and 2ºC, global mitigation efforts in AFOLU are increased 5-fold within the next decade, and more than 10-fold by 2050. Given current institutional and policy constraints, an estimated investment shift of more than $400 billion $yr^{-1}$ and potential trade-offs with other ecosystem services, this level of abatement is difficult to achieve despite the technical potential (*high confidence*). AFOLU is challenging because of its decentralised nature and the distinct value systems associated with land tenure and management, with millions of landowners under diverse cultural, economic and political circumstances (*high confidence*). {7.5, 7.6}

C9.3. Agricultural land requirements may be reduced through sustainable intensification, reduced food loss and wastes, and dietary change (*medium confidence*). Active management approaches that maintain carbon stocks on the land while sufficiently producing food, feed, fuel and fibre can deliver mitigation while making land available for other uses, including agricultural and forestry renewables resources. {7.4, 7.7}

C9.4. Improved quantification of land-based mitigation activities and their additionality in recent years has provided better insights about where and which land-based activities can be implemented, their positive and negative interactions mitigation activities with other ecosystem services, and their potential costs. These data products and new technologies will allow a wider array of actors, including private businesses to take more meaningful actions and provide funding (*medium confidence*). The move to 'net zero' cities, buildings, industries and organisations is expected to increase the financing for carbon offsets and production of renewable materials in the AFOLU sector (*high confidence*). {7.4}

**C10. Carbon dioxide removal (CDR) is necessary to achieve net zero GHG emissions and is an element in most scenarios that limit warming to 1.5°C–2°C by 2100 (*high confidence*). The amount of CDR deployment depends largely on supply- and demand-side emission reductions. CDR options vary in their mitigation potentials, technology readiness, co-benefits and trade-offs with other societal goals, and governance requirements. {12.3, 12.7}**

C10.1. In the context of net zero emissions, CDR can counterbalance residual GHG emissions that are difficult to abate (e.g., from, aviation, shipping, agriculture and some industrial activities). CDR could also provide net negative emissions at the global level enabling the return from temporary overshoot of temperature thresholds. {12.3}

C10.2. Biological CDR methods are generally less expensive but more vulnerable to reversal than technological approaches. Some biological methods such as afforestation/reforestation or ecosystems restoration (e.g., wetlands) have long been practiced. Practical experience with technological approaches such as, Direct Air Capture and Carbon Storage (DACCS), Enhanced Mineral Weathering or Ocean Alkalinity Enhancement, or hybrid approaches such as BECCS, is still limited, with greater needs for R&D. {7.4, 12.3}

C10.3. The potential for DACCS is limited primarily by access to low carbon energy and cost (60-500 USD $tCO_2^{-1}$). Enhanced Weathering has the potential to remove 4-100 $GtCO_2$ $yr^{-1}$, at costs ranging from 24–578 USD $tCO_2^{-1}$. Ocean-based approaches have the potential to remove 1–100 $GtCO_2$ $yr^{-1}$ at costs of 40-500 USD $tCO_2^{-1}$ (*medium confidence*). {12.3}

C10.4. Governance challenges for CDR options at the national level are not fundamentally different from those for emissions reduction measures. CDR options may have positive or adverse side effects on ecosystem services and the SDGs. Incentivising CDR is currently hampered by a range of socio-economic, technical and governance barriers (*medium confidence*). {12.3, 12.7}

**C11. Achieving ambitious mitigation depends on costs as well as on overcoming a wider range of societal feasibility challenges. Mitigation likely to limit global warming to below 2°C may affect global GDP growth by less than 0.1 percentage points per year, without accounting for the co-benefits of mitigation, and the benefits of avoided climate change impacts. Costs in each sector depend on the realised mitigation potential; in aggregate, low-cost abatement options could reduce emissions by more than 50% below 2018 levels by 2030. Early action and a diversified mitigation portfolio can smooth out feasibility challenges and reduce disruptions, while delayed**

**action increases challenges to both economic and societal feasibility after 2030.** (*high confidence*) **(Figure SPM.9, Figure SPM.10) {3.6, 3.8, 12.2, 12.3}**

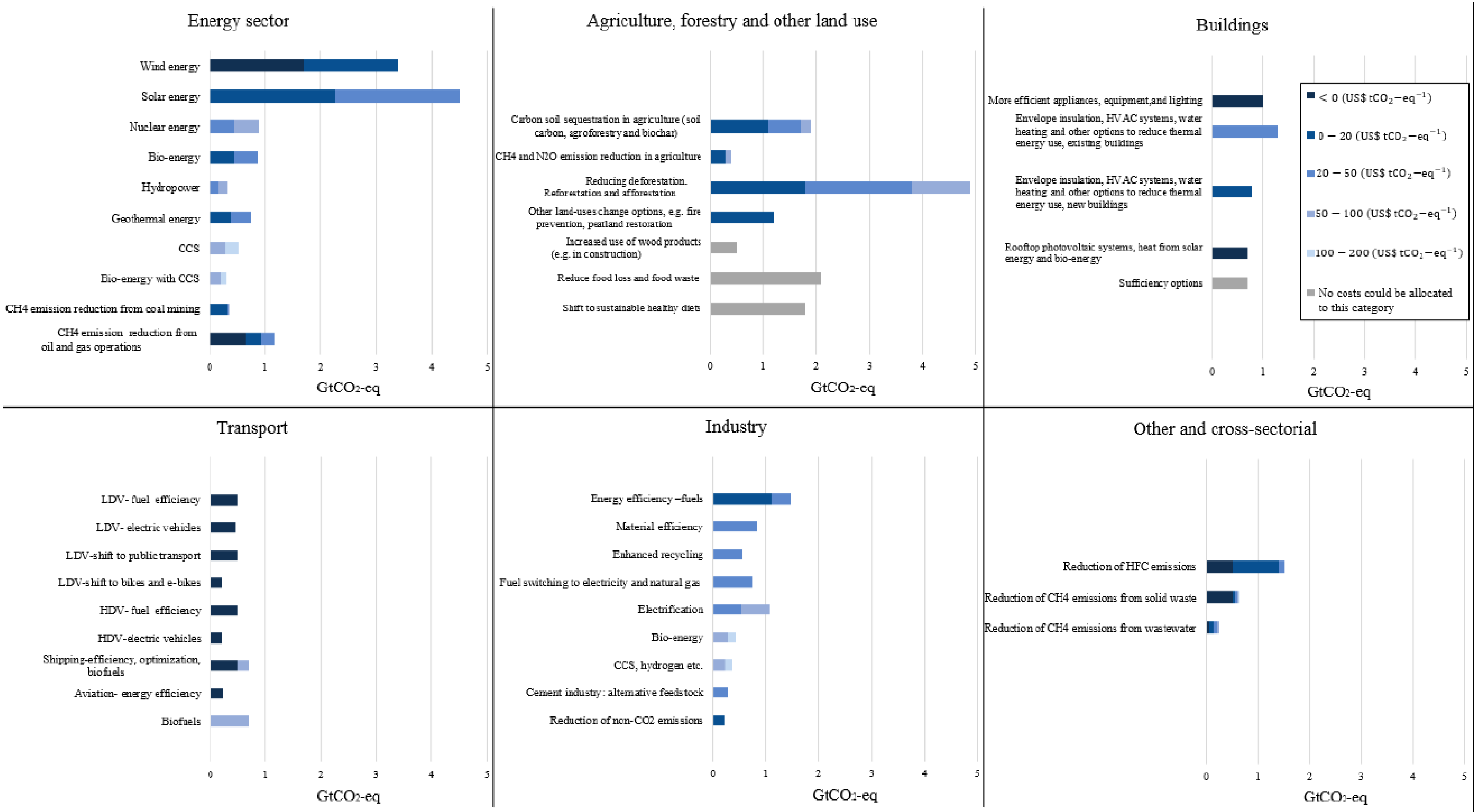
C11.1. The total mitigation potential achievable by the year 2030, based on sectoral assessments, is sufficient to reduce global GHG emissions to half of their 2018 level. Options with mitigation costs lower than USD 20 $tCO_2^{-1}$ make up more than half of this potential, and some have benefits that exceed costs. The potential for such options has increased since AR5. Low-cost options are available for all sectors. (*high agreement, medium evidence*) (Figure SPM.9) {12.2}

