Opportunities for Enhanced Action to Keep Paris Goals in Reach

Contribution to the Talanoa Dialogue by the COMMIT and CD-LINKS projects

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About COMMIT:

The COMMIT project, Climate pOlicy assessment and Mitigation Modeling to Integrate national and global Transition pathways, aims to improve modelling of national low-carbon emission pathways, and to improve analysis of country contributions to the global ambition of the Paris Agreement. The consortium consists of 18 international research teams, including 14 national modelling teams in G20 countries, who regularly support domestic policy-making, and global integrated assessment modelling teams with extensive experience on global-scale modelling of climate change policies. The project is financed by the European Commission's Directorate-General for Climate Action (DG CLIMATE).

More info on: www.pbl.nl/commit-project

See also the country fact sheets: *Long-term, Low-Emission Pathways in Brazil, Canada, EU, India and Japan - Contribution to the Talanoa Dialogue by the COMMIT project*

About CD-LINKS:

The CD-LINKS research, *Linking Climate and Development Policies – Leveraging International Networks and Knowledge Sharing*, brings together a consortium of 19 leading international research organisations to explore national and global climate transformation strategies and their linkages to a range of SDGs. The project is financed by the European Commission's Horizon 2020 programme.

More info on: www.cd-links.org

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Executive summary

Where are we?

Current climate policies are inconsistent with the objectives of the Paris Agreement. The Paris Agreement's objectives to hold the increase of global mean temperature to well below 2 °C relative to pre-industrial levels and pursue efforts to limit warming to even 1.5 °C, requires a rapid reduction of greenhouse gas emissions world-wide. Currently implemented climate and energy policies, however, imply that emissions are still expected to rise in many G20 countries. In fact, in nearly all countries projected emissions by 2030 do not meet national mitigation pledges submitted under the Paris Agreement as part of the Nationally Determined Contributions (NDCs).

The NDCs are projected to lead to global greenhouse gas emissions in the range of 52-58 GtCO$_2$-eq by 2030. These emissions levels would very likely lead to more than 1.5 °C warming by mid-century.

The differences between current policies trends and the emissions levels consistent with the Paris Agreement amount, at the global level, to an 'emissions gap' from NDCs of approximately 15 and 22 GtCO$_2$-eq by 2030 for well below 2 °C and 1.5 °C respectively. This consists of an 'implementation gap' (current policies do not meet the NDCs) and an 'ambition gap' (the emissions reduction resulting from the NDCs is not sufficient to meet the Paris Agreement's long-term goals). It will be necessary to take action in the short-term to keep the Paris objectives within reach.

The current gaps go beyond emissions. The gap between current policies and what is needed for the Paris objectives can be seen in many different dimensions, including investments, introduction of renewable energy sources, and efficiency improvements. In order to meet these targets, it will be necessary to rapidly scale up the use of emissions-free energy technologies, increase energy efficiency, reduce emissions of non-CO$_2$ greenhouse gases and change land-use trends.

Not ratcheting up ambition for 2030 would require an even faster pace of decarbonisation after 2030, and/or the deployment of larger amounts of carbon dioxide removal (CDR) technologies in the long term to still meet the Paris temperature targets by the end of the century after a significant overshoot. More rapid emission reduction after 2030 is associated with higher transitional and long-term economic costs. Moreover, CDR is often associated with higher technological, ecological, social and climate risks.

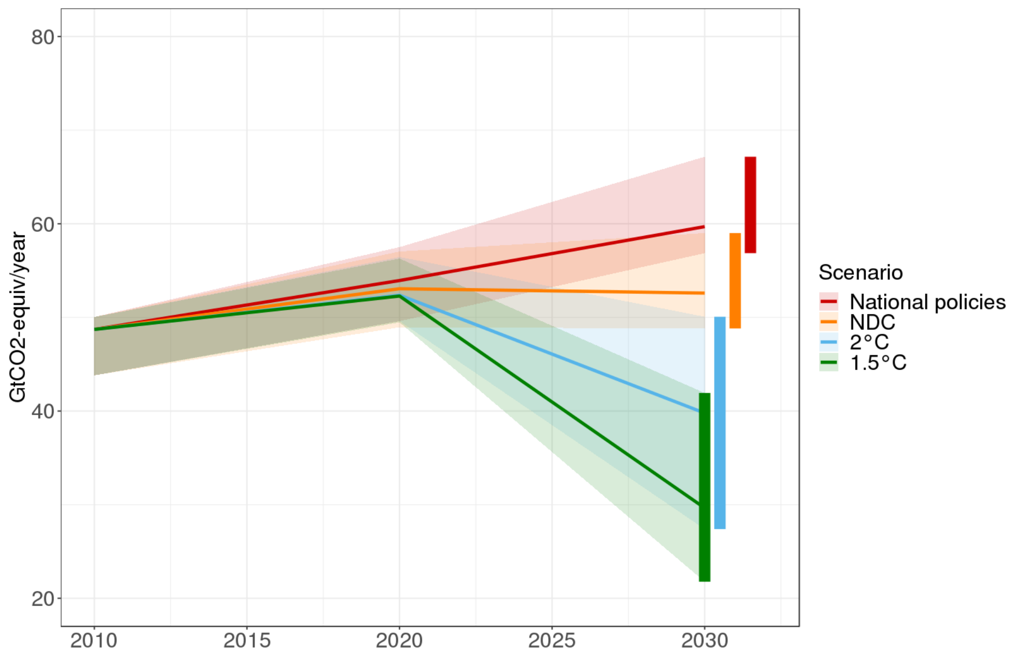


Figure ES.1: Global greenhouse gas emission pathways that limit global warming to well below 2 °C (global carbon budget 1000 GtCO₂ over 2010-2100) and 1.5 °C (global carbon budget 400 GtCO₂), starting cost-optimal mitigation in 2020, versus full implementation of conditional NDCs and current national policies trajectories. Figure source: Roelfsema et al. (submitted)

Where do we want to go?

Scenarios limiting global warming to well below 2 °C or 1.5 °C project global emissions peaking by 2020, and declining rapidly afterwards to reach net zero CO_2 emissions between 2070 and 2090 (2 °C) or between 2040 and 2060 (1.5 °C). In the second half of the century, sustained net negative emissions may be needed, but its scale and nature depends on progress in other areas such as energy demand reduction, expansion of renewable energy, efficiency improvement and anthropogenic enhancement of carbon storage on land. The energy sector is a main contributor to emission reductions through electrification and replacing fossil fuels with renewable and other low-carbon energy sources. Sustainable land use management is critical to bring land use CO_2 emissions to net zero and eventually use the land to remove CO_2 from the atmosphere by, e.g., afforestation, soil carbon enhancement and natural land restoration.

It is important to have a near-zero emissions vision as orientation for long-term planning, both for individual regional entities such as countries, regions or even cities, and for individual sectors. It is clear that the Paris Climate targets require CO_2 emissions to go to zero in the next couple of decades. This is a massive challenge that requires planning and a redirection of policies in all sectors already now. Having a clear long-term vision might help to gear such redirection. So far, only a few front-runner countries have formulated decarbonisation targets and there still are methodological questions.

A cost-optimal carbon neutral global energy system might still imply that certain sectors or countries have residual CO_2 emissions that are compensated by net negative CO_2 emissions elsewhere. Net negative CO_2 emissions, however, can be associated with several risks. Most techniques and processes that can lead to negative emissions are associated with risks including for land use, possibly high costs and uncertainties with respect to storage capacity. As a result, the potential for sustainable use of net negative emissions is limited. Some studies have looked into the question how to minimise the use of negative emissions. This is possible, although it seems not likely that very stringent targets can be reached without negative emissions.

