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Insights from the IPCC Special Report on 1.5°C for preparation of long-term strategies

Michiel Schaeffer, Ursula Fuentes Hutfilter, Robert Brecha, Claire Fyson, Bill Hare

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Executive Summary

For guiding implementation of the Paris Agreement, the Intergovernmental Panel on Climate Change (IPCC) recently published its Special Report on 1.5°C (SR15), following the invitation in the Agreement to do so by 2018. In its SR15, the IPCC assessed the best available science on how global temperature rise can be limited to 1.5°C, consistent with the long-term temperature goal of the Paris Agreement. As signatories to the Paris Agreement, governments are tasked with developing long-term low emission sustainable development strategies (LT-LEDS) in line with this goal, and are invited to submit them by 2020.

This process is now in full play and development and submissions of LT-LEDS was, for example, welcomed by the G20[1] in 2017. While expressing his disappointment with the outcome of the December 2018 UNFCCC Conference of the Parties (COP24), Fiji Prime Minister and COP23 President Frank Bainimarama stated[2]: "*All governments must now return home and launch or ramp up domestic review processes to prepare new or enhanced NDCs, and develop long-term emissions strategies.*" To support enhanced ambition, UN Secretary-General Guterres said[3] "*In the coming year, U.N. agencies will work with governments to strengthen their climate action plans covering the decade to 2030, as well as their long-term strategies*."

The IPCC report focuses on the transformations at global and sectoral levels that are necessary for achieving the 1.5°C goal, as well as opportunities, challenges, and key enabling factors for achieving these transformations, which are relevant for the development of these strategies. This briefing lays out the key findings of the IPCC SR15 that inform governments in their task to develop and submit LT-LEDS, and at the same time inform the continuous scaling up of near- and mid-term action and targets, including in Nationally Determined contributions (NDCs), in line with the ratcheting-up mechanism enshrined in the Paris Agreement. Enhancing current NDCs is urgent by 2020, even if a 1.5°C-compatible LT-LEDS is not yet available during that process, and thus may need to be based on preliminary guidance on 1.5°C compatibility. Coupling the development of LT-LEDS with the process of updating of NDCs is very important to avoid inconsistencies between short-term goals and longer term required outcomes.

The IPCC shows that projected greenhouse gas emissions levels for 2030 resulting from present NDCs and current policies far exceed the levels that are consistent with the Paris Agreement, and, unless significantly reduced, could render 1.5°C unattainable. As a consequence, NDCs need a transformative leap forward, and near-term transformations are essential for ramping them up in the coming years, including by 2020. Substantially enhanced NDCs would need to be on a trajectory towards long term strategies that are truly in line with the Paris Agreement. This would be an essential function of the LT-LEDS, which will also provide guidance for the next five-yearly update of the Paris agreement NDCs due by 2025, following the Global Stocktake in 2023/24.

The SR15 Summary for Policymakers (SPM) establishes 1.5°C compatible mitigation pathways as being pathways with "no- or limited overshoot". In addition, it establishes limits for sustainable use of carbon

[1] See G20 Hamburg Climate and Energy Action Plan for Growth: "We welcome the submission of long-term strategies by some G20 countries and on-going efforts by others", https://www.consilium.europa.eu/media/23547/2017-g20-climate-and-energy-en.pdf

[2] https://cop23.com.fj/statement-prime-minister-fiji-president-cop23-outcome-cop24/

[3] https://www.reuters.com/article/us-climatechange-accord-un-summit/u-n-chief-urges-leaders-to-inject-momentum-at-2019-climate-summit-idUSKBN1O323R

dioxide removal (CDR) options. Taken together, key global benchmarks of pathways consistent with the PA LTTG can be identified based on these criteria and are reflected in the SPM:

- Peaking of greenhouse gas (GHG) emissions and of CO_2 by around 2020
- Rapid decline of GHG and CO_2 emissions by around 45% by 2030 (from 2010)
- Net zero CO_2 emissions by around 2050, negative thereafter
- Net zero GHG emissions by around 2070, negative thereafter
- Net zero AFOLU emissions by around 2030 (between 2025 and 2040) then negative
- Bioenergy with Carbon Capture and Storage (BECCS) deployment by around 2040

Achieving the Paris Agreement Long-term Temperature Goal requires transformative systemic change across the whole economy and society that is integrated with sustainable development. The key characteristics of 1.5°C consistent sectoral transformations are:

- Fully decarbonised primary energy supply by mid-century (including with CCS)
- Large energy demand reductions across all end-use sectors by 2030
- Large reductions of fossil fuel use, in particular coal (-64% by 2030, -75% by 2050) and oil (- 11% by 2030, -60% by 2050)
- Rapid increase in use of renewable energy
- Bioenergy is used in many 1.5°C pathways, both with CCS (BECCS) and without, with uncertainties regarding limits to sustainable use
- Full decarbonisation of electricity generation by 2050, mainly through increased use of renewable energy reaching shares of over 50% by 2030 and over three-quarters by 2050 globally
- Coal use for electricity reduced dramatically by around 70% in 2030 and complete global phase out by 2050. Due to high carbon intensity, no role for coal even with CCS by 2050.
- Electrification of end-use sectors (transport, buildings, and some industry processes) and decarbonisation of final energy other than electricity, for example through the use of biofuels, hydrogen or other energy carriers (aviation, shipping, and some industry processes)
- Net-zero land-use emissions between 2025 and 2040, requiring a steep reduction in deforestation and the adoption of policies to conserve and restore land carbon stocks and protect natural ecosystems. By 2050, negative emissions will already need to be on a multi-Gigatonne scale
- All these sectoral transformations imply a major and timely shift in investment patterns:
    - Investment in low-carbon energy technologies and energy efficiency needs to be doubled in the next 20 years, and investment in fossil-fuel extraction and conversion needs to decrease
    - This represents a major shift in investments, where global annual investments in low-carbon energy technologies overtake fossil investments already by around 2025
- There is an opportunity to address presently underinvested assets such as infrastructure and buildings, and redirect financial flows in a timely manner to achieve the transformation needed without creating stranded assets

Some transformations are well underway, in particular the shift to renewable energy-based electricity and electrification of mobility, as well as other social and technical innovations transforming urban and transport infrastructure. These need to be accelerated, and challenges for other transformations, in particular in the industry sector need to be addressed early, taking into account inertia and longevity of infrastructure and industry processes. The following sectoral 1.5°C-consistent trajectories provide essential guidance for LT-LEDS in particular:

- **Electricity** – Decarbonising electricity generation implies phasing out coal-fired power globally by 2050 and a rapid increase in the renewable share of electricity generation, building on the rapid decline in costs in particular for solar and wind energy and storage technologies. Natural gas, replacing more carbon-intensive coal, can play a transitional role in decarbonising electricity generation but its continued use would only be consistent with the Paris Agreement temperature goal if it is used with carbon capture and storage (CCS), which is increasingly unlikely to be able to compete with renewable energy due to incomplete capture rates, no observed cost improvements and more limited co-benefits.
- **Transport** - electrification of rail travel (passenger and freight), heavy-duty vehicles (HDV) for freight transport, but most especially, for light-duty vehicles (LDV) is key in transport, in parallel with modal shifts (e.g. increases in passenger-trips by public transportation, shifts from freight trucks to rail, more bicycles and walking as part of urban planning). Electrification of LDVs represents a dramatic increase in efficiency, decrease in emissions, and decrease in operating and maintenance costs for consumers.
- **Industry** - changing processes through electrification, or use of hydrogen (e.g. direct reduction of iron ore with hydrogen for steel production, or heat generation with electricity) and sustainable bio-based feedstocks for non-electric energy demands or for chemical feedstocks. For some processes, the use of Carbon Capture, (Utilisation) and Storage (CC(U)S) is part of this strategy, in particular where process-related emissions cannot be avoided, such as cement production, but progress has been very slow thus far. Another important strategy is substituting carbon intensive products with other products (e,g, replacing steel or cement with wood or plastic with textile fibres).
- **Buildings** - electrification of and higher efficiency in thermal conditioning (e.g. heat pumps with an increase in efficiency of a factor of two to three compared to typical present-day systems).
- **Sector coupling** - with far-reaching electrification of sectors, sector coupling becomes essential with a fully decarbonised electricity sector.
- **Agriculture** - enhanced agricultural management (e.g. rice paddy water management, manure management, improved livestock feeding practices, and more efficient fertiliser use), as well as demand side measures such as dietary shifts to healthier, more sustainable, low-meat diets and measures to reduce food waste.