C11.2. Pathways likely to limit global warming to below 2°C entail losses in global GDP between 1.6% and 3.5% of baseline levels in 2050, and between 2.1% and 4.3% in pathways that are likely to limit global warming to below 1.5ºC with or without temperature overshoot. The aggregate economic costs of least-cost mitigation pathways likely to limit warming to 2°C are likely to be smaller over the long-term than the aggregate economic benefits in terms of avoided impacts, even without accounting for the co-benefits of mitigation and non-market damages from climate change. These monetary estimates undervalue impacts on the well-being of poorer households and countries. (*high confidence*) {3.6}

C11.3. Modelled mitigation pathways which limit global warming to 1.5ºC or likely 2ºC without temperature overshoot are characterised by high upfront investments and rapid near-term transformations, but have lower long-term costs than those with temperature overshoot. The modelled cost-optimal balance of mitigation effort over time strongly depends on the social discount rate used. Lower discount rates favour earlier mitigation, reducing both temperature overshoot and reliance on net negative carbon emissions. {3.6}

C11.4. The feasibility challenges associated with response options depend on sector-specific enabling conditions and barriers. Solar energy, wind energy, demand side management, changes in building construction methods, fuel efficiency, electromobility and transitions in urban systems generally experience more enabling conditions and face fewer barriers than nuclear energy and technological CDR options (*high confidence*). (Figure SPM.10) {Table 12.2, 12.3}

C11.5. The feasibility of transitions at the system level is context-specific and depends on development levels and institutional capacity. Feasibility challenges are linked to emission reduction rates rather than emission levels. Early action to mitigate climate change can smooth out feasibility challenges and reduce disruptions, and avoid increasing challenges to feasibility beyond 2030. A diversified portfolio of mitigation options can improve the feasibility of transitions at the system level (*high confidence*). (Figure SPM.10) {3.8, Cross-Chapter Box 4 in Chapter 4}




Note: The various options show competition and overlap and cannot be summed together. The uncertainty range for each of the options is 25 – 50%, except for the options indicated in grey, for which the uncertainty is larger.

**Figure SPM.9 | Overview of emission reduction options per sector, providing an indicative value of the emission reduction potential in 2030 ($GtCO_2$-eq), broken down into cost categories. {Table 12.2}**