Climate policies need to be integrated with broader sustainable development policies. In addition to the Paris Agreement's climate goals, the UN Agenda 2030 established 17 Sustainable Development Goals (SDGs). To maximise the synergies between these global agendas, ambitious yet carefully designed climate policy is needed. Other sustainability dimensions can therefore pose additional constraints on future net-zero energy and land-use systems. Alternative scenarios show that the scale of carbon dioxide removal can be significantly reduced if a number of other mitigation options are dramatically scaled up. Major changes on the energy and food demand side offer the biggest lever for reducing the need for the deployment of carbon dioxide removal on the supply side. Importantly, these scenarios characterised by high energy efficiency and limited use of CDR technologies imply co-benefits for multiple sustainable development goals.

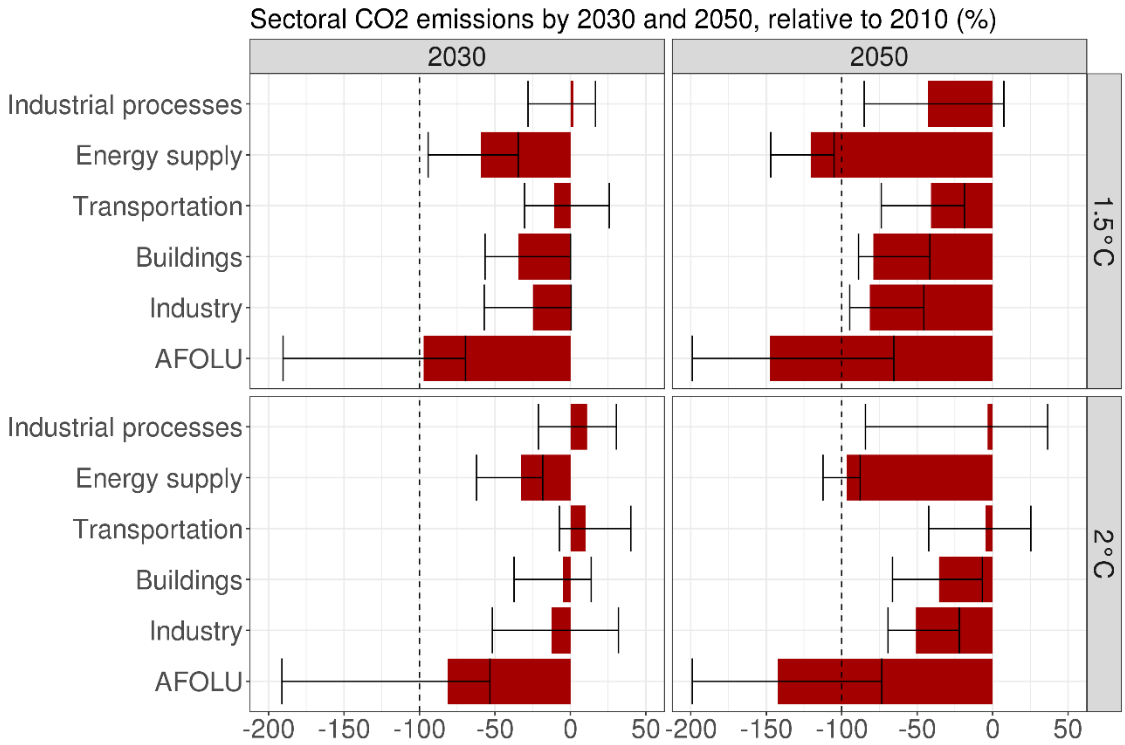


Figure ES.2: CO_2 emissions (%) by 2030 and 2050, relative to 2010, per sector. Red bars: model median, error bars: 10th - 90th percentile range (note that the axis is cut off at -200%, while the error bar for AFOLU in 2050 reaches -266% in 2 °C and -292% in 1.5 °C). Values left from the dashed vertical line at -100% imply net negative emissions, while values to the right indicate residual emissions. Emissions from 'Industrial processes' correspond to IPCC categories 2A, B, C, E, while emissions from 'Industry' relate to fuel combustion in industry (IPCC category 1A2). Based on CD-LINKS database (McCollum et al., 2018)

How do we get there?

Analysis shows that there are several opportunities to strengthen current climate policies. We identified emission reduction pathways at the global but also at the national level that are consistent with the Paris Agreement. Although these policies will require a massive redirection of current trends, they are feasible from a technical and economic perspective.

If all countries were to implement sectoral climate policies similar to successful examples as observed in some countries (good practice policies), annual GHG emission levels could reach approximately 50 $GtCO_2e$ by 2030, compared to 60 $GtCO_2e$ in the current policies scenario. Three examples of successful policies that can be replicated elsewhere and with potentially large benefits include: the German feed-in tariff for renewable energy, the carbon tax in Norway to reduce flaring and venting, and the Action Plan for Deforestation in Brazil.

The massive transformation of global energy, industry, and land-use systems required to achieve the 1.5 and well below 2 °C global warming goals depends critically on policies that incentivise changes in investment patterns, technology uptake and household/business and community behaviour. In both the 2 °C and 1.5 °C cases, the GHG emission peak in 2020 is followed by a steep emissions reduction. This is initially realised by a rapid decarbonisation of the power sector, spearheaded by a phase-out of unabated coal power plants (i.e., those not equipped with carbon capture and storage: CCS). As a result, near-carbon neutrality of the power sector is expected to be reached around 2050. Energy demand-side emissions reduction efforts can be broadly categorised into energy demand savings, replacing combustible fuels by electricity or hydrogen, and moving toward very low carbon intensities of these advanced energy carriers. To compensate for the residual greenhouse gas emissions in the demand sectors, most scenario studies point to the need for large scale carbon dioxide removal (CDR) in the second half of the century. This is true for the 2 °C case, but even more so in the 1.5 °C scenario.

The 2 °C and 1.5 °C pathways exhibit a shift from fossil (especially coal) to low-carbon and energy efficiency investments. Policies promoting deep decarbonisation through a global energy system transformation would require an increase in total energy system investments, but above all a redirection of already planned investments. The low-carbon and energy efficiency investment gap in 2030 is projected to be 130 billion US$/year for NDCs, 300 billion US$/year for 2 °C and 460 billion US$/year for 1.5 °C. The world's largest economies have already agreed that spurring low-carbon energy investments should be placed high on their collective priority list and G20 countries have reemphasised the previously agreed commitment of wealthy countries to jointly mobilise 100 billion $/year (during the period 2020-2025) for mitigation actions in developing countries. This would go a long way toward fulfilling the NDC commitments; however, it would not nearly close the investment gap for a 2 °C- or 1.5 °C-consistent future.