Developing a LT-LEDS is an opportunity for countries to address the systemic and transformational change in all economic sectors and integrate these with sustainable development by implementing the following key elements:

Develop strategies and benchmarks for sectoral transformations

- Defining short- and mid-term benchmarks consistent with the scale and pace of the required transformation across all sectors, with the SR15 helping to guide priorities and coupling between sectors, to reduce costs and avoid locking in carbon intensive infrastructure and practices;
- Addressing and enhancing synergies with adaptation, and with other objectives and goals, in particular

related to sustainable development and goals such as food security and public health, access to clean energy, of alleviation of poverty, reducing impacts on biodiversity;

- Build on and accelerate ongoing transformations, such as the uptake of renewable energy and social innovations towards zero carbon solutions for energy, and urban and transport infrastructure
- Address remaining challenges, closing knowledge gaps and implementing iterative and participative processes, in particular for questions regarding sustainable use and management of biomass, as well as of carbon dioxide removal (CDR), management of land-use change and addressing needs and goal related to food security and biodiversity
    - How much biomass use is necessary and sustainable? How to manage?
    - How much CDR is necessary and sustainable? How to get it started?
    - How to manage land-use change to address all needs/goals in different country contexts?
    - How to decarbonise carbon-intensive industry sectors and processes?

Develop and implement robust and inclusive policies to support systemic transformations

- Develop policies in line with robust strategies with multiple benefits:
    - Follow a whole of economy approach, considering opportunities and challenges in each sector
    - Reduce demand and improve efficiency across all sectors, while addressing the need for access to modern services
    - Accelerate the uptake of renewable energy and storage technologies
    - Electrification of end-use sectors – transport, building, industry
- Implement well established robust policies (incl. removing fossil fuel subsidies and implementing effective carbon pricing) and mobilise resources and capacities to ensure timely shifting of investments at scale
- Develop and implement policy packages and management of structural change to address trade-offs and equity and distributional impacts
    - Engage government departments across sectors and levels and enhance institutional strength
    - Engage all actors/stakeholders to enable societal transformation and strengthen contributions
- Implement monitoring and evaluation processes, and engage scientific institutions, to strengthen learning from and improvement of LT-LEDS policy processes, and inform and implement a ratcheting up process as provided by the PA
- For developing countries: Identify the needs for financial, technological and other forms of support to build capacity to mobilise resources

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1. Introduction

Under Article 4.19 of the Paris Agreement (PA), Parties should "*formulate and communicate long-term low greenhouse gas emission development strategies*" consistent with the Agreement's Long-Term Temperature Goal (LTTG). Article 2 specifies the LTTG as "*[h]olding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*". The Agreement's decision text "*invites*" Parties to communicate their Long-Term low-emissions sustainable development Strategies (LT-LEDS) by 2020, to be published on the UNFCCC website.

For guiding implementation of the Paris Agreement, the Agreement invited the IPCC to "*provide a special report in 2018 on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways*". The IPCC Special Report on 1.5°C (SR15) adopted and published in October 2018 outlines pathways for limiting global warming to 1.5°C and assesses global, regional, and sectoral transformations in the near-, mid-, and long-term, as well as synergies and trade-offs for sustainable development.

The current 2030 NDC targets are not consistent with the 1.5°C limit. The IPCC SR15 found projected GHG emissions levels for 2030 resulting from present NDCs and current policies far exceed the levels that are consistent with the Paris Agreement, and if not reduced substantially could render 1.5ºC unattainable. Emissions would have to reach a level of 25-30 $GtCO_2eq$/year by 2030 if all pathways consistent with the PA LTTG are considered. This is about half the level of emissions implied by full implementation of current NDCs (52-58 $GtCO_2eq$/year). The IPCC therefore concludes that pathways reflecting the ambition level of current NDCs would not limit global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030. Substantially enhanced NDCs would need to be on a trajectory towards long term strategies that are truly in line with the Paris Agreement. This would be an essential function of the LT-LEDS, which will also provide guidance for the next five-yearly update of the Paris agreement NDCs due by 2025, following the Global Stocktake in 2023/24. Enhancing current NDCs is urgent by 2020, even if a 1.5°C-compatible LT-LEDS is not yet available during that process, and thus may need to be based on preliminary guidance on 1.5°C compatibility.

The findings of the SR15 can now inform Parties to the Paris Agreement in their task to submit their Long-Term low-emissions sustainable development Strategies (LT-LEDS) by 2020. The report is timely, as for instance Fiji Prime Minister and President of the 23rd UNFCCC Conference of the Parties (COP23) Frank Bainimarama, while expressing his disappointment with the outcome of the December 2018, stated[4]: "*All governments must now return home and launch or ramp up domestic review processes to prepare new or enhanced NDCs, and develop long-term emissions strategies.*" To support enhanced ambition, UN Secretary-General Guterres said[5] "*In the coming year, U.N. agencies will work with governments to strengthen their climate action plans covering the decade to 2030, as well as their long-term strategies*."

This briefing lays out the most important findings of the SR15 in relation to the development of LT-LEDS, focusing on the mid- and long-term transformations at global and sectoral level that are consistent with achieving the Paris Agreement Long-Term Temperature Goal (LTTG), and findings on opportunities, challenges, and key enabling factors for achieving these transformations.

[4] https://cop23.com.fj/statement-prime-minister-fiji-president-cop23-outcome-cop24/
[5] https://www.reuters.com/article/us-climatechange-accord-un-summit/u-n-chief-urges-leaders-to-inject-momentum-at-2019-climate-summit-idUSKBN1O323R

2. Pathways consistent with Paris Agreement Long-term temperature goal

Article 2.1 defines the PA Long-term temperature goal (LTTG) as "[h]olding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change".

The SR15 currently provides the best available science for operationalising the LTTG. It provides the most comprehensive and up-to-date assessment of mitigation pathways. The SR15 Summary for Policymakers (SPM) establishes 1.5°C-compatible mitigation pathways as being pathways with no or limited overshoot. These pathways limit median global warming to 1.5°C throughout the 21st century without exceeding that level ("no-overshoot"), or allow warming to drop below 1.5°C by the end of the century (around 1.3°C warming by 2100) after a brief and limited overshoot of median peak warming below 1.6°C around the 2060s ("low-overshoot").

With a peak warming of 1.6°C these pathways meet several tests with reference to the LTTG, whereas the "hold below 2°C" pathways (used to inform the former Cancun Agreements temperature goal) peaked warming at up to 1.8°C, the 1.5°C-compatible pathways peak warming at a significantly lower level (1.5-1.6°C), hence they can be said to hold warming "well below 2°C", while warming by 2100 typically drops below 1.5°C with chance greater than 50% (see Annex I for background).

In these 1.5°C mitigation pathways, total greenhouse gas emissions peak around 2020 and decrease rapidly to global zero around 2070.