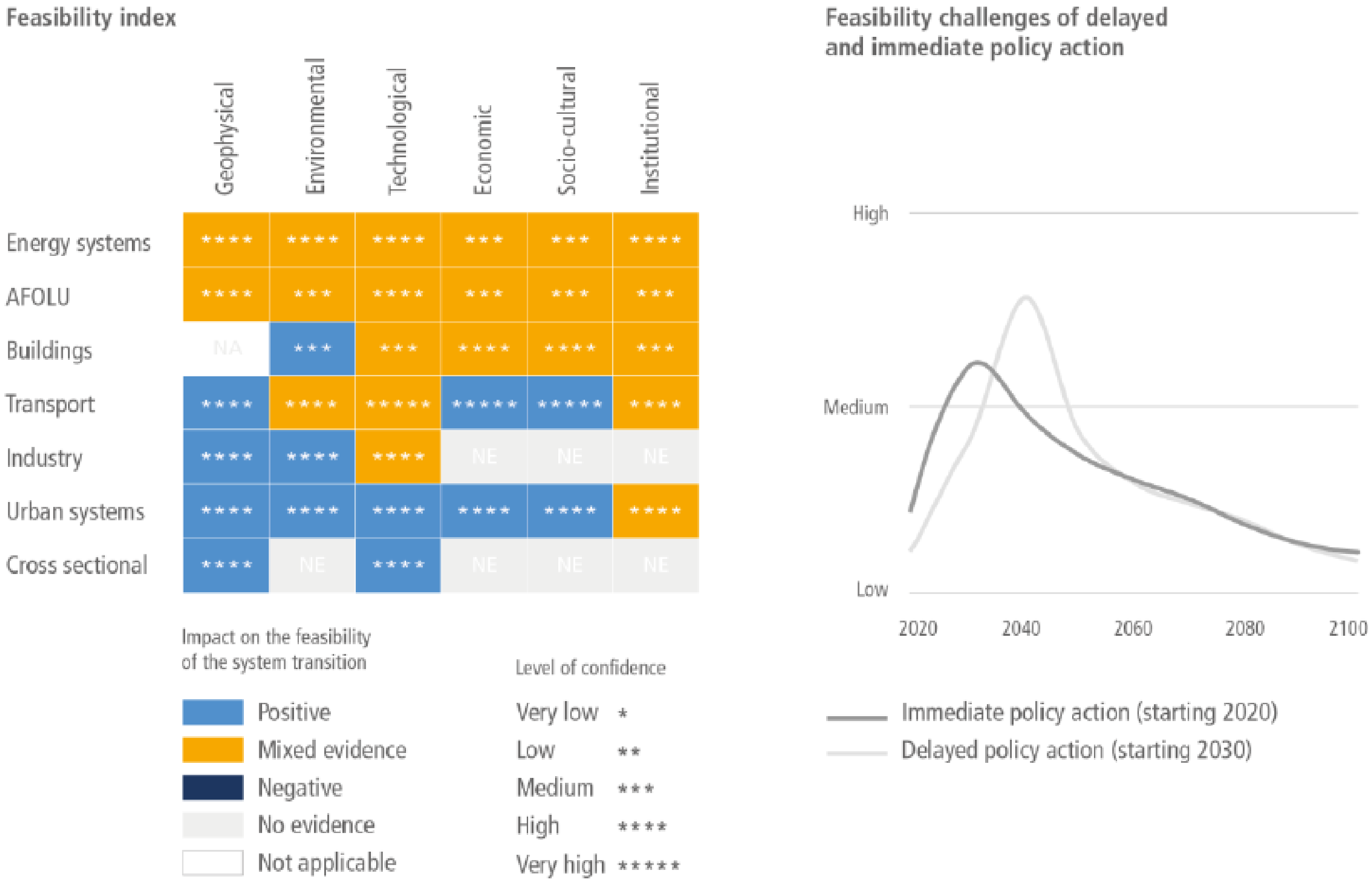



**Figure SPM.10 | Feasibility challenges of sectoral transitions and system wide changes**: The left panel shows that the feasibility of response options depends on geophysical, environmental, technological, economic, social and institutional enabling conditions and barriers which vary across sectors. The right panel shows the time evolution of a composite indicator of feasibility challenges, aggregating multi-dimensional metrics computed from AR6 scenarios compatible with 1.5°C-2°C end-of-century temperatures. The 'black' and 'grey' lines represent averages of scenarios with global climate policy starting in 2020 or in 2030 respectively. {3.8, 6.4, 7.4, 8.6, 9.10, 10.8, 11.4, 12.3}

# D. Mitigation, adaptation, and sustainable development

**D1. Ambitious mitigation and development goals cannot be met through incremental change. Shifting development pathways towards sustainability opens up a wider range of options than focusing on mitigation alone (*medium evidence, high agreement*). The way countries develop determines their capacity to accelerate mitigation and at the same time achieve other sustainable development objectives (*medium confidence*). (Figure SPM.1) {Cross-Chapter Box 4 in Chapter 4, 4.3}**

D 1.1. In the absence of climate mitigation, development objectives are likely to be compromised. With the careful design of mitigation policies, reducing GHG emissions and the achievement of other development objectives can go hand in hand. Mitigation may nevertheless entail trade-offs with the achievement of other national development objectives, which need to be addressed in policy implementation. Conflicts between mitigation and other development objectives can act as an impediment to climate action and can be amplified by vested interests. {Cross-Chapter Box 4 in Chapter 4, 4.3, 13.2}

D 1.2. Continuing along existing development pathways is unlikely to achieve rapid and deep emission reductions. Mitigation conceived as incremental change would achieve less than approaches which broaden the set of levers and enablers of transformational change. Adopting policy packages aimed at shifting development pathways towards sustainability opens up opportunities to achieve multiple development objectives, including climate mitigation, simultaneously (*medium confidence*). Pathways in which policies are designed to reach multiple sustainable development objectives can in some cases entail additional costs that are lower than the benefits. {3.6, 4.3, 13.8, 13.9, WGII SPM}

D 1.3. Choices made by decision-makers, citizens, the private sector and social stakeholders can influence societies' development pathways. Such shifts can be enabled by drawing upon a range of policies and actions going beyond mitigation. Shifting development pathways entails fundamental changes in energy, urban, building, industrial, transport, and land-based systems, as well as changes in behaviour and social practices. Overcoming inertia and locked-in practices may face opposition. The necessary transformational changes are likely to be more acceptable if rooted in the development aspirations of the economy and society within which they take place (*medium confidence*). {13.8}

**D2. Transition pathways entail distributional consequences such as changes in employment and economic structure (*high confidence*). Pathways that prioritise equity and allow broad stakeholder participation can enable broader consensus for the transformational changes implied by deeper mitigation efforts (*high evidence, medium agreement*). {4.3, 4.5, 13.2, 17.3, 17.4}**

D 2.1. Transition pathways depend on countries' specific resource endowments, equity considerations, existing development patterns, the speed of action, and context-specific issues that may enable or act as a barrier. They may imply large employment and economic structural changes, and stranded assets, and may have distributional consequences (*high confidence*). Ambitious mitigation pathways will affect industries, individuals, and societies that depend on fossil revenues and fossil-related jobs with particular challenges in developing countries. {4.3, 4.5, 17.3}

D 2.2. The just transition concept has become recognised internationally, tying together social movements, trade unions, and other key stakeholders to ensure equity is better accounted for in low-carbon transitions. Just transitions at international, national, regional and local scales can ensure that workers, frontline communities and the vulnerable are not left behind in low-carbon pathways (*medium confidence*). Estimates show larger employment opportunities associated with cleaner forms of energy than fossil fuels. In the land sector, mitigation is most successful where synergies with other functions of land are addressed in an equitable manner. {4.5, 6.3, 7.4,17.3}

D 2.3. Lack of integration of environmental justice in climate mitigation activities, including inclusive participation and distribution of institutional capacities, risks growing inequality at all levels. Pathways that take into account equity can enable broader consensus for the transformational changes implied by deeper mitigation efforts. (*high confidence*). Equity and justice are important enabling conditions for effective climate mitigation. Institutions and governance that address equity and supporting narratives that promote just transitions can build broader support for climate policymaking (*medium confidence)*. Multiple countries now have 'Just Transition' institutions or framework agreements. {4.5, Figure 4.10, 13.2, 13.3, 13.6, 13.8, 13.9, 17.4}.