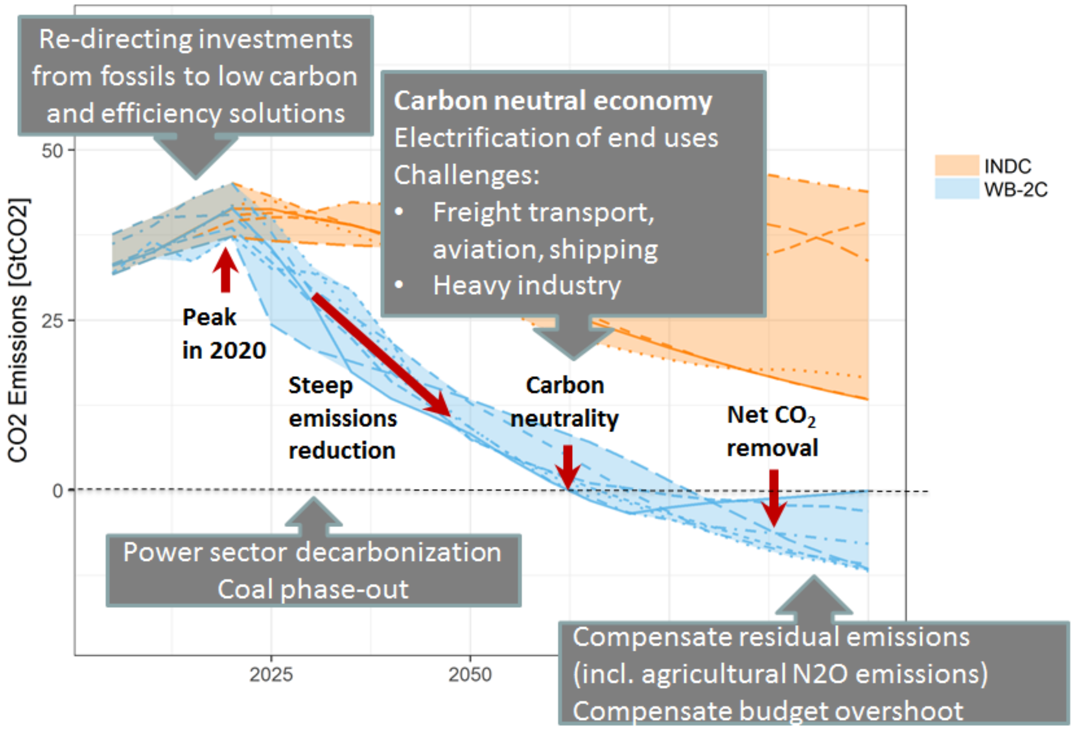


Figure ES.3: Key characteristics of decarbonisation pathways, based on Luderer et al. (2018). WB-2C: well below 2 °C scenario. 'Coal phase-out' refers to phase-out of conventional coal (without CCS). 'Residual emissions' refer to long-lived GHG emissions.

Chapter 1: Where do we want to go?

Paris Agreement requires rapid reduction of global greenhouse gas emissions

Scenarios consistent with the targets of the Paris Agreement show rapid reductions of global emissions. In the Paris Agreement, governments worldwide agreed on global goals to limit global warming to well below 2 °C and possibly 1.5 °C above pre-industrial levels (Article 2). Article 4 sets a goal to peak global greenhouse gas (GHG) emissions as soon as possible and to achieve a balance between anthropogenic emission sources and removals by sinks of GHGs in the second half of the century. Scenarios developed with Integrated Assessment Models (IAMs)[1] show possible pathways towards these goals, based on various assumptions. Figure 1 shows global cost-optimal greenhouse gas emissions under scenarios that limit global warming to well below 2 °C and 1.5 °C with a likely chance[2] starting from 2020.

Most cost-optimal scenarios consistent with targets of the Paris Agreement rely on carbon dioxide removal in the second half of the century. Cost-optimal scenarios reduce emissions where and when it is cheapest to do so, thereby minimising global mitigation costs. Net negative emissions in the second half of the century are attractive to minimise costs. However, there are also important limitations to the use of carbon dioxide removal technologies, including risks related to land use, possibly high costs and uncertainties with respect to storage capacity. Scenarios that use less or even no net negative emissions also exist. These scenarios assume a combination of larger energy efficiency in demand sectors, more rapid electrification of energy end-use sectors based on renewable energy, lifestyle changes, and additional reduction of non-CO_2 greenhouse gas emissions.

[1] The findings presented in this policy brief are largely based on work done under the CD-LINKS (Linking Climate and Development Policies – Leveraging International Networks and Knowledge Sharing) and COMMIT (Climate pOlicy assessment and Mitigation Modeling to Integrate national and global Transition pathways) projects, financed by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 642147 (CD-LINKS) and by the European Union's DG CLIMA and EuropeAid under grant agreement No. 21020701/2017/770447/SER/CLIMA.C.1 EuropeAid/138417/DH/SER/MulitOC (COMMIT).

[2] The two classes of mitigation pathways presented in this policy brief were designed to (a) hold global warming below 2 °C with a two-in-three chance throughout the 21st century and (b) returning global warming to 1.5 °C by the end of the century with a one-in-two chance after a temporary overshoot of 1.5 °C. The degree of overshoot will depend on whether cost-effective mitigation action is adopted in 2020 or only in 2030. More recent insights on carbon budgets, given the IPCC's special report on 1.5 °C, might mean a higher probability of meeting the temperature targets can be assigned to these pathways.

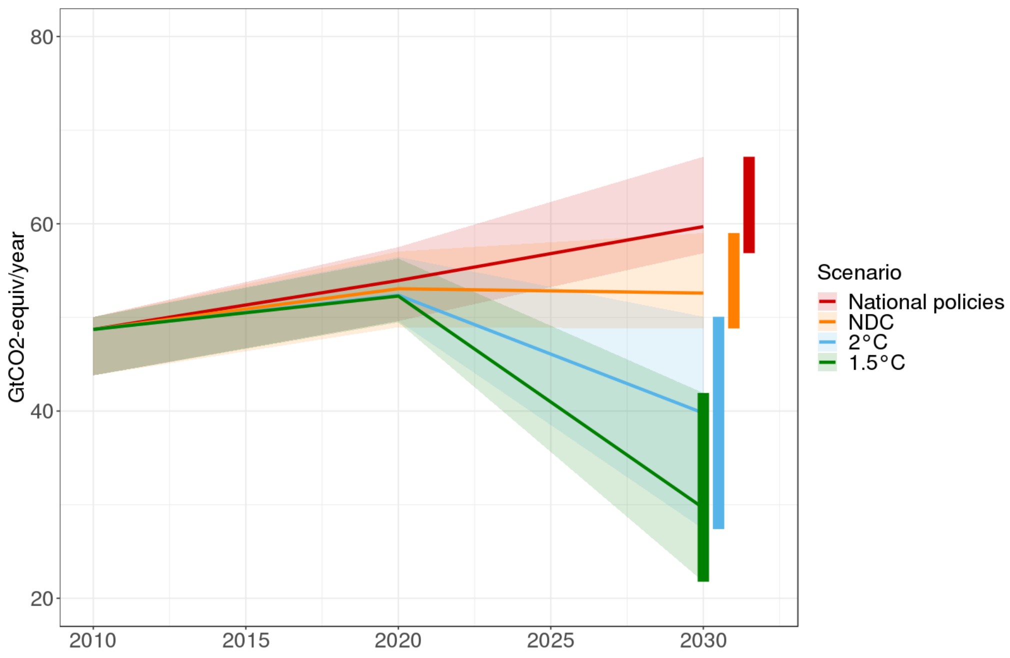


Figure 1: Global greenhouse gas emission pathways that limit global warming to well below 2 °C (global carbon budget 1000 $GtCO_2$ over 2010-2100) and 1.5 °C (global carbon budget 400 $GtCO_2$), starting cost-optimal mitigation in 2020, versus full implementation of conditional NDCs and current national policies trajectories. Figure source: Roelfsema et al. (submitted)

Operational targets: emission reductions, peak years, and phase-out years

Cost-optimal scenarios have been developed using global and national models. These show significant emission reductions for all regions. Cost-optimal 2 °C scenarios show median GHG emission reductions of 16% by 2030 and 65% by 2050 for China, 33% by 2030 and 66% by 2050 for the EU, 37% by 2030 and 75% by 2050 for the USA, and an increase of 10% by 2030 followed by a reduction of 51% by 2050 for India, relative to 2010 and including LULUCF emissions. For the 5 aggregated regions, emission reductions by 2030 are projected to be 11% for Asia, 30% for Latin America, 10% for Middle East and Africa, 35% for OECD90+EU and 25% for reforming economies. Achieving the aspirational 1.5 °C target would require a further acceleration of GHG emission reductions for all countries. Various studies have calculated emission allowances by applying different equity principles to global emissions pathways consistent with achieving 2 °C or 1.5 °C. These studies show larger reductions targets for OECD countries.