In the context of defining the broad features of these pathways it is important to note that the IPCC SR15 identified limits based on sustainability and economic constraints on Carbon Dioxide Removal (CDR). These limits were found for BECCS[6] to be below 5 $GtCO_2$/yr globally in 2050 and for AFOLU[7] below 3.6 $GtCO_2$/yr sequestration globally in 2050). We follow these limits in this briefing in order to define Paris Agreement LTTG-compatible pathways as pathways that limit global warming to 1.5°C, or below, throughout the 21st century with no or limited (<0.1°C) overshoot. They are drawn from the "below 1.5°C" and "low overshoot 1.5°C" pathways in the new set pathways from Integrated Assessment Models (IAMs) assessed in the IPCC SR15, filtered to exclude those that exceed the BECCS and AFOLU sustainability limits identified in the IPCC SR15. In these pathways global average temperature increases above pre-industrial are limited to below 1.6°C over the 21st century and below 1.5°C by 2100 (typically 1.3°C).

With these considerations the implications for operationalising the Article 4.1 global emission pathways can be outlined. Article 4.1 of the Paris Agreement is designed to operationalise the LTTG with global emission goals "in order to achieve the long-term temperature goal set out in Art. 2.1" – to peak global emissions "as soon as possible", followed by "rapid reductions thereafter", and to reach a balance between anthropogenic sources and sinks of greenhouse gases emissions in the second half of this century – are to be determined "according to best available science" so as to be consistent with the LTTG.

Excluding pathways that exceed the BECCS and AFOLU sustainability limits identified in the IPCC SR15 implies faster reduction of greenhouse gas emissions by 2030 – to a level of 25-28 $GtCO_2eq$/year, instead of 25-30 $GtCO_2eq$/year if all pathways consistent with the PA LTTG are taken into account.

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[6] Bio-energy with Carbon Capture and Storage, defined in SR15 glossary as: "Carbon dioxide capture and storage (CCS) technology applied to a bioenergy facility. Note that depending on the total emissions of the BECCS supply chain, carbon dioxide can be removed from the atmosphere."

[7] SR15 refers to CDR measures in the Agriculture, Forestry and Other Land Use sector and notes such measures are mainly represented in the models as afforestation and reforestation.

Figure 1 illustrates the PA 1.5°C pathways and the three stages of global transformation and mitigation strategies as outlined in Art. 4.1 (peak, rapid decline and zero GHG emissions) as well as the fourth key mitigation benchmark for decarbonisation (zero CO_2 emissions around 2050). These four key global mitigation benchmarks and others are also shown in Table 1.

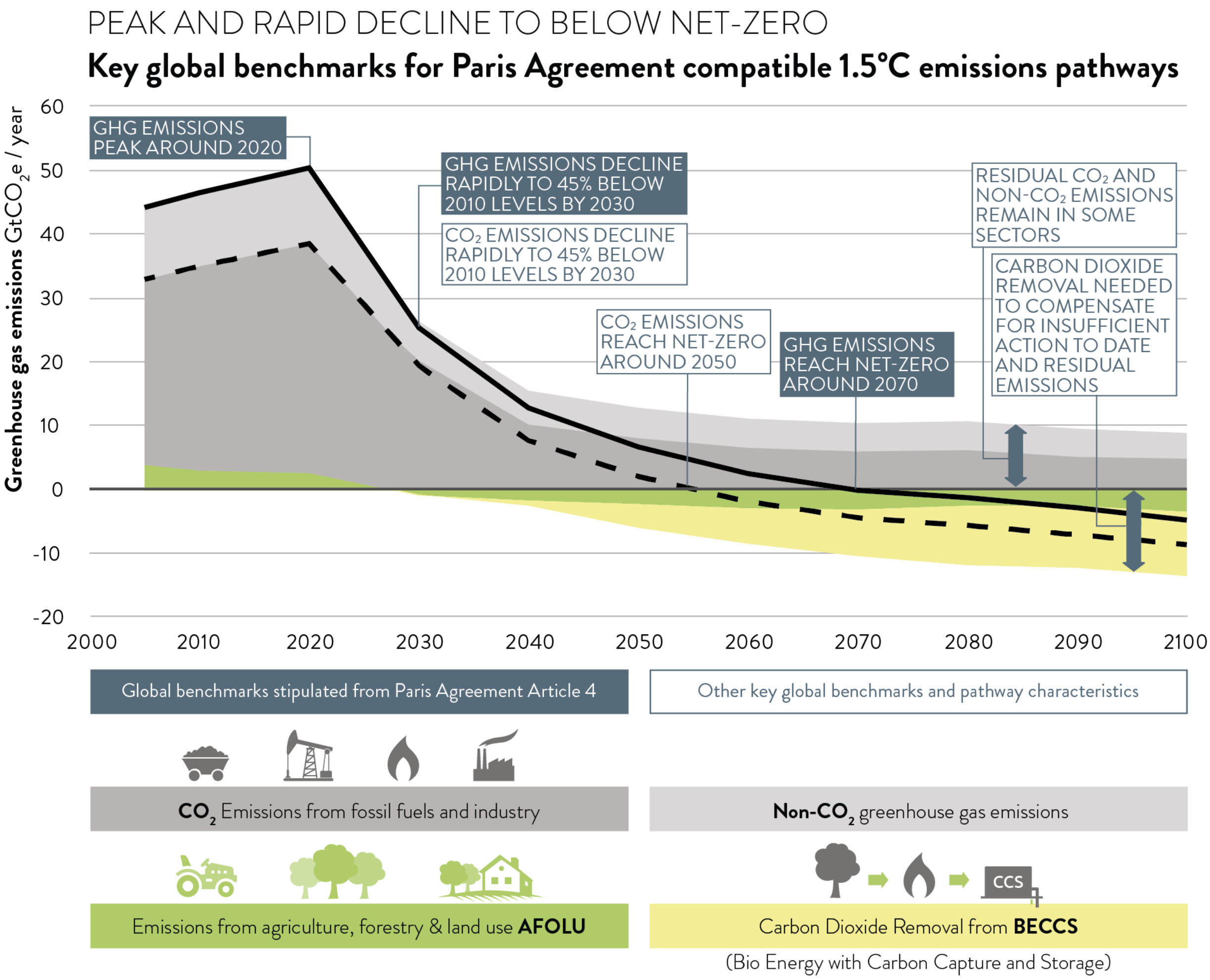

Figure 1. Illustration of the three benchmarks in Paris Agreement Article 4.1 for operationalisation of Article 2.1 (dark blue boxes) and global decarbonisation benchmarks (white box). This representative pathway is the median across all 1.5°C-compatible pathways from the IPCC SR15 that reach levels of Carbon Dioxide Removal (CDR) below the upper end of estimates for sustainable, technical and economic potential around 2050 from SR15 in the sector of Agriculture, Forestry and Land-Use (AFOLU), as well as via Bioenergy combined with Carbon Capture and Storage (BECCS)[8].

[8] All emissions and removals where calculated from the median emissions levels across the 46 pathways in the SR15 scenario database that are 1.5°C compatible and that reported data for all variables included here (Source: SR15 scenario database https://data.ene.iiasa.ac.at/iamc-1.5c-explorer, accessed 22 October, 2018)

Table 1 Total GHG emissions and fossil-fuel and industry emissions of CO_2 for all 1.5°C-compatible pathways from the IPCC SR15 ("no or limited overshoot") that reach levels of Carbon Dioxide Removal (CDR) below the upper end of estimates for sustainable, technical and economic potential around 2050 from SR15 in the sector of Agriculture, Forestry and Land-Use (AFOLU), as well as via Bioenergy combined with Carbon Capture and Storage (BECCS)[9]. Values represent median (25th to 75th percentile) levels across pathways.