**D3. Mitigation options are linked to the Sustainable Development Goals (SDGs) in multiple ways, involving both synergies and trade-offs. The linkages are context specific, depending on the sector, the timing of mitigation actions, policy design and effectiveness. Many adverse linkages can be compensated or avoided with complementary policies, integrated cross sectoral responses, finance, and partnerships (*medium confidence*). {5.3, 7.4, 9.8, 10.1, 11.5, 12.4, 12.6, 13.8, 17.1, 17.3}**

D 3.1. Ambitious mitigation is a pre-requisite for achieving the SDGs, with particular challenges in relation to vulnerable populations and ecosystems whose capacity to adapt to climate impacts is limited *(medium confidence)*. Synergies and trade-offs between mitigation and sustainable development concern access to food, water and energy and rivalry for resources. Synergies and trade-offs can result directly from mitigation action in a given sector or indirectly from mitigation actions in other sectors. {3.7, 12.6, 13.8, 17.1, 17.3}

D 3.2. In the building sector, energy efficiency and integration of renewable energy contribute to achieving almost all SDGs (*high confidence*). In the transport sector, the adoption of electro-mobility, shifts to public transport and active travel can benefit air quality, health, improve access to education and financial services and promote gender equality *(medium confidence)*. In the AFOLU sector, agroforestry, avoided deforestation and reforestation can provide land carbon storage and biomass for multiple uses, while enhancing biodiversity and essential ecosystem services. Practices such as soil and livestock management can promote conservation of biodiversity and ecosystem services as well as human well-being. Depending on the starting point, dietary choices involving food with low GHG emissions can be associated with health co-benefits (*high confidence*). (Figure SPM.11) {5.3, 7.4, 9.8, 10.1, 12.4}

D 3.3. Potential trade-offs between mitigation measures and sustainable development exist in areas such as employment, food deprivation, water stress, land use, biodiversity and local building materials, as well as access to and the affordability of energy, food and water. If deployed poorly, AFOLU options that displace other land uses, such as widespread planting of monoculture plantations providing biomass for biochar, bioenergy and other biobased products, can cause negative outcomes for food security and other aspects of sustainable development. At very high deployment, bioenergy with CCS (BECCS) could lead to adverse side effects (*medium confidence)*. Trade-offs can be addressed by complementary policies and investments or with the design of integrated cross sectoral policies (*medium confidence*). (Figure SPM.11) {3.7, 7.4, 17.1, 3.7}

D 3.4. Increasing welfare and meeting the SDGs implies an increase in demand for materials, products and services. Meeting demands for renewable materials and products and access to services has positive impacts on human wellbeing and participation in mitigative action. Literature published since AR5 shows that decent living standards, encompassing many SDG dimensions, are achievable with lower energy use. Development pathways involving lower energy demand and greater use of land-based resources have overall lower trade-offs with sustainable development than those involving high levels of energy demand and large-scale deployment of CDR. (*medium confidence)* {5.2, 11.5}