There are important differences between long-term emissions reductions among the various regions in global models, among others based on reduction potential. As global greenhouse gas emissions need to reach net zero in the second half of the century, either all countries would need to reach net zero emissions, or, more likely, some countries with larger emission reduction potential compensate for others with smaller reduction potential. In model-based projections, this is generally the case. Their cost-optimal scenarios limiting global warming to 2 °C show that many countries are projected to peak emissions by 2020 (noting some have already peaked, such as the EU and Russia), after which first CO_2 and then total greenhouse gas emissions are projected to be phased out: by 2050 for CO_2 and 2060 for total GHG emissions at the earliest. Brazil, Latin America, and the USA are projected to reach net zero greenhouse gas emissions earlier than the global average, due to relatively large potential for carbon dioxide removal (e.g. from biomass with CCS). Regions with larger shares of non-CO_2 emissions or less potential to deploy carbon dioxide removal generally need more time to reach net zero greenhouse gas emissions.

There are many open questions with respect to country-level targets corresponding to the Paris goals. Critical questions that define the ambition at the global scale include the overall target, the ambition with respect to the likelihood of achieving the target and the choice with respect to the use of carbon dioxide removal. At the national scale, also the distribution of commitment among countries plays an important role. Finally, also the allocation and accounting rules matter when looking at regional phase-out years. In models, carbon dioxide removal by biomass with carbon capture and storage (BECCS) is assigned to the region applying BECCS, i.e. at the power plant. Alternatively, carbon dioxide removal by BECCS could be assigned to the region producing biomass for energy use and exporting it (such as Brazil). Still, for most countries it can be assumed that the Paris objectives would require reaching net zero CO_2 emissions in the next few decades.

In some sectors, reaching zero emissions is relatively difficult. In the scenarios some sectors never reach net zero, while other sectors compensate for these remaining emissions by phasing out greenhouse gas emissions by 2050 and maintaining net negative emissions thereafter (Figure 2). The sectors that are relatively hard to abate include non-CO_2 emissions from agriculture, freight and air transport and specific industry sectors such as steel and cement.

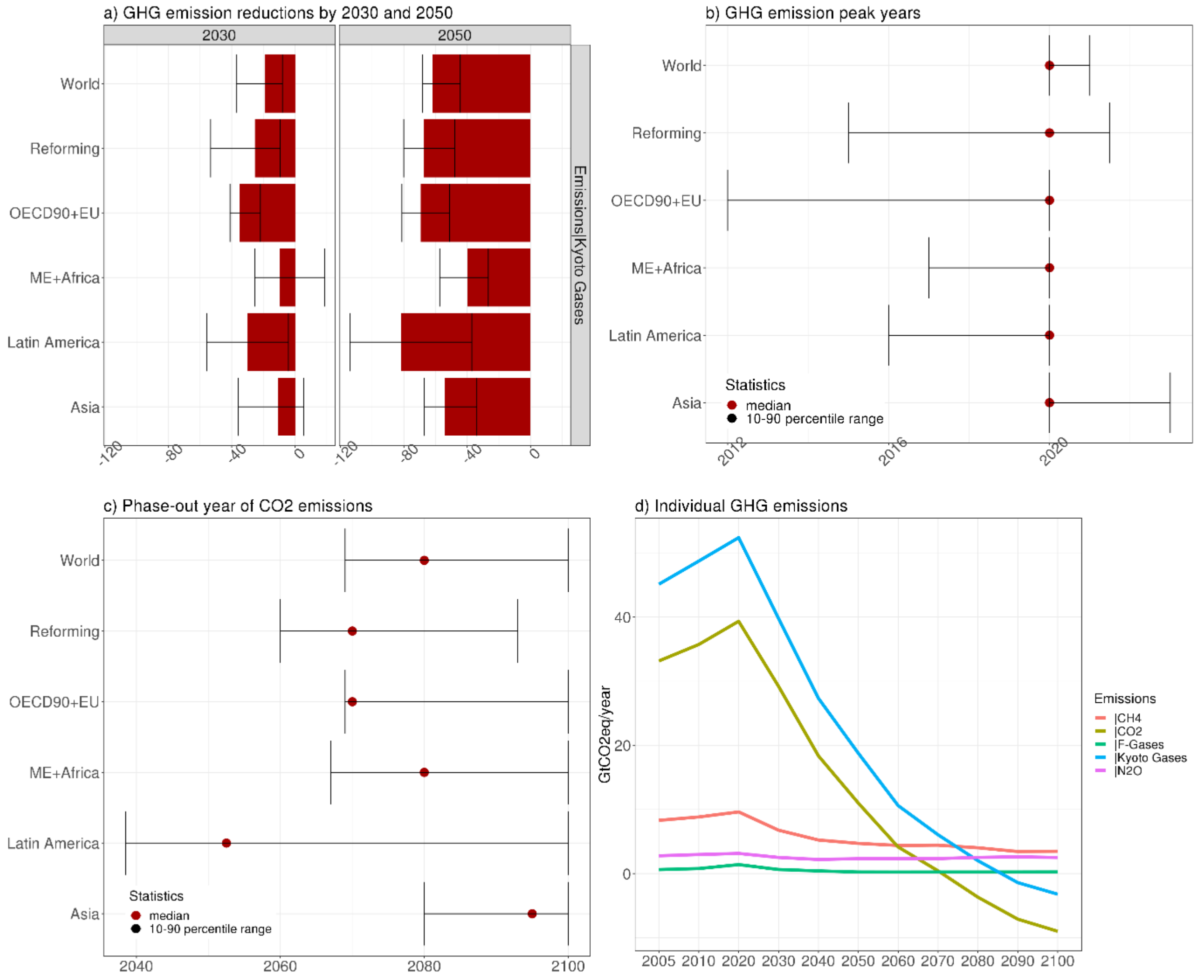
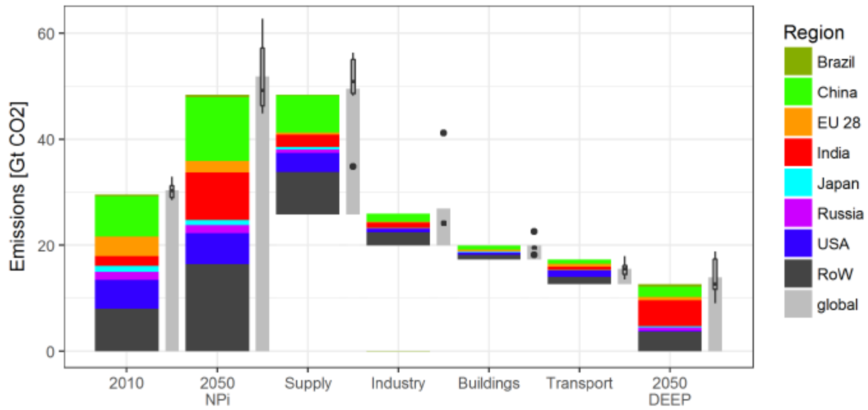
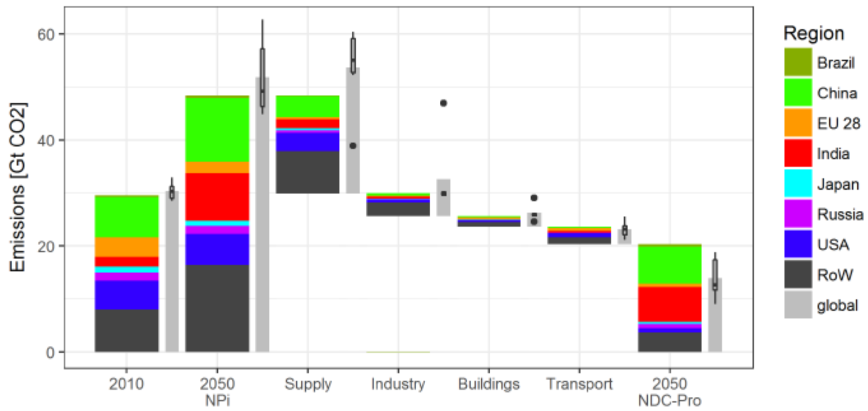