SR15 1.5ºC compatible pathways	Year of peak emissions	Absolute annual change in emissions 2020-2030 ($GtCO_2e/yr$)	Emissions 2030 (% below 2010)	Emissions 2050 (% below 2010)	Year of zero emissions	Cumulative emissions 2016 to year of zero emissions ($GtCO_2$)	Cumulative emissions 2016-2100 ($GtCO_2$)
Total GHG emissions	2020	-2.7 (-3.1 -2.4)	48% (45 to 60%)	86% (81 to 90%)	2068 (2061 to 2084)		
Total CO_2 emissions	2020	-2.3 (-2.0 -1.8)	42% (38% to 54%)	94% (88% to 97%)	2055 (2053 to 2063)	640 (590 to 740)	370 (250 to 620)
Fossil-fuel and Industry CO_2 emissions	2020	-1.4 (-1.8 -1.1)	44% (34% to 50%)	85% (82% to 91%)	2064 (2057 to 2081)	680 (630 to 800)	540 (390 to 770)

3. Global transformations compatible with 1.5°C

The IPCC SR15 outlines the range of mitigation strategies that can achieve the emissions reductions required to follow the pathways consistent with the PA LTTG described above. All pathways require a rapid decarbonisation of energy systems, with global net anthropogenic CO_2 emissions declining by about 45% from 2010 levels by 2030 and reaching net zero around 2050. In addition, substantial reductions of emissions of non-CO_2 greenhouse gases such as methane and nitrous oxide from agriculture, industry and other sectors are needed, and as well a phase-out of HFCs. Air-pollution components, such as black carbon, are reduced as well. Some of the reductions are a result of targeted measures in industry, agriculture and waste sectors, but a large part, in particularly for methane and aerosols, results from mitigation measures in the energy sector[10]. Examples for the latter are phasing-out fossil fuel extraction and therefore associated methane emissions, and reductions in black carbon from eliminating the combustion of coal and oil. The SR15 shows that the mitigation pathways and benchmarks for CO_2 already account for reductions in co-emitted pollutants such as black carbon. Therefore, addressing these co-emitted pollutants has no place in an LT-LEDS, because they are already accounted for under 1.5°C-compatible benchmarks for CO_2 mitigation and provide no additional reduced warming.

Non-CO_2 greenhouse-gas emissions, however, cannot all be reduced to zero. In addition, while CO_2 emissions from fossil fuel and industry can be reduced to zero for all energy-related and some process-related emissions, there are some processes where options to reduce to zero have not yet been fully identified, such as for cement production. These emissions are reduced by between 80 and 90% by 2050

[9] All emissions and removals where calculated from the median emissions levels across the 46 pathways in the SR15 scenario database that are 1.5°C compatible and that reported data for all variables included here (Source: SR15 scenario database https://data.ene.iiasa.ac.at/iamc-1.5c-explorer, accessed 22 October, 2018)

[10] For example, SR15 Chapter 4 writes: "low-emissions pathways include a transition away from the use of coal and natural gas in the energy sector and oil in transportation, which coincides with emission reduction strategies related to methane from the fossil fuel sector and BC from the transportation sector", while Chapter 2 writes: "Because the dominant sources of certain aerosol mixtures are emitted during the combustion of fossil fuels, the rapid phase-out of unabated fossil-fuels to avoid CO_2 emissions would also result in removal of these […]"

in the 1.5°C mitigation pathways (see Figure 1, Table 1) alongside a fully decarbonised energy system. This still includes emissions from some processes that can be decarbonised (see section 4).

To compensate for the remaining emissions, all of these pathways use Carbon Dioxide Removal (CDR) in order to achieve net zero greenhouse gas emissions in line with the PA LTTG. The contribution of the primary options – Afforestation/Reforestation (AR) and Bioenergy with Carbon Capture and Storage (BECCS) – varies, depending on assumptions about mitigation strategies, socioeconomic developments, the balance between energy intensity reduction, rate of decarbonisation of energy systems, and estimated CDR potential.

Rapidly reducing emissions by 2030 – by around 45% compared to 2010 - is an important strategy to lower the challenge in achieving the Paris Agreement 1.5°C and to avoid the risk of escalating costs and institutional and economic lock-in in carbon intensive infrastructure, that will then be costly or more difficult to phase out later. Delaying emissions reductions would reduce flexibility in future response options and increase the reliance on CDR.

To illustrate the range of mitigation strategies, the SR15 has selected four illustrative individual pathways, three of those (labelled P1, P2, P3 in the SR15 SPM) consistent with the PA LTTG as outlined above. P1 is a low energy demand pathway with rapid decarbonisation of energy supply and without any use of Carbon Capture and Storage (CCS), and afforestation as the only CDR option considered. P2 is a sustainability-oriented scenario with low-carbon technology innovation and limited use of Bioenergy and CCS (BECCS) as CDR. P3 is a middle-of-the-road scenario with reductions focused on energy supply. A fourth illustrative pathway, P4, describes a fossil-fuel intensive and high energy demand scenario, which leads to an overshoot of warming to about 1.8°C and only returns to below 1.5°C by 2100 via extremely high use of CDR reaching 2050 values of global CO_2 removals 3-9 times higher than the 1.5°C compatible pathways. The P4 pathway does not belong to the category of 1.5°C consistent pathways.

4. Sectoral transformations compatible with 1.5°C

To achieve the required deep cuts in GHG, and in particular CO_2 emissions, as well as necessary decreases in non-CO_2 forcings, all sectors will require rapid and far-reaching transitions unprecedented in scale but not necessarily in speed. These transitions include lower energy use through enhanced energy efficiency and electrification of energy end-use, for example in transport, buildings, industry, and a transition to renewables as the main source of electricity generation. These dimensions are discussed in this section.

Energy system transformation

A rapid and profound energy supply decarbonisation is a key and driving characteristic of 1.5°C pathways, leading to a net-zero-emissions energy supply system by mid-century. Energy system transformation is characterised by:

- Major changes in primary energy supply with large reductions in fossil fuel use
- Demand reductions to limit the increase of final energy demand
- Decarbonisation of electricity generation, mainly through increased use of renewable energy

- Electrification of end-use sectors; while electrification leads to an increased demand in electricity, reducing energy demand to meet energy services, including through enhanced energy efficiency is an important element of all mitigation pathways
- Decarbonisation of final energy other than electricity, for example through the use of biofuels, hydrogen or other energy carriers

The extent to which a decarbonised energy supply relies on CCS, including with bioenergy (BECCS) varies between pathways. Some pathways (P1 above) as well as an increasing number of regional or national pathways show the possibility of decarbonising the energy supply without the use of CCS by around mid-century.

As shown in Table 2, coal and oil use decreases dramatically over the next three decades in 1.5°C-compatible pathways. Natural gas shows a more complex behaviour, with many models relying on CCS combined with natural gas in electricity generation as a low-emissions source. Most striking of all is the rapid increase in use of renewable energy sources.

Table 2 - Primary energy sources in IAM 1.5°C compatible pathways. In each column the entries represent the percentage increase in primary energy source consumption with respect to 2010. The values are medians with interquartile ranges given in parenthesis.

Major primary energy sources	2020	2030	2050
Coal	-1% (-6% to +16%)	-64% (-60% to -71%)	-75% (-73% to - 80%)
Oil	+17% (+15% to +19%)	-11% (-23% to -3%)	-60% (-81% to -30%)
Natural Gas	17% (11% to 25%)	8% (-10% to +22%)	7% (-28% to +14%)
Non-biomass renewable	79% (60% to 91%)	310% (280% to 370%)	570% (460% to 670%)

Renewable energy increases substantially in all mitigation pathways, including biomass use for primary energy. Bioenergy use represents a key area of uncertainty in Integrated Assessment models[11] and it is important to consider assessments of limits to the sustainable potential for bioenergy use, considering sustainable development needs for food production and limiting biodiversity impacts, as well as address the need for sustainable management.