| Sector/System | Mitigation option | SDG 1 | SDG 2 | SDG 3 | SDG 4 | SDG 5 | SDG 6 | SDG 7 | SDG 8 | SDG 9 | SDG 10 | SDG 11 | SDG 12 | SDG 13 | SDG 14 | SDG 15 | SDG 16 | SDG 17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Energy systems** | Solar Energy | + | +/- | + | n.a | + | + | + | + | + | + | +/- | +/- | + | n.a | n.a | n.a | + |
| | Wind energy | + | +/- | + | n.a | + | + | + | + | + | + | +/- | +/- | + | - | n.a | na | + |
| | Hydroelectric power | - | +/- | +/- | n.a | n.a | + | + | +/- | n.a | n.a | n.a | n.a | + | + | + | n.a | n.a |
| | Nuclear | +/- | n.a | +/- | n.a | n.a | - | +/- | +/- | - | - | n.a | + | n.a | n.a | +/- | n.a | n.a |
| | Carbon Dioxide Capture, Utilization, & Storage | - | n.a | + | n.a | n.a | - | +/- | + | + | n.a | n.a | +/- | + | n.a | n.a | n.a | +/- |
| | Bioenergy | +/- | - | +/- | n.a | n.a | - | + | + | + | + | + | + | n.a | n.a | n.a | n.a | + |
| | Fossil fuel phaseout | + | n.a | + | n.a | n.a | n.a | + | +/- | + | + | + | +/- | + | + | +/- | n.a | + |
| | Geothermal | + | n.a | +/- | n.a | n.a | +/- | + | n.a | n.a | n.a | + | +/- | + | n.a | - | n.a | n.a |
| | Energy storage for low-carbon grids | +/- | n.a | n.a | n.a | n.a | n.a | + | n.a | n.a | n.a | + | - | n.a | n.a | - | n.a | + |
| | Demand side mitigation | + | +/- | + | n.a | n.a | + | + | n.a | + | n.a | + | + | n.a | n.a | n.a | n.a | +. |
| | System integration | +/- | n.a | n.a | n.a | n.a | n.a | + | n.a | n.a | n.a | + | +/- | n.a | n.a | n.a | n.a | n.a |
| **Agriculture, Forestry & Land use** | Healthy balanced diets, rich in plant-based food (less animal-based) | +/- | + | + | n.a | n.a | + | + | n.a | +/- | n.a | n.a | + | + | + | + | n.a | n.a |
| | Reduce non-CO2 emissions from agriculture | +/- | + | + | n.a | n.a | + | n.a | +/- | +/- | n.a | n.a | + | + | + | + | n.a | n.a |
| | Restore forests and other ecosystems | + | - | + | n.a | n.a | + | n.a | - | n.a | n.a | + | n.a | + | + | + | n.a | n.a |
| | Enhance carbon in agricultural systems | + | + | +/- | n.a | n.a | + | n.a | + | n.a | n.a | n.a | +/- | + | + | + | n.a | n.a |
| | Protect and avoid conversion of forests and other ecosystems | +/- | - | + | n.a | n.a | + | n.a | + | n.a | n.a | +/- | n.a | + | + | + | - | n.a |
| | Sustainably manage forests and other ecosystems | + | +/- | + | n.a | n.a | + | +/- | + | + | n.a | +/- | n.a | + | + | + | n.a | n.a |
| | Bioenergy and BECCS | +/- | - | +/- | n.a | n.a | +/- | + | +/- | + | n.a | n.a | +/- | +/- | +/- | +/- | n.a | n.a |
| **Buildings** | Envelope improvement | +/- | + | +/- | + | n.a | + | + | +/- | +/- | +/- | + | + | + | n.a | n.a | + | + |
| | Heating, ventilation and air conditioning (HVAC) | +/- | + | + | n.a | n.a | + | + | +/- | - | +/- | + | + | + | n.a | n.a | n.a | n.a |
| | Efficient Appliances | +/- | + | + | + | + | + | + | +/- | - | +/- | n.a | +/- | + | n.a | + | n.a | n.a |
| | Change in construction methods and materials | +/- | n.a | +/- | n.a | n.a | n.a | + | +/- | +/- | +/- | + | + | + | n.a | + | +/- | n.a |
| | Active and passive management and operation | + | + | + | n.a | n.a | + | + | +/- | +/- | + | + | + | + | n.a | n.a | n.a | n.a |
| | Digitalization | + | + | + | + | n.a | + | + | +/- | + | + | + | + | + | n.a | n.a | n.a | n.a |
| | Flexible comfort requirements | + | + | + | n.a | n.a | + | + | +/- | +/- | + | + | + | + | n.a | n.a | + | n.a |
| | Circular and shared economy | n.a | n.a | + | n.a | n.a | + | + | + | + | n.a | + | + | + | n.a | + | n.a | n.a |
| | Renewable energy production | +/- | +/- | + | + | + | +/- | + | +/- | +/- | +/- | + | + | + | n.a | + | + | + |
| **Transport** | Fuel efficiency | n.a | n.a | + | n.a | n.a | + | + | + | + | n.a | + | + | + | n.a | n.a | n.a | n.a |
| | Electromobility | n.a | n.a | + | n.a | + | + | + | + | + | n.a | n.a | n.a | + | n.a | n.a | n.a | n.a |
| | Heavy vehicle transition fuels | n.a | n.a | + | n.a | n.a | n.a | + | + | + | n.a | n.a | n.a | + | n.a | n.a | n.a | n.a |
| | Demand reductions | n.a | n.a | + | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | + | n.a | n.a | n.a | n.a |
| **Industry** | Energy efficiency | n.a | n.a | n.a | n.a | n.a | n.a | + | + | + | n.a | n.a | n.a | + | n.a | n.a | n.a | n.a |
| | Materials efficiency and Demand management | n.a | n.a | n.a | n.a | n.a | + | n.a | +/- | + | n.a | n.a | + | + | n.a | n.a | n.a | n.a |
| | Circular economy | n.a | n.a | + | n.a | n.a | + | + | + | n.a | n.a | + | + | n.a | n.a | + | n.a | n.a |
| | Electrification fuel switching | + | + | + | n.a | + | n.a | + | n.a | n.a | n.a | n.a | n.a | + | n.a | n.a | n.a | n.a |
| | CCU | n.a | n.a | n.a | n.a | n.a | n.a | + | + | + | n.a | n.a | n.a | + | n.a | n.a | n.a | n.a |
| | CCS | n.a | n.a | + | n.a | n.a | n.a | + | + | + | n.a | n.a | n.a | + | n.a | n.a | n.a | n.a |
| **Cross sectional** | Direct air capture | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a |
| | Enhanced weathering | + | + | + | n.a | n.a | + | n.a | + | n.a | n.a | n.a | + | + | + | + | n.a | n.a |
| | Reduce overconsumption | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a | n.a |

**Figure SPM.11 | Impact of mitigation options on SDGs.** Trade-offs and synergies between sectoral mitigation options and the SDGs. Dark blue implies that synergies are expected, light blue that both synergies and trade-offs could be expected, and brown/red that trade-offs can be expected. Grey is used to indicate that the measure is not applicable for the particular SDG based on the literature.

**D4. Some response options have implications for both adaptation and mitigation, involving both synergies and trade-offs. Integrated approaches to adaptation and mitigation planning and implementation could lead to more efficient and cost-effective policies aligned with sustainable development, providing trade-offs are identified and addressed. {13.8, 17.1, 17.3}**

D 4.1. Both climate change mitigation and adaptation are scale dependent and context specific. Especially in developing countries, there is a strong link between sustainable development, vulnerability and climate risk because limited economic, social and institutional resources can result in low adaptive capacities (*high confidence*). Resource constraints also lead to low capacities in relation to climate change mitigation. {17.3}

D 4.2. Many mitigation actions in urban settlements have adaptation benefits. Green roofs and green facades, networks of parks and open spaces, protection of urban nature (e.g., forests and wetlands), urban agriculture, and water-sensitive design can support flood mitigation, reduced pressure on urban sewer system and reduce urban heat island effects. {8.2}

D 4.3. Many land-related actions that contribute to climate change mitigation can also contribute to adaptation, combatting desertification and land degradation, enhancing food security through increases in yields, and improving resilience by maintaining the productivity of the land. Restoration of mangroves and coastal wetlands increases carbon sinks, reduces coastal erosion and protects from storm surges, and can also mitigate the impacts of sea level rise and extreme weather along the coastline (*high confidence*). Careful integration of mitigation options with existing land uses helps to minimise trade-offs and maximise synergies (*medium confidence*). {4.4, 12.5, 13.8}

D 4.4. Some mitigation options in the agriculture, food and land use sectors have mixed impacts on food and water access, and poverty alleviation, despite having positive mitigation and adaptation impacts. These include agroforestry and large-scale bioenergy plantations. Fast growing monocultures and hydropower plants can compromise food and water access and poverty alleviation. {17.3}

D 4.5. Financial, technical and human resources for implementing joint mitigation and adaptation are limited. International climate finance has been dominated by mitigation projects. Financial constraints in relation to joint mitigation and adaptation relating to the agricultural and forestry sectors apply to green funds, government organisations and international climate finance, including multilateral development banks. {17.3}