Figure 2: Three indicators for possible country-level operational targets under 2 °C scenarios starting cost-optimal mitigation in 2020 (red bars and circles: model median, error bars: 10th - 90th percentile range). a) Greenhouse gas emission reductions by 2030 and 2050, relative to 2010, b) greenhouse gas emissions peak years, c) phase-out years (CO_2 emissions reaching net zero). Aggregated regions shown are reforming economies of the former Soviet Union, OECD (1990) + EU, Middle East + Africa, Latin America and Caribbean, and Asia. Panel d) further shows the contribution of net negative emissions (yellow line) to reaching net zero greenhouse gas emissions (blue line), globally. Source: CD-LINKS database, McCollum et al., 2018.

Energy supply sector could be a major contributor to emission reductions

In cost-optimal mitigation scenarios[3], the energy supply sector and in particular electricity generation is projected to be the largest contributor to greenhouse gas emission reductions, with a near complete decarbonisation by 2050. Figure 3 shows emission reductions per sector. The model calculations identify low-cost potential to mitigate greenhouse gas emissions in all countries, with the largest contribution in absolute terms coming from China, the US and India. The largest contribution comes from the energy sector (mostly electricity production): here, many options exist to reduce emissions at relatively low costs. The industry and transportation sector also have potential for further emission reductions, with accelerated electrification and a more limited reduction of carbon intensity of fuel use. The buildings sector offers more limited potential for further decarbonisation until 2050. Regional differences in mitigation potential arise from differences in the development stage, existing differences in energy systems and economic structure, differences in energy resource potentials (renewable and fossil energy resources), and existing expertise and specialisation.





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[3] These scenarios were developed in the CD-LINKS project, with both global and national models. Country-specific carbon budgets were determined in an iterative dialogue between national and global modeling teams, taking into account regional budget estimates from global cost-effective 2 °C pathways (assuming that emissions reductions after 2020 are made where they are cheapest), as well as national objectives and capabilities for implementing mid-century emissions strategies.