Bioenergy is a major part of the global energy mix, both today and in projected pathways (1.5°C, 2°C and higher). Deep mitigation pathways find that bioenergy is combined with CCS (BECCS), but also find robust deployment of bioenergy independent of availability of CCS. Deployment is similar in 1.5°C and 2°C consistent pathways. The IPCC refers to high agreement in the literature that the sustainable bioenergy

[11] https://climateanalytics.org/publications/2018/integrated-assessment-models-what-are-they-and-how-do-they-arrive-at-their-conclusions/

potential in 2050 would be restricted to around 100 EJ per year. This is about double the current primary energy supply from bioenergy and accompanied by a shift from traditional to modern biomass more dependent on future societal development and preferences, and technologies, while only only mildly affected by climate policy. There is large uncertainty and limited information on post-2050 deployment, for which technical and economic potential is found to be substantially larger. While many 1.5°C pathways constrain bioenergy deployment to sustainable limits, many others reach levels that may put significant pressure on food production and prices, and biodiversity (and were excluded from the pathways in Section 2).

An area of investigation that is widely thought to have great potential for emissions reductions, but is under-investigated, is that of demand-side changes in energy use, and especially, behavioural changes.[12] Some investigation of these aspects of climate change mitigation were included in pathways assessed in the SR15 SPM.[13]

Power sector

The power sector contributes approximately 40% of global energy-related CO_2 emissions and is key to all decarbonisation strategies, also because electrification is a key strategy to decarbonise end-use sectors such as transport, buildings, and industry.

Decarbonising electricity generation at the scale and speed necessary to be consistent with the Paris Agreement LTTG implies that global coal-fired power will be reduced dramatically to around 70% below 2010 levels by 2030, and phased out globally by 2050. This is an area of high agreement between all energy-economy models. Another robust finding in all mitigation pathways is that the renewable share of electricity generation will increase significantly, to over 50% by 2030 and to over three-quarters by 2050 with fast technical and economic improvements in particular of wind and solar, as well as storage technologies. Nuclear power plays a larger or smaller role depending on modelling assumptions of IAMs, with some pathways showing a decline in capacity and share.

While the use of natural gas for electricity generation, replacing more carbon-intensive coal, plays a transitional role in decarbonising electricity generation, its continued use would only be consistent with the Paris Agreement temperature goal if used with carbon capture and storage (CCS). Even then it would play only a small role in electricity generation by 2050 at around 8% of global electricity generation. Due to incomplete CO_2 capture rates, the use of gas with CCS would have to be balanced out with additional carbon dioxide removal (CDR).

The political, economic, social and technical feasibility of solar energy, wind energy, and electricity storage technologies has improved dramatically over the past few years, with costs dropping rapidly over the last few decades with corresponding growth trajectories much faster over the last years than expected (IRENA 2018). These fast developments enable more stringent near-term mitigation than currently planned. For example, rooftop solar has been identified as competitive in many areas, and solar PV with batteries are cost effective in many rural and developing areas, with small-scale distributed energy projects already being implemented in many countries with potential for consumers becoming producers. Several countries and other constituencies have adopted targets of 100% renewable electricity as this meets multiple social, economic, and environmental goals apart from mitigation of climate change.

[12] Creutzig et al. (2018) "Towards demand-side solutions for mitigating climate change" *Nature Climate Change* **8**, 268-271
[13] For example in the illustrative pathway labelled P1 in IPCC SR15 SPM

Nuclear energy and CCS in the electricity sector have not shown similar improvements, with costs of nuclear power having increased over time in some developed countries, and costs of CCS not coming down over the last decade. Together with more limited co-benefits than renewable energy, this cost trend makes these technologies increasingly unlikely to be able to compete with renewable energy, which is not reflected in many energy-economy models.

Domestic and international transport

Transportation currently accounts for 28% of final energy demand globally, as well as 23% of CO_2 emissions. Much of the primary energy for transport comes from oil. In 1.5°C-compatible pathways, consumption of oil decreases strongly, especially by 2050, by between more than a quarter to more than three quarters.

The strategies incorporated in mitigation pathways are varied. Modal shifts can play a large role, for example increases in passenger-trips by public transportation or to non-energy intensive means (i.e. bicycles and walking as part of urban planning), or from trucks to rail for movement of goods. In the short term, improving the efficiency of light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) can help reduce emissions and consumption of primary energy.

A key strategy for reducing emissions in the transportation sector is the electrification of rail travel (passenger and freight) and heavy-duty vehicles (HDV) for freight transport, but most especially, for light-duty vehicles (LDV). Electrification of LDVs would bring a dramatic increase in efficiency, reduced emissions, and decrease in operating and maintenance costs for consumers. Lifetimes of LDVs are typically 15 years, 14 being a "natural" retirement rate of 4-5% per year if uniform, but in reality, 80% of LDVs are still on the road after ten years. Thus, a near complete switch to electric LDVs will require both a very rapid scale-up in sales of new vehicles, and likely an accelerated retirement of old vehicles. Electrification, including through hydrogen powered fuel cell vehicles, is increasingly an option for HDVs.

Uncertainty in the potential for decarbonisation of international aviation and shipping leads to remaining oil consumption in many pathways. For aviation and shipping, biofuels and the use of synfuels created from renewable electricity and CO_2 have gained momentum.

Industry

Industry forms the largest end-use sector with currently 25% of total share of global direct (energy related and process) CO_2 emissions, which are growing faster than total CO_2 emissions. Industry contributes about one third of global GHG emissions, if indirect emissions, for example from electricity generation, are considered. In 1.5°C-compatible pathways, direct CO_2 emissions are reduced by more than three quarters (about 75-90%) by 2050 compared to 2010.

Material industries such as steel and other metals, chemicals, minerals, and pulp and paper account for 72% of direct industry sector emissions. Most of energy use in manufacturing industries is required for process heating and steam generation, and electricity use is important for mechanical work.

Reducing demand and increasing energy and process efficiency (e.g. through recycling and replacement of materials) is an important but not sufficient strategy to reduce emissions. A key mitigation strategy identified for this sector is changing processes through electrification, or use of hydrogen (for example

[14] https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/ldv_mileage_improvement_en.pdf

direct reduction of iron ore with hydrogen for steel production, or heat generation with electricity) and sustainable bio-based feedstocks for non-electric energy demands or for chemical feedstocks. For some processes, the use of Carbon Capture, (Utilisation) and Storage (CC(U)S) is part of this strategy, in particular where process-related emissions cannot be avoided, such as cement productions. Development and demonstration of CCS projects in industry has been slow, with only two large-scale industrial CCS projects in operation.

Another important strategy is substituting carbon intensive products with other products (for example replacing steel or cement with wood or plastic with textile fibres).

While all these options such as new steelmaking, aluminium smelting, and clinker production processes are technically proven at various scales, their large-scale commercial deployment requires significant investment in research and development.

Given the longevity of large-scale industrial installations and inertia, economic and financial challenges and institutional constraints need to be addressed early on to achieve the necessary emissions reductions.

Buildings

Buildings are currently responsible for 31% of global final energy demand, more than 50% of final electricity demand, and 23% of energy-related CO_2 emissions. The challenge in this sector is threefold – reducing energy intensity of buildings through renovations to existing stock and more ambitious codes for new construction, through behavioural changes by occupants of buildings, and through changes to equipment to take advantage of efficient electrification of heating, ventilation and air-conditioning (HVAC) systems. The latter of these assumes as a precondition that the power system is increasingly decarbonised.