## E. Strengthening the response

**E1. Accelerated system transitions consistent with sustainable development can be supported by enhancing enabling conditions, including governance and institutions, international cooperation, policy instruments, finance and investment, innovation, capacity building, and behaviour and lifestyle change. Successful system transitions require different combinations of enabling conditions that depend on local contexts. No single enabling condition, nor any single policy instrument, is sufficient. (*very high confidence*) {3.8, 4.4, 5.6, 13.9, 13.2, 15.6, 16.5, 17.4}**

E 1.1. Stringent mitigation pathways are associated with accelerated system transitions. Different emission pathways face different feasibility challenges and patterns of lock-in. Context-dependent combinations of enabling conditions can accelerate and strengthen system transitions, initiate self-reinforcing dynamics, and overcome barriers, realising both mitigation and broader sustainable development goals (*high confidence*). {3.8, 4.4, 13.8, 13.9, 17.4}

E 1.2. Strong institutions and governance arrangements enable ambitious climate action and can help bridge implementation gaps. Key challenges include strategy setting, coordination and mediating divergent interests. Climate governance includes both direct efforts to target greenhouse gas emissions, as well as mitigation outcomes resulting from efforts that achieve multiple mitigation and development objectives. (*medium confidence*) {13.2, 13.4, 13.8}

E 1.3. Governance for climate mitigation and shifting development pathways is enhanced when tailored to national and local contexts. Climate governance is impacted by material endowments, cultural-institutional understandings, levels of economic development, domestic political systems, and national regulatory systems. (*very high confidence*). Sub-national and urban actors are playing a growing role, reflecting local concerns and context in decision-making and stimulating experimentation (*high confidence*). {13.2, 13.3, 13.4, 13.5, 13.8}

**E2. Accelerating action on climate mitigation and shifting development pathways requires the presence of enabling conditions that integrate policy goals and cross-society responses to meet multiple, linked objectives. Policy mixes can help address multiple objectives. (*very high confidence*) {9.9, 13.6, 13.7, 13.8, 13.9, 16.5}**

E 2.1. Climate legislation can incentivise mitigation by providing directional signals to actors via: targets; creating institutions and legally enforceable implementation mechanisms; enabling coordination; creating a basis for transparency and accountability; mainstreaming mitigation into development processes; establishing and reinforcing changes in technology and infrastructure; and creating focal points for collective action (*medium confidence*). {13.2}

E 2.2. Market-based instruments are increasingly prevalent, with carbon pricing covering about 20% of global $CO_2$ emissions (*high confidence*). Design decisions such as coverage, exemptions, adjustments to the emissions cap or tax level and redistribution of the revenue generated affect the outcome of these instruments. Carbon pricing is most effective if implemented along principles of fairness and equity. Earmarking revenue for green infrastructures or transparently returning it to taxpayers increases the political acceptability of carbon pricing (*high confidence*). {5.4, 9.9, 13.6}

E 2.3. Regulatory instruments can play an important role in mitigation. Financial incentives and regulations have contributed to cost reductions and increases in the deployment of renewable energy (*high confidence*). Voluntary approaches may also reduce GHG emissions and support transformation towards low emissions systems (*medium confidence*). {9.9, 13.6}

E 2.4. International interactions of national mitigation policies can both negatively and positively impact other countries. Reductions in quantities and prices of fossil fuels produced and exported and the value of fossil fuel assets tend to negatively affect other countries (*medium confidence*). Markets for emission reduction credits and spill over effects from technology development and diffusion tend to benefit other countries *(high confidence)*. Emissions 'leakage' – the change in emissions arising from shifts in production, consumption and investment elsewhere as a result of mitigation policies in one country – has been limited in practice *(high confidence)*. {13.7}

E 2.5. Climate mitigation, shifting development pathways, and exploiting synergies between multiple objectives can be achieved by integrating policy across different domains. Well-designed policy mixes can address multiple objectives and enable a transition, if they are comprehensive, balanced across objectives, and consistent in terms of design. *(very high confidence)* {13.8, 13.9, 16.5}

**E3. People act and contribute to climate change mitigation as consumers, role models, citizens, investors, and professionals. In all roles, individuals can contribute to overcoming barriers and enable climate change mitigation. (*high confidence*). Individual behavioural change in isolation cannot reduce GHG emissions significantly (*medium confidence*). {5.2, 5.3, 5.4, 5.5, 5.6, 9.9, 13.2, 13.5, 13.8}**

E 3.1. Social, infrastructural, and cultural lock-in can act as a barrier to change at individual and sectoral levels. Behavioural change cannot reduce GHG emissions significantly if it is not embedded in structural, cultural and institutional change (*medium confidence*). Behavioural nudges, choice architectures and the provision of information can make modest contributions to reduce GHG emissions at the individual level, and work in synergy with price signals. The coordination of policies, choice architectures, physical infrastructures, new technologies and related business models could realise rapid system-level change (*medium confidence*). {5.4, 5.4.5.1, 5.5, 9.9, 13.8}

E 3.2. Intermediaries such as building managers, landlords, energy efficiency advisers, technology installers and car dealers can influence patterns of mobility and energy consumption by establishing low-carbon professional standards and practices (*medium confidence*). Providing them with greater capacity and motivation to play these roles enables climate mitigation. Individuals with high socio-economic status have the capacity and the flexibility to reduce their GHG emissions by, for example, avoiding flying, living car free, switching to electro-mobility, becoming role models for low-carbon lifestyles, investing in low-carbon businesses, and actively supporting ambitious climate policies. If 10-30% of the population were to demonstrate commitment to low-carbon technologies, behaviours, and lifestyles, new social norms would be established (*high confidence*). {5.2, 5.4, 5.5, 5.6, 9.9, 16.4}

E 3.3. Social equity increases social trust and thus the capacity for good governance and the implementation of direct mitigation efforts as well as those embedded in multiple objectives. Mitigation policies that take account of diverse perspectives and knowledge bases can build social trust, establish new coalitions and legitimise change, thus initiating a self-reinforcing cycle in governance capacity and policy development (*high confidence*). Increasing the participation of women, and racialised and marginalised groups, amplifies the impetus for climate action. Collective action through formal social movements and informal lifestyle movements expands the potential for climate policy and supports system change. (*high confidence*). Climate strikes have given voice to youth in more than 180 countries. {5.2, 5.4, 5.5, 5.6, 13.5, 13.8}.