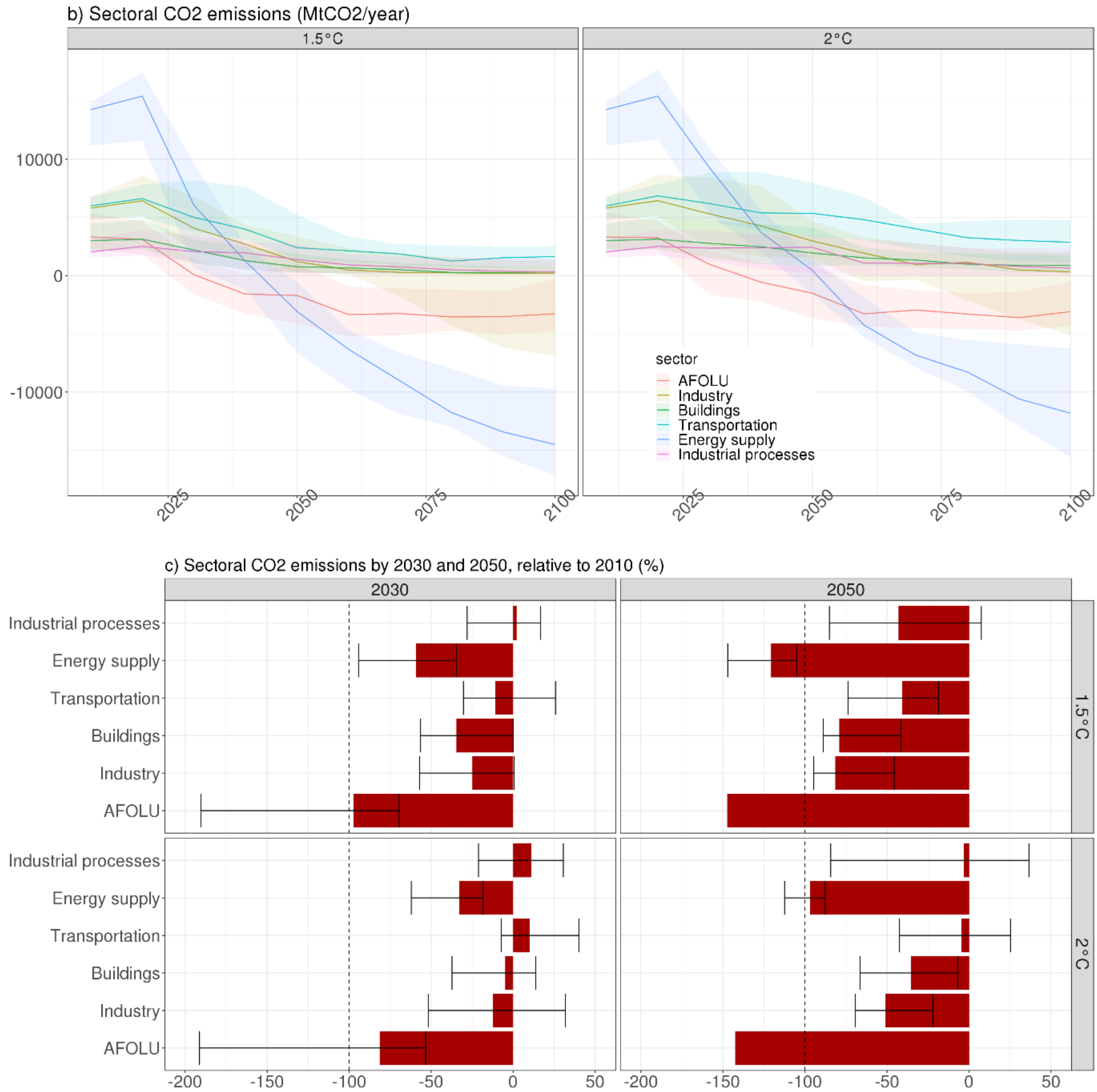

Figure 3: a) CO_2 emissions in 2010, by 2050 under current policies, and by 2050 under a 2 °C scenario starting cost-optimal mitigation in 2020 (following current policies until 2020, upper panel) or 2030 (following NDCs until 2030, lower panel). Elements in between the second and last bar show sectoral contributions to emission reductions (energy supply, industry, residential and commercial buildings, and transportation), also broken down by region. The coloured bars represent the results from national models (with the exception of ROW), while the grey bars and box-plots show the aggregate results of scenarios from global models, illustrating the high level of compatibility between the national deep decarbonisation scenarios with strengthening before 2030 and a global 2 °C trajectory. Figure source: Kriegler et al. (under review). b) Sectoral CO_2 emissions over time in 1.5 and well below 2 °C scenarios (median and 10-90th percentile range), c) CO_2 emission (%) by 2030 and 2050, relative to 2010, per sector. Note that the axis is cut off at -200%, while the error bar for AFOLU in 2050 reaches -266% in 2 °C and -292% in 1.5 °C. Values left from the dashed vertical line at -100% imply net negative emissions, while values to the right indicate residual emissions. Emissions from 'Industrial processes' correspond to IPCC categories 2A, B, C, E, while emissions from 'Industry' relate to fuel combustion in industry (IPCC category 1A2).

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Chapter 2: Where are we going?

Implementation and ambition gaps

There is a significant gap between the aggregate effect of current policies and Nationally Determined Contributions (NDCs) and the ambition of the Paris Agreement. This gap (based on cost-optimal scenarios towards the Paris Agreement's targets) is about 15-20 GtCO_2-eq in 2030. The gap between the NDCs and the cost-optimal pathways is sometimes referred to as the ambition gap. As result, the total required additional emissions reductions amount to 15.3 GtCO_2eq for well below 2 °C and to 21.9 GtCO_2eq for 1.5 °C in 2030 (Roelfsema et al., submitted).

Currently implemented policies are insufficient to reach the level of the NDCs. In many G20 countries, emission reductions by 2030 under current policies fall short of NDC targets, the 'implementation gap'. The difference between the aggregate effect of current policies and the targets formulated in the Nationally Determined Contributions is about 7.7 GtCO_2eq in 2030. Global greenhouse gas emissions would need to be reduced much more quickly and deeply in order to meet the long-term targets than currently included in national policies. The results of integrated assessment models can be used to explore such emission trajectories.

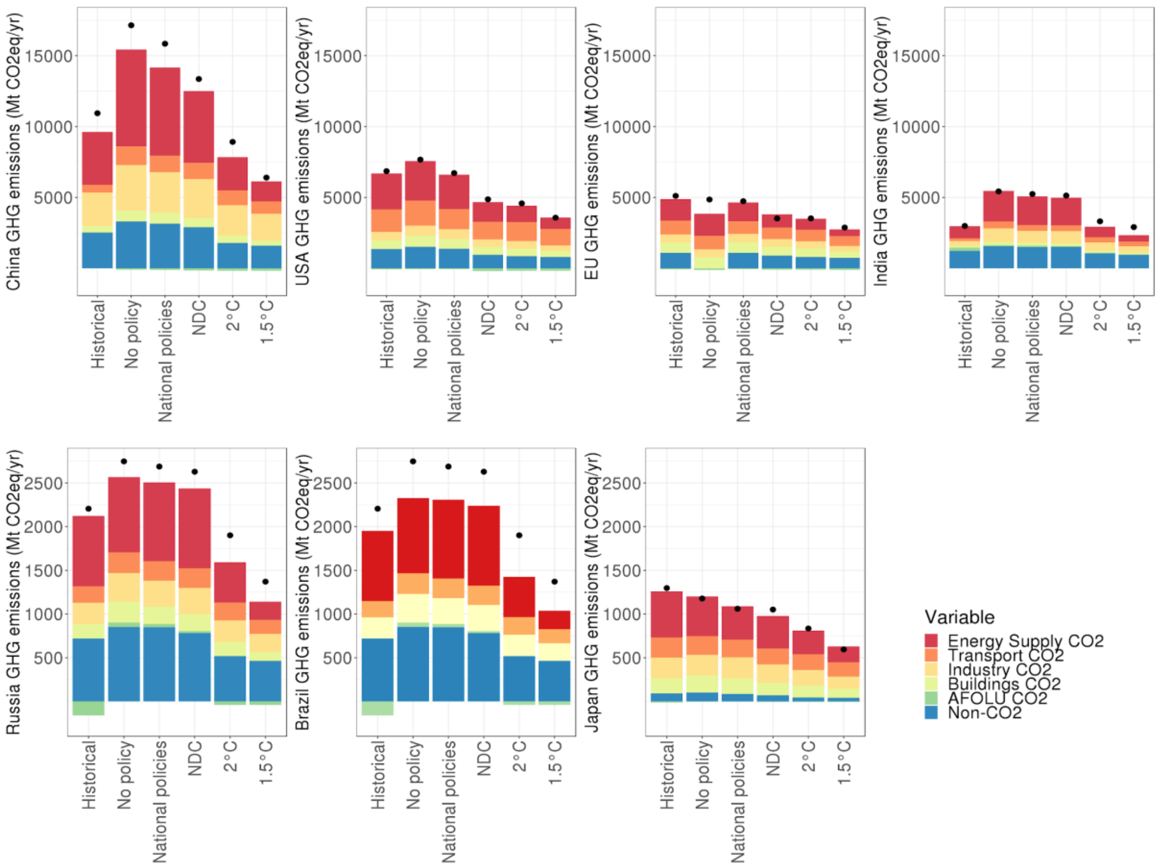
In contrast to cost-optimal scenarios, based on currently implemented climate and energy policies[4], emissions are projected to rise in many G20 countries. The exceptions to this observation are the EU and Japan, which show declining emissions under current policies. Energy-related CO_2 emissions are the main contributors to total greenhouse gas emissions in many countries, with Brazil being a notable exception (with high AFOLU[5] and non-CO_2 emissions). Current policies scenarios show increasing emissions from energy supply, except in Australia, the EU, China (after 2050), Japan, and Russia (second half of the century). Of the G20 countries, only Japan shows declining demand sector CO_2 emissions (industry, transportation and residential and commercial buildings) under current policies, consistently across models. CO_2 emissions from land-use change are projected to decline in almost all G20 countries under current policies. Under current policies, CH_4 emissions are projected to rise in most G20 countries. N_2O emissions are projected to decline in the EU and Japan, in current policies scenarios. Finally halogenated greenhouse gases are projected to rise in most G20 countries, except Japan, Russia, Republic of Korea, China, and the EU (according to some models).

Gaps go beyond emissions. Based on the model output, it is possible to show where current policies are insufficient. For instance, the share of renewable energy sources in the power generation mix will need to increase (figure 4b). China, EU, India, Japan, Russia and USA all have potential to scale up renewable energy deployment according to the models, with USA projected to reach 95% low-carbon energy by 2050, EU 85% and Japan 70%. India and OECD countries are leading in scaling up solar and wind power, while China and Russia lead in scaling up nuclear power. Ratcheting up of short-term ambitions in different policy areas is necessary to keep the Paris climate goals in reach.

[4] An inventory is available from http://www.climatepolicydatabase.org/index.php/CDlinks_policy_inventory. These policies were implemented in the integrated assessment models participating in the CD-LINKS project, to create the current policies scenario.