As in the case of electrification of transportation, increased conversion of HVAC systems in buildings to electricity carries with it an enhancement in efficiency. Thermal conditioning of buildings that are currently using boilers or direct electrical heating, can be converted to the use of ground- or air-source heat pumps with an increase in efficiency (heating service per unit of input energy) of a factor of two to three.[15] Therefore, the same level of comfort can be achieved with significantly less primary energy input; as the power system is decarbonised, the longer-term trend will be toward strongly decreased CO_2 emissions. At the same time, climate change and in some areas, increasing levels of affluence, will lead to additional building electricity consumption for air-conditioning.

Land-use sectors

CO_2 emissions from land use change have contributed about 12% of total anthropogenic CO_2 emissions over the last 5 years, driven largely by deforestation. Together with non-CO_2 emissions from the agriculture sector (from livestock, soil and nutrient management), the total greenhouse gas emissions from agriculture, land-use change and forestry (AFOLU) add up to over 10 $GtCO_2e$/yr. Limiting warming to 1.5°C will therefore require global-scale transitions in global and regional land use, and in agricultural practices.

In the near term a focused effort will be needed to rapidly reduce and then reverse CO_2 emissions from land use. The majority of 1.5°C-compatible pathways achieve net zero land use emissions between 2025

[15] https://www.energy.gov/energysaver/heat-and-cool/heat-pump-systems

and 2040, requiring a steep reduction in deforestation and the adoption of policies to conserve and restore land carbon stocks and protect natural ecosystems. By 2050, negative emissions will already need to be on a multi-gigatonne scale. This will likely require the deployment of bioenergy with carbon capture and storage in addition to reforestation, afforestation, and other land-based activities for sequestering carbon, such as land restoration and improved soil management.

A key challenge for mitigation in the AFOLU sector is the need to balance the many competing demands for land, such as food production, settlements, bioenergy, carbon sequestration, biodiversity and other ecosystem services. The land use transitions that will be needed to limit warming to 1.5°C will be largely driven by changes in these demands, efficiency of agricultural and forestry production, and the policy environment. Therefore, they will depend to a large degree on socio-economic conditions (e.g. population growth, diet composition, globalisation of trade) and well as technological change (e.g. crop yield growth or advances in technologies for CDR) and near-term success in protecting and restoring forests and reducing emissions from other sectors enough to lower the need for CDR. However, some robust trends for the next few decades are evidence in the majority of mitigation pathways consistent with the Paris Agreement. By 2030-3050, forested land is set to increase, while pasture land and cropland decline, enabled by an increase in crop yields, an intensification of livestock production, and shifts in consumption patterns. Meanwhile, bioenergy demand will drive an expansion in land used for second-generation energy crops, even if BECCS is not deployed at scale.

Limiting warming to 1.5°C will require marked reductions in non-CO_2 emissions in the agriculture sector, which can be achieved through enhanced agricultural management (for example, rice paddy water management, manure management, improved livestock feeding practices, and more efficient fertiliser use), as well as through demand side measures such as dietary shifts to healthier, more sustainable diets and measures to reduce food waste. As bioenergy production grows, measures will also be needed to address the potential rise in N_2O emissions.

The agriculture sector is highly vulnerable to climate change in many regions, especially in the tropics, and adaptation measures will be important for ensuring access to sufficient, good quality food. There are good examples of win-win options that have benefits for both adaptation and mitigation, including conservation agriculture, mixed crop-livestock systems and agroforestry as well as more novel concepts involving biotechnology and climate services. The costs, benefits and feasibility of many of these options vary between geographies, and are influence by the demand for different types of food product.

5. Synergies and trade-offs with sustainable development

Strategies consistent with limiting warming to 1.5°C can have multiple benefits for sustainable development, even if we do not consider the benefits from avoided climate-change impacts. In return, pursuing sustainable development goals can facilitate the societal and systems transformations needed to limit warming to 1.5°C, reducing the costs of mitigating climate change.

However, there are a number of different ways to limit warming to 1.5°C, and choices over which portfolio of mitigation options to deploy, at what scale and speed, and how to govern these actions will play a key role in determining how beneficial mitigation can be for other societal goals. Some options come with potential negative side-effects for sustainable development, hence there is a need for careful management to prevent or limit adverse effects.

The SR15 clearly shows that rapidly shifting towards low carbon – in particular renewable - energy, industrial and food systems, and reducing energy demand, would have the most pronounced benefits for sustainable development, provided that mitigation policies are carefully designed to shield vulnerable people.

Some more concrete examples of linkages between mitigation options and the Sustainable Development Goals (SDGs) are given below.

Energy demand

Mitigation options in the energy demand sectors have many potential synergies with the SDGs. The energy efficiency improvements required to limit warming to 1.5°C could facilitate an acceleration in energy access (SDG 7), sustainable cities and infrastructure (SDGs 9, 11 and 12), as well as strengthened collaboration between countries and companies (SDG 17). A shift to a more efficient transport and buildings could reduce water demand (SDGs 6 and 12), and the transition to a circular economy could have benefits for economic growth by reducing the resource needs of industry. In developing countries, a more rapid uptake of efficient cook stoves could lower the incidence of child asthma and thereby reduce school absences (SDGs 3 and 4). However, reductions in energy demand need to be balanced with the need to enhance access to clean and affordable energy, and pro-poor redistributive policies may be necessary to allow both goals to be reached.

Energy supply

A more rapid reduction in fossil fuel use for energy supply would generate substantial air quality benefits, preventing respiratory health problems and premature deaths (SDG 3) and reducing the cost of pollution control. Meanwhile, the rapid deployment of renewable energy can lead to improved energy access in rural regions, providing income-generating opportunities for women (SDG 5) and enabling rural development (SDG 1), as well as encouraging greater levels of community participation in energy-related decisions (SDG 10). In urban areas a shift to low carbon electricity, transport and buildings could result in more sustainable cities and communities (SDG 11), provided that policies are put in place to shield the poor and vulnerable from fuel price increases.

Land-based mitigation options

The impact of land-based mitigation options on sustainable development will depend in large part on the portfolio of options used, the scale and pace of their deployment, and the governance mechanisms in place for preventing potential negative side effects.

Carbon sequestration options that involve ecosystem restoration or land management come with a number of potential benefits. Land management practices such as climate smart agriculture and agroforestry can improve rural livelihoods, increase resilience to climate change, and raise crop yields, thereby contributing to the reduction of poverty and an improved food security and nutrition (SDGs 1, 2 and 3). Forest restoration can conserve biodiversity and reduce erosion (SDG 15), and can provide income generating opportunities for small holders (SDG 8).

Conversely, reforestation or afforestation of arable lands or lands that were not previously forest (e.g. grasslands) could have negative impacts for biodiversity and water security if monocultures or invasive alien species are introduced, and could create challenges for food production or land ownership. Deployment of any land management options at larger scales will require governance mechanisms to prevent negative impacts on water security, nutrient availability, biodiversity, and other land demands.

Bioenergy production, which may or may not be combined with CCS, also has the potential both for positive and negative linkages with sustainable development, its overall effect being largely dependent on how land use is governed. A growing body of research has highlighted the potential constraints for poor and vulnerable populations posed by bioenergy production, if poorly governed. For example, large-scale bioenergy production could increase pressure on water and nutrient resources and lead to competition with efforts to restore and protect natural ecosystems, unless good governance and sound implementation practices are put in place. There is also a risk that large-scale production would change global agricultural markets in a way that disadvantages small-holder farmers.

Conversely, increased demand for bioenergy crops could create agricultural jobs and provide farmers with more diversified income streams, and the use of marginal lands could have benefits for soil and water quality. There is a need for more research into regionally-specific biomass potentials and socio-economic impacts to better understand these potential synergies and trade-offs at the more local level.

6. How to achieve transformational change

Achieving the Paris Agreement Long-term Temperature Goal requires transformative systemic change across the whole economy and society, rather than incremental change in individual sectors. It requires far-reaching multi-level and cross-sectoral climate mitigation actions and integration with sustainable development.