**E4. Effective international cooperation, including financial flows, technology development and transfer, and capacity-building for developing country parties, particularly the least developed and most vulnerable, can support ambitious climate goals. New forms of international cooperation have emerged since AR5 in line with an evolving understanding of effective mitigation policies, processes, and institutions. (*high confidence*) {14.1, 14.2, 14.3, 14.4, 14.5, 14.6}**

E 4.1. International cooperation is a driver of enhanced national ambition and is a pre-requisite for the fulfilment of many national pledges. International cooperation enables and strengthens national and sub-national action, at multiple levels involving diverse actors. (*high confidence*) {14.3, 14.4, 14.6}

E 4.2. The Paris Agreement's enhanced transparency-related requirements, and the increased information flow, enables adequacy assessments and comparisons by diverse actors at multiple levels. The extent to which transparency requirements lead countries to increase the ambition of and implement their pledges will depend in part on the successful implementation of other forms of international cooperation. (*medium confidence*) {14.3, 14.4}

E 4.3. Transnational partnerships involving a range of non-state actors, including cities, non-governmental organisations, and private sector entities are playing a growing role in stimulating low-carbon technology diffusion and emissions reductions (*medium confidence*). {13.3, 14.2, 14.5}

E 4.4. Some sectoral agreements and institutions focus on reducing emissions and help push sectors on to a low-carbon development pathway. Others, particularly related to trade and investment, tend to reinforce the prominence of fossil fuels in specific sectors. At the national scale, smaller-scale efforts have been more effective than REDD+ in achieving emissions reductions from deforestation. (*medium confidence*) {14.5, 14.6}

E 4.5. The ability of countries to produce clean technologies domestically depends on the complexity of the technologies, domestic capabilities, and the policy framework (*medium confidence*). International cooperation can play a role in building global capacity, adapting technologies to local conditions, and developing local innovation, analysis and transition planning capabilities. Enhancing financial support through existing or other arrangements for technology development and transfer may contribute to improving their implementation and effectiveness. The lack of enhanced action on technology and capacity building has the potential to undermine climate ambition and action. (*high confidence*) {16.5, 16.6}

**E5. Financial flows fall short of what is needed to achieve climate goals across all sectors and regions. The ability to mobilise finance varies substantially by country, resulting in a varied outlook for the accelerated deployment of funding *(high confidence)*. Political leadership and signalling, along with fiscal interventions and central bank regulation can facilitate the role of finance in tackling climate change (*medium confidence*). (Figure SPM.12) {14.4, 15.2, 15.3, 15.4, 15.5, 15.6}**

E 5.1. Current financial flows across all sectors and regions are not consistent with climate goals (*high confidence)*. In particular, international climate finance flows are not on track to meet goals established under the UNFCCC, including mobilisation by 2020 of USD 100 billion per year and progression beyond previous efforts. This has the potential to undermine climate ambition and action. (*high confidence*) {14.4, 15.1, 15.2, 15.3, 15.4}

E 5.2. Near-term barriers to increased funding include rising levels of income inequality, macroeconomic uncertainty, mismatch between capital and investment needs, and bias towards investing in domestic markets. Substantially increased levels of credible public finance commitments are a crucial element of a just transition. (*high confidence*). COVID-19 is exacerbating national differences in terms of fiscal headroom and the ability to tap capital markets and is burdening many developing countries. {15.2, 15.5}

E 5.3. A strong alignment of COVID-19 recovery packages with climate targets has the potential to address financing needs efficiently, and to reduce lock-in effects. This reduces the burden for taxpayers in the mid-term *(high confidence)*. Misalignment bears a substantial risk of an increase in stranded assets. {Cross Chapter Box 1 in Chapter 1, 15.2, 15.5}

E 5.4. Aligning financial sector and real economy regulation will facilitate an accelerated transformation of the financial sector. Relying only on financial sector regulation and the financial sector's own initiatives is unlikely to result in substantial progress in the short-term (*medium confidence*). Credible signaling by governments and the international community reduces uncertainty for financial decision makers and closes transition risk gaps *(high confidence)*. The role of the financial sector as an enabler of climate action can be strengthened through political leadership and intervention that ensures an alignment between the financial sector and mitigation policies (*high confidence*). {15.6}

E 5.5. Given the inertia of the financial system, its vulnerability to physical and transition climate risk in terms of financial stability as well as current lengthy cycles between the commitment and disbursement of international public climate financing, short-term action is required to meet 2030 funding needs. {15.2, 15.5}