[5] Agriculture, Forestry and Other Land Uses

a) National greenhouse gas emissions by 2030, per sector



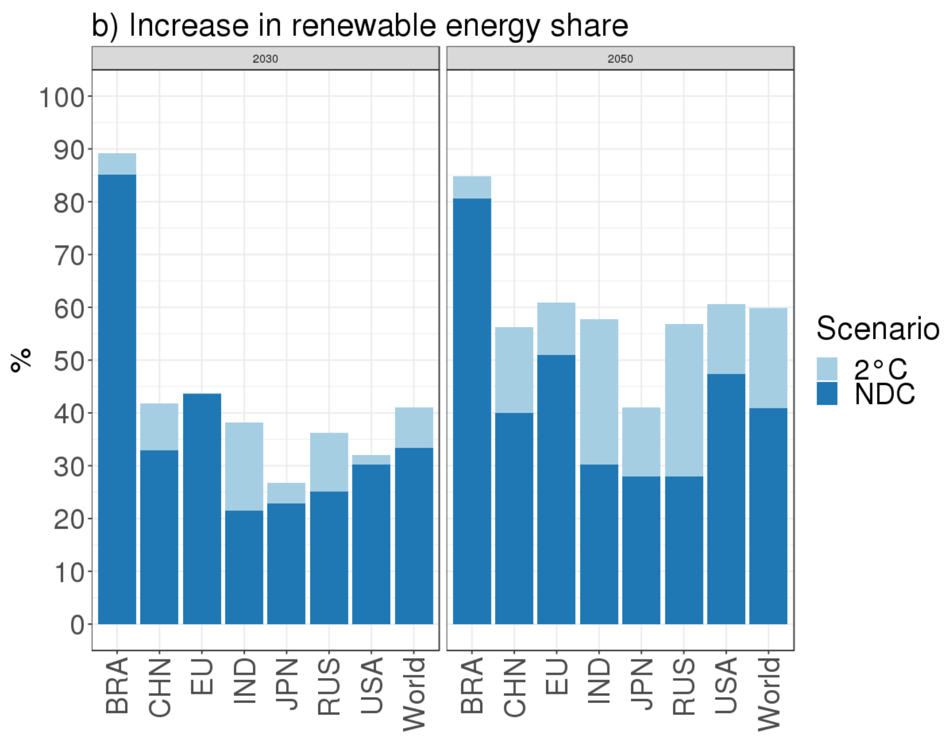
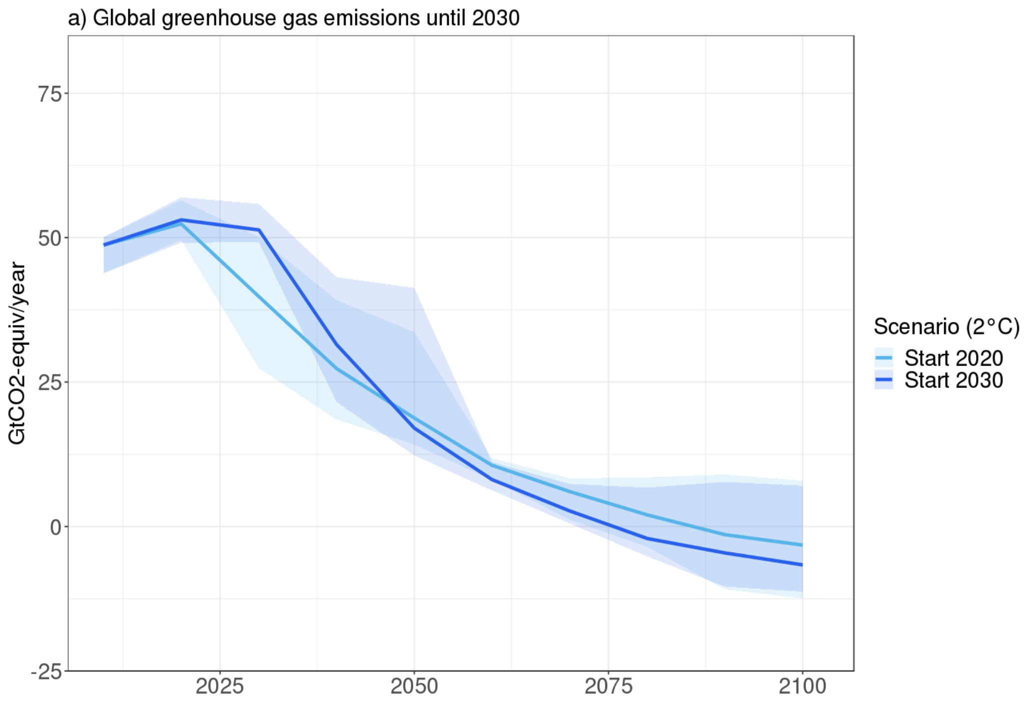


Figure 4: Gaps: Current policies to NDCs and NDCs to Paris, in terms of global emissions (see figure 1), regional and sectoral emissions (panel a, dots show total Kyoto GHG emissions), and renewable electricity share (panel b). Renewables include hydropower, biomass, geothermal, solar and wind. In panel c, the 2 °C bar shows the increase from the NDC scenario to the 2 °C scenario.

Benefits of early action and risks of delayed action

Enhancing NDC ambition and starting stringent mitigation before 2030 would make it possible to meet the Paris objectives while creating co-benefits and reducing the dependence on carbon dioxide removal. When comparing scenarios that start globally cost-optimal mitigation in 2020 (following current policies until then) to scenarios that do so in 2030 (following NDCs until then), the benefits of early action become visible (Figure 5). Delaying the peaking of global emissions until 2030 drastically increases mitigation challenges, in terms of technology upscaling requirements, stranded assets, medium to long-term clean energy investments and mitigation costs for climate stabilisation, requirement for large-scale deployment of CDR, and even the achievability of the 1.5 °C limit (Kriegler et al. 2018).