It is critical to achieve the required change at the scale and pace consistent with the Paris Agreement 1.5°C limit. This has important implications for designing short-term mitigation action and policies. This holds in particular for those changes related to infrastructure, buildings and industry installations with long lifetime and institutional or human inertia needs to be considered.

The following sections describe some of the key overarching opportunities and challenges as well as enabling factors identified in the IPCC SR15 that inform the development of LT-LEDS.

Opportunities and challenges

The currently ongoing systemic transformation of energy systems with dramatic cost reductions in particular for solar photovoltaics, wind energy, and storage technologies and related momentum for coupling the electricity sector with other sectors in particular through electric mobility as well as related innovations in local and regional communities presents an important opportunity to scale up action and accelerate the transformation with strong benefits for sustainable development, through avoided air pollution, local employment creating and avoided costs, including through avoided costs of energy imports.

While the challenge here is to support, scale up and accelerate this ongoing innovation and transformation, there are other sectors and aspects of the transformation with some important challenges that need to be addressed through increased research and development and careful assessment of synergies and trade-offs with sustainable development. This relates to the sustainable use and management of biomass for energy and feedstock, the sustainable use of CDR options.

Commercial deployment of existing options to decarbonise a wide range of processes in the industry sector in particular related to non-energy related process emissions, and parts of the transport sectors such as aviation and shipping still face some challenges that need to be addressed through focused research and development and incentives to overcome barriers and inertia. One example is the question whether biofuels or rather synthetically created so-called synfuels based on decarbonised electricity generation are the best solutions for aviation and shipping or to replace fossil-fuel based heating processes in industry.

The sectoral transformations described in the previous section imply a major and timely shift in investment patterns: investment in low-carbon energy technologies and energy efficiency needs to be doubled in the next 20 years, and investment in fossil-fuel extraction and conversion needs to decrease. This represents a major shift in investments, where global annual investments in low-carbon energy technologies overtake fossil investments already by around 2025. There is an opportunity to address presently underinvested assets such as infrastructure and buildings and redirect financial flows in a timely manner to achieve the transformation needed without creating stranded assets.

How to enable the required transformations

It is important to develop policy packages that bring together multiple enabling conditions and provide building blocks for a strategy to scale up implementation and intervention impacts. It is clear that no single solution can enable the necessary global transformation at the scale and pace required. Solutions need to take into account feasibility, potential for synergies, and address trade-offs. These will vary from country to country.

However, there are some robust policy implications highlighted in the IPCCC SR15. Key enabling policies are the removal of socially inefficient fossil fuel subsidies and the implementation of higher effective carbon prices (either through direct carbon pricing or indirectly, for example through regulation) and a complementary mix of policies including technology and performance standards and regulation.

While carbon pricing is an important policy to enable the shift in investments and behaviour needed for a systemic transition, it will need to be complemented with other policies in particular to compensate unintended distributional effects across sectors, and within and across countries. Further instruments are needed to enable the financial architecture and mobilise investors to support the transition, for example de-risking financial instruments and low or zero emissions assets, and mainstreaming climate finance within financial and banking system regulation.

This requires careful planning and strong institutions to drive the necessary technological change and at the same time reduce inequality and alleviate poverty. It also requires stronger coordination and monitoring of policy actions across sectors, actors and levels of governance, and encouraging social innovation and participation of non-state actors from industry, civil society, and scientific institutions can support this. Education and public awareness can also enable accelerated behavioural change.

The IPCC SR15 identifies the need to strengthen institutional capabilities in all countries, including public, private, and financial institutions, and to address social justice and equity for transformational social change. Inclusive processes can facilitate transformations by ensuring participation, transparency, capacity building, and iterative social learning. The IPCC identifies a number of encouraging examples for existing processes and development of joint, iterative planning and transformative visions in urban contexts and in Pacific Small Island Developing States (SIDS).

For developing countries and poor and vulnerable people, all this implies the need for additional financial, technological and other forms of support to build capacity and mobilise resources.

For all countries, knowledge gaps and the opportunities of an iterative learning process imply strengthening research and development as well as developing continuous and iterative monitoring and evaluation systems that enable learning processes and ratcheting up action over time.

7. Implications for national Long-term low carbon development strategies

The findings of the SR15 described in previous sections highlight the need for coherent long-term planning and inform Parties to the Paris Agreement in their task to submit their Long-Term low-emissions sustainable development Strategies (LT-LEDS) by 2020 and at the same time inform the continuous scaling up of near- and mid-term action and targets, including in NDCs, in line with the ratcheting-up mechanism enshrined in the Paris Agreement.

Several of the sectoral 1.5°C-consistent trajectories provide essential guidance for LT-LEDS, in particular:

- **Electricity** – Decarbonising electricity generation implies phasing out coal-fired power globally by 2050 and a rapid increase in the renewable share of electricity generation, building on the rapid decline in costs in particular for solar and wind energy and storage technologies. Natural gas, replacing more carbon-intensive coal, can play a transitional role in decarbonising electricity generation but its continued use would only be consistent with the Paris Agreement temperature goal if it is used with carbon capture and storage (CCS), which is increasingly unlikely to be able to compete with renewable energy due to incomplete capture rates, no observed cost improvements and more limited co-benefits.
- Electrification of rail travel (passenger and freight), heavy-duty vehicles (HDV) for freight, but most especially, for light-duty vehicles (LDV) is key in transport, in parallel with modal shifts (e.g. increases in passenger-trips by public transportation, shifts from freight trucks to rail, more bicycles and walking as part of urban planning). Electrification of LDVs would bring a dramatic increase in efficiency, decrease in emissions, and decrease in operating and maintenance costs for consumers.
- For industry, changing processes through electrification, or use of hydrogen (e.g. direct reduction of iron ore with hydrogen for steel production, or heat generation with electricity) and sustainable bio-based feedstocks for non-electric energy demands or for chemical feedstocks. For some processes, the use of Carbon Capture, (Utilisation) and Storage (CC(U)S) is part of this strategy, in particular where process-related emissions cannot be avoided, such as cement production, but progress has been very slow thus far. Another important strategy is substituting carbon intensive products with other products (e,g, replacing steel or cement with wood or plastic with textile fibres).
- Electrification of and higher efficiency in thermal conditioning of buildings (e.g. heat pumps with an increase in efficiency of a factor of two to three compared to typical present-day systems).
- With far-reaching electrification of sectors, sector coupling becomes essential with a fully decarbonised electricity sector
- Enhanced agricultural management (e.g. rice paddy water management, manure management, improved livestock feeding practices, and more efficient fertiliser use), as well as through demand side measures such as dietary shifts to healthier, more sustainable, low-meat diets and measures to reduce food waste
- Investment in low-carbon energy technologies and energy efficiency needs to be doubled in the next 20 years, and investment in fossil-fuel extraction and conversion needs to decrease. Global annual investments in low-carbon energy technologies overtake fossil investments already by around 2025. There is an opportunity to address presently underinvested assets such as infrastructure and buildings

and redirect financial flows in a timely manner to achieve the transformation needed without creating stranded assets.

Developing a LT-LEDS is an opportunity for countries to address the systemic and transformational change in all economic sectors and integrate these with sustainable development by implementing the following key elements:

Develop strategies and benchmarks for sectoral transformations

- Defining short- and midterm benchmarks consistent with the scale and pace of the required transformation across all sectors, with the SR15 helping to guide priorities and coupling between sectors, to reduce costs and avoid locking in carbon intensive infrastructure and practices;
- Addressing and enhancing synergies with adaptation, and with other objectives and goals, in particular related to sustainable development and goals such as food security and public health, access to clean energy, of alleviation of poverty, reducing impacts on biodiversity;
- Build on and accelerate ongoing transformations, such as the uptake of renewable energy and social innovations towards zero carbon solutions for energy, and urban and transport infrastructure
- Address remaining challenges, closing knowledge gaps and implementing iterative and participative processes, in particular for questions regarding sustainable use and management of biomass, as well as of carbon dioxide removal (CDR), management of land-use change and addressing needs and goal related to food security and biodiversity
    - How much Biomass use is necessary and sustainable? How to manage?
    - How much CDR is necessary and sustainable? How to get it started?
    - How to manage land-use change to address all needs/goals in different country contexts?
    - How to decarbonise carbon-intensive industry sectors and processes?