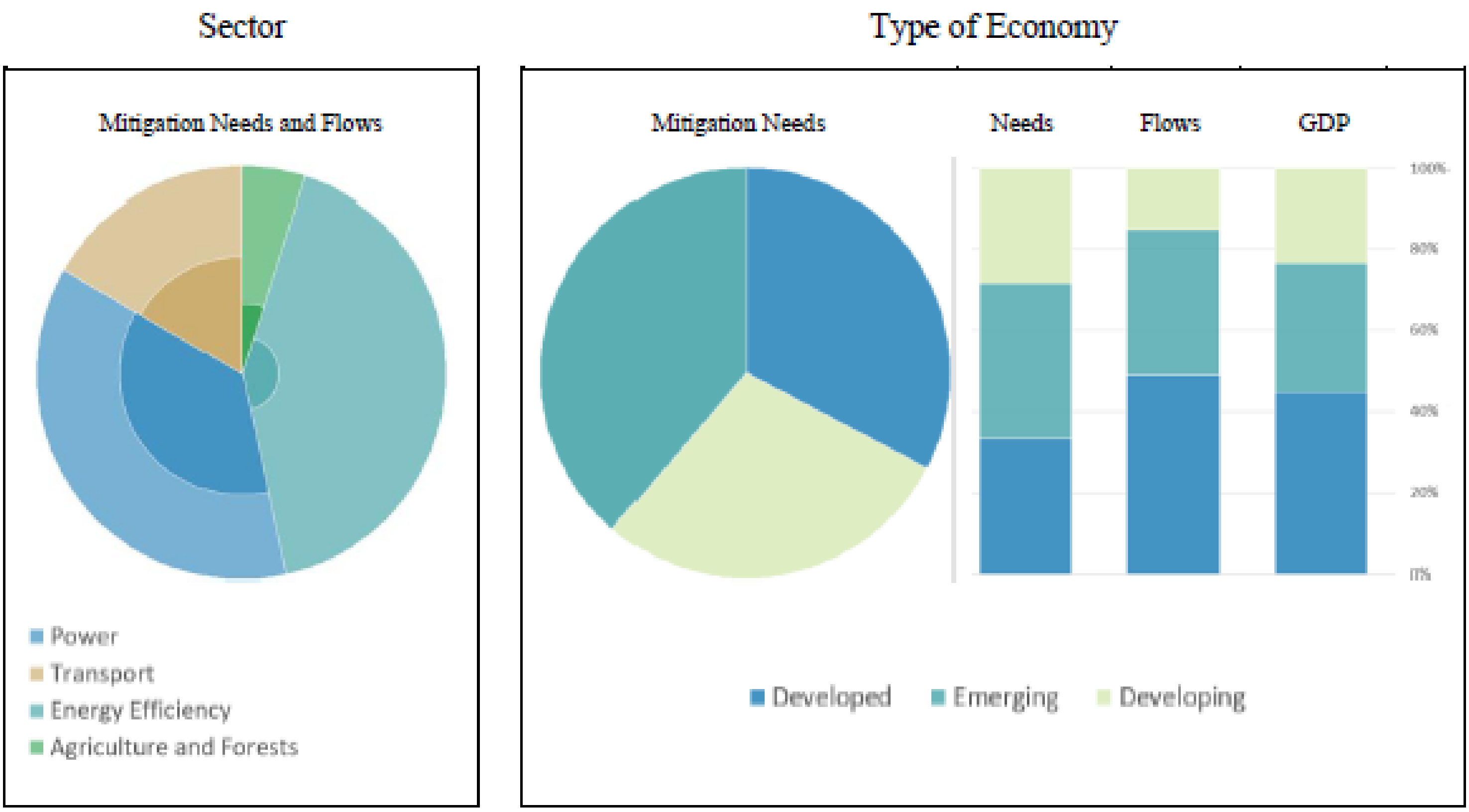



**Figure SPM.12: Breakdown of average investment needs until 2030.**

Left chart: Inner boundary represents current flows (mean average of 2017 and 2018), outer boundary represents average mitigation investment needs until 2030. Wing area in between represents resulting finance gaps by sector. Agriculture and Forests (USD 145 billion) are based on The Food and Land Use Coalition adjusted for higher afforestation needs based on New Forest Declaration Progress Reports. Energy Efficiency needs (USD 1099 billion) are based on IRENA (2020). Electricity sector needs (USD 974 billion), including T&D and storage, are derived from the AR6 scenario database. These are estimated as the incremental investment needs for pathways which limit warming to 1.75°C–2.25°C compared with the average of those consistent with warming of 3.0°C–4.0°C. Transport needs (USD 425 billion) are based on estimates for new rail infrastructure from the G20 Infrastructure Initiative. No estimates for new EVs are available. Flows represent only mitigation pegged flows (including multiple objectives, which accounts around 2% of total flows) by sectors provided by CPI. Cross-sectoral flows such as policy and national budget support and capacity building are excluded (2% of total non-adaptation flows).

Right chart: 'Emerging' represents BRICS countries. 'Developing' and 'developed' country classifications are according to the IPCC country classification (See Annex B). Flows: Mean average of 2017 and 2018 as per CPI breakdown, trans-regional and non-regional flows (approximately 20% of flows) allocated pro rata. Breakdown of needs for agriculture and forests is based on current Bonn Challenge commitments due to lack of better data, afforestation needs represent >50% of total needs; power (electricity sector) by type of economy based on AR6 IAM database; energy efficiency needs based on IRENA data; transport needs based on Global Infrastructure Outlook for Rail Infrastructure needs. Total GDP 2018 in constant 2017 international dollars, World Bank Indicator (NY.GDP.MKTP.PP.KD).

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**E6. The development, deployment and transfer of climate technologies can help achieve climate and sustainable development goals synergistically. Achieving this potential entails taking a system perspective, covering the social, economic, environmental, financial, institutional, infrastructural, capacity and behavioural dimensions of technological change. (*high confidence*) {4.4, 5.3, 5.6, 9.9, 14.4, 16.1, 16.2, 16.3, 16.5, 16.6, Cross-Chapter Box 8 in Chapter 16}**

E 6.1. Technology can contribute to decoupling growth in human well-being from increased emissions, environmental impacts, and demand for natural resources. Yet, if current patterns of technological change continue, it may also lead to higher emissions or other side-effects, for instance through rebound effects whereby falling costs incentivise higher levels of consumption. (*medium confidence*) {16.1, 16.2}

E 6.2. Digitalisation is fundamentally changing all economies and societies. Digital technologies can increase energy and material efficiency, making transport and building systems less wasteful, and improving access to services. Without active governance or management, they could increase energy demand, exacerbate inequalities and the concentration of power, raise ethical issues, reduce labour demand and compromise citizens' welfare. (*medium confidence*) {4.4, 5.3, 5.6, 9.9, 16.3, Cross-Chapter Box 8 in Chapter 16}

E 6.3. Technological change, technology development and diffusion processes, and innovation policies and practices are not fully represented in modelled emission pathways. Many modelling exercises have underestimated cost reductions in renewable energy supply and granular end-use technologies. The role of innovation in accelerating systems transitions and triggering socio-technical tipping points, especially for deep emission reductions, may also be underestimated. (*medium confidence*) {5.4, 16.3, 16.4}

E 6.4. Policy instruments used to promote innovation and the deployment and diffusion of new and improved technologies include public research, development and demonstration (RD&D) investments and innovation procurement. Direct technology policy instruments have had a positive impact on innovation outputs and outcomes as measured by patents, publications, and cost reductions (*medium confidence*). {16.3, 16.5}

E 6.5. Policy approaches that involve a holistic perspective, encompassing all aspects of the innovation process along with sustainable development goals are more effective than those that do not (*medium confidence*). Mixes of climate, industrial and trade policies could induce progress in low-emission technologies, with spill-over effects across regions contributing to global emission reductions. {16.4, 16.5}