Robust and inclusive policies to support systemic transformations

- Develop policies in line with robust strategies with multiple benefits:
    - Follow a whole of economy approach, considering opportunities and challenges in each sector
    - Reduce demand and improve efficiency across all sectors, while addressing the need for access to modern services
    - Accelerate the uptake of renewable energy and storage technologies
    - Electrification of end-use sectors – transport, building, industry
- Implement well established robust policies (incl. removing fossil fuel subsidies and implementing effective carbon pricing) and mobilise resources and capacities to ensure timely shifting of investments at scale
- Develop and implement policy packages and management of structural change to address trade-offs and equity and distributional impacts
    - Engage government departments across sectors and levels and enhance institutional strength
    - Engage all actors/stakeholders to enable societal transformation and strengthen contributions
- Implement monitoring and evaluation processes, and engage scientific institutions, to strengthen learning from and improvement of LT-LEDS policy processes, and inform and implement a ratcheting up process as provided by the PA
- For developing countries: Identify the needs for financial, technological and other forms of support to build capacity to mobilise resources

Annex I Background on Paris Agreement long-term temperature goal

The Paris Agreement's long-term temperature goal is a strengthening of the previous goal of holding warming "below 2°C", as agreed in Cancun in 2010. Pathways in the scientific literature, including in IPCC's Fifth Assessment Report (AR5), compatible with the former "below 2°C" goal have a typical peak warming of up to 1.8°C, and have a 66% or higher probability of holding warming during the 21st century below 2°C, but generally less than 50% probability of holding warming below 1.5°C. Given the strengthening of the long-term temperature goal in the Paris Agreement, emissions pathways compatible with the Paris Agreement must increase significantly both the margin and likelihood by which warming is kept below 2°C when compared with these former "below 2°C" emissions pathways, and simultaneously satisfy the 1.5°C limit.

Table I.1 shows data on projected temperature increase and I.2 on emissions, both tables for two categories of pathways from IPCC SR15 consistent with the PA LTTG and two categories of pathways described in the IPCC SR15 that can be related to the former Cancun Agreement's "below 2°C" goal[16]. The two categories we classify as PA consistent here were assessed in SR15 Summary for Policy Makers (SPM) as one single category of "1.5°C with no or limited overshoot". Numbers in the main text of this briefing represent that single overall category.

Table I.1. Selected pathway characteristics from IPCC Special Report on 1.5°C focused on climate-projections. Bold table rows indicate pathways that can inform implementation of the Paris Agreement. Values in this table were taken from Table 2.A.12 in Chapter 2 Annex. Values represent median (25th to 75th percentile) levels across pathways.

SR15 pathway category	Peak warming (°C above PI))	Probability of peak warming <2°C (%)	Probability of warming by 2100 <1.5°C (%)	Probability of warming by 2100 <2°C (%)
No-overshoot 1.5°C ("hold well below 2°C, limit to 1.5°C")[17]	1.5°C (1.4-1.5°C)	95% (93-96%)	84% (76-88%)	97% (94-98%)
Low-overshoot 1.5°C ("hold well below 2°C, limit to 1.5°C")[18]	1.6°C (1.5-1.6°C)	90% (86-93%)	72% (55-83%)	93% (88-96%)
Below 2°C – return to 1.5°C by 2100 ("hold below 2°C")[19]	1.7°C (1.6-1.9°C)	82% (66-89%)	66% (50-80%)	92% (86-96%)
Below 2°C ("hold below 2°C")[20]	1.7°C (1.5-1.8°C)	74% (66-88%)	35% (20-49%)	80% (66-87%)

[16] See Climate Analytics (2018) "How do we limit warming to 1.5°C: informing the Talanoa Dialogue question, "How do we get there?" ", https://unfccc.int/sites/default/files/resource/463_CA_Input_Talanoa_Dialogue_October_2018.pdf
[17] SR15 label is "1.5°C-no-OS"
[18] SR15 label is "1.5°C-low-OS"
[19] SR15 label is "1.5°C-high-OS"
[20] SR15 label is "Lower-2°C"

Table I.2. Selected pathway characteristics from IPCC Special Report on 1.5°C focused on global emissions. Bold table rows indicate pathways that can inform implementation of the Paris Agreement. Note GHG emissions are aggregated with GWP-100 values from IPCC Fourth Assessment Report (AR4). Values in this table were taken from Table 2.4 in Chapter 2, except for GHG emissions (reductions) in 2030 and 2050, which were calculated from the SR15 scenario database https://data.ene.iiasa.ac.at/iamc-1.5c-explorer (accessed 22 October, 2018). Values represent median (25th to 75th percentile) levels across pathways.

SR15 pathway category	Year of peak GHG emissions	CO2 emissions reduction rate 2020-2030 (Absolute annual change in GtCO2/year)	GHG emissions 2030 (% below 2010)	GHG emissions 2050 (% below 2010)	Year of zero GHG	Year of zero CO2	Cumulative CO2 emissions 2016-2100 ($GtCO_2$)
No-overshoot 1.5°C (“hold well below 2°C, limit to 1.5°C”)[21]	**2020**	**-2.5 (-2.8 to -1.8)**	**58% (56 to 69%)**	**94% (92 to 95%)**	**2044 or later**	**2037-2054**	**150 (5 to 260)**
Low-overshoot 1.5°C (“hold well below 2°C, limit to 1.5°C”)[22]	**2020**	**-1.7 (-2.3 to -1.4)**	**41% (37 to 49%)**	**85% (78 to 90%)**	**2061-2080**	**2047-2055**	**260 (-130 to 790)**
Below 2°C – return to 1.5°C by 2100 (“hold below 2°C”)[23]	2020	-1.1 (-1.5 to -0.5)	19% (3 to 28%)	83% (76 to 88%)	2058-2067	2049-2059	340 (-90 to 820)
Below 2°C (“hold below 2°C”)[24]	2020	-1.2 (-1.9 to -0.9)	24% (15 to 35%)	65% (57 to 72%)	2099 or later	2065-2095	880 (190 to 1420)

21 SR15 label is “Below 1.5°C”
22 SR15 label is “1.5°C-low-OS”
23 SR15 label is “1.5°C-high-OS”
24 SR15 label is “Lower-2°C”

Annex 2 List of Acronyms

AFOLU - agriculture, forestry and other land use

AR - Afforestation/Reforestation

AR5 - IPCC's Fifth Assessment Report

BECCS - bio-energy with carbon capture and storage

CC(U)S -carbon capture, (utilisation) and storage

CCS - carbon capture and storage

CDR - carbon dioxide removal

GHG - greenhouse gas

GWP - global warming potential

HDV - heavy-duty vehicles

HFCs - hydro fluorocarbons

HVAC - heating, ventilation and air-conditioning

IAMs - integrated assessment models

IPCC - Intergovernmental Panel on Climate Change

LDV -light-duty vehicles

LT-LEDS - long-term low-emissions sustainable development strategies

LTTG - long-term temperature goal

NDC - nationally determined contribution

PA - Paris Agreement

SDGs - sustainable development goals

SIDS - Small Island Developing States

SPM - summary for policy makers

SR15 - IPCC Special Report on 1.5°C

UNFCCC - United Nations Framework Convention on Climate Change