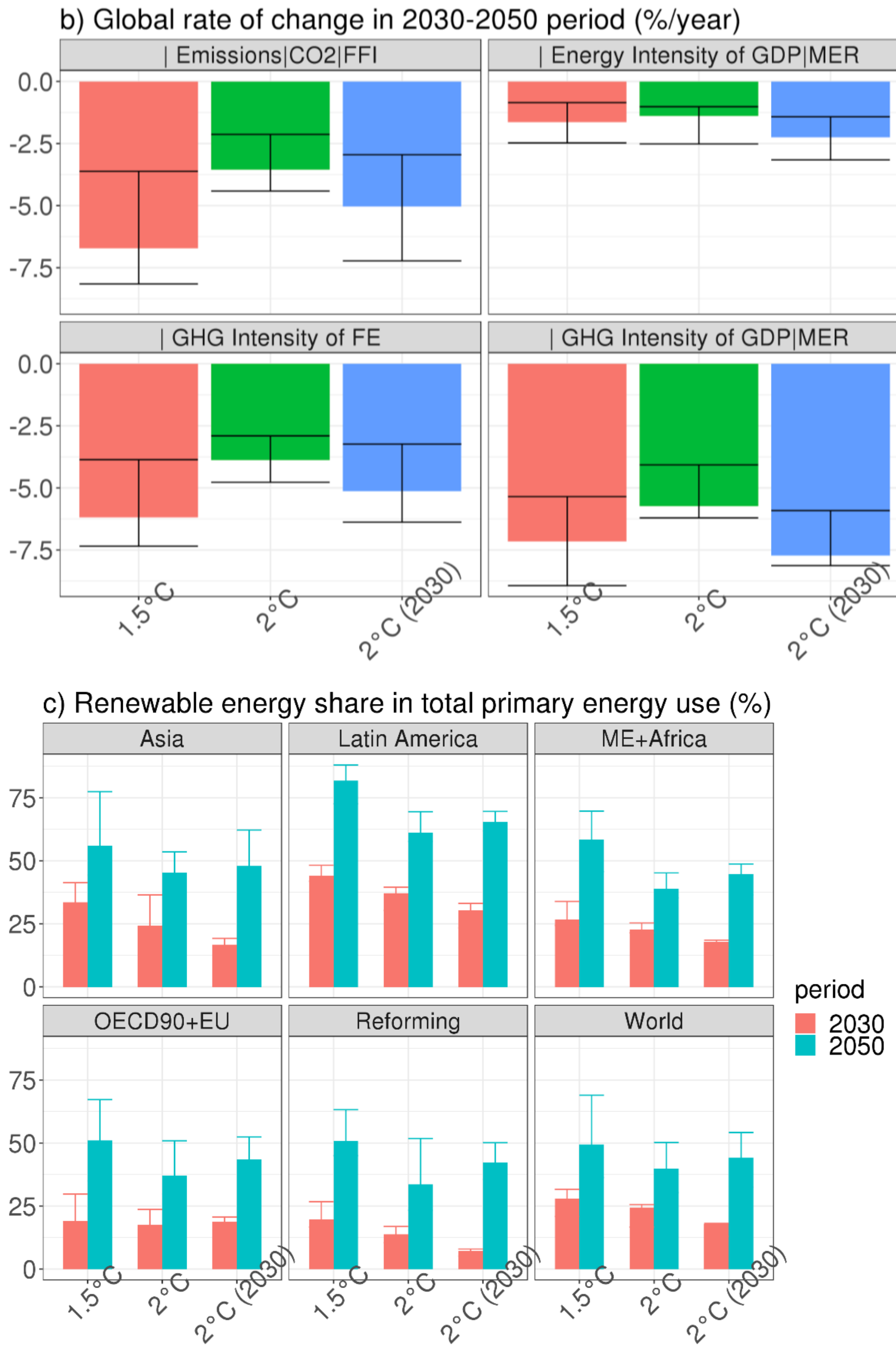


Figure 5: 2 °C (2030) vs 2 °C (2020) (start year of cost-optimal mitigation) emissions trajectories (panel a) and implications: rate of change (%/year over 2030-2050 period) in CO_2 emissions from energy and industrial processes (FFI), final energy (FE) intensity of GDP, GHG intensity of final energy, and GHG intensity of GDP (panel b), and regional renewable energy share in total primary energy supply by 2030 and 2050 (panel c). In panel b, MER stands for Market Exchange Rates.

Scenario analysis can show the possible emission reduction pathways towards implementing the Paris Agreement, showing the choices between net negative emissions and the 2030-2050 emission reduction rate. Figure 6 shows that more ambitious near term mitigation, for example by strengthening the aggregate effect of NDCs by 20%, significantly decreases the need for carbon dioxide removal (CDR) technologies to keep the Paris climate targets within reach. In contrast, following the NDCs until 2030 means CDR will need to be deployed extensively to limit global warming to 2 °C. Not ratcheting up ambition implies either a faster decarbonisation after 2030, which is associated with higher transitional and long-term economic costs, or the deployment of larger amounts of CDR associated with higher technological, ecological, social and climate risks (Strefler et al. 2018). In addition, not strengthening NDCs runs the risk of carbon-lock in and stranded assets in carbon-intensive infrastructure, with additional future emissions and a decrease in mitigation potentials in the longer term, and could push the 1.5 °C target out of reach (Luderer et al., 2018).

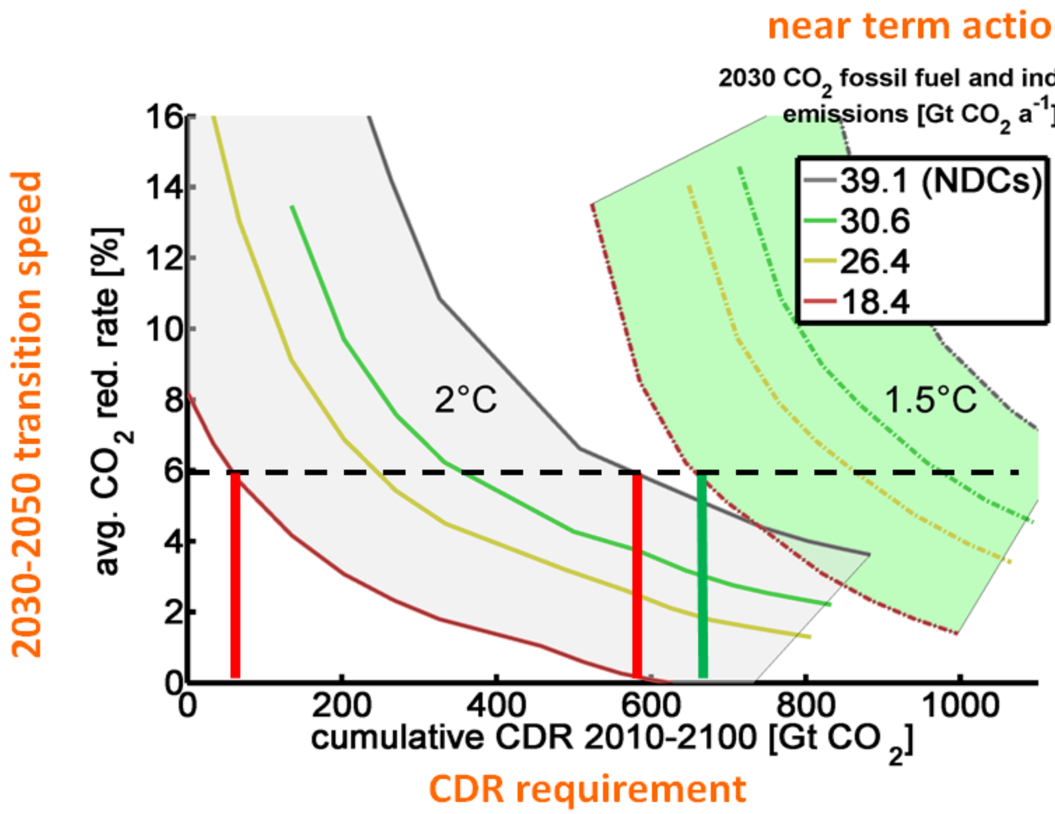


Figure 6: Trade-offs of delayed action, carbon lock-in and CDR requirements (Strefler et al., 2018).

Success stories

Despite the global (implementation and ambition) emission gaps, there are success stories. These can help to identify potential new policies in various parts of the world. Several studies have identified success stories. If all countries were to implement sectoral climate policies similar to these examples it would be possible to rapidly reduce emissions world-wide (good practice policies, Figure 7). Replicating the good practice policies worldwide could result in projected annual GHG emission levels of approximately 50 $GtCO_2e$ by 2030 (2% above 2010 levels), compared to 60 $GtCO_2e$ under the current policies scenario, thus reducing roughly by half (about 50%), but not closing the emissions gap with 2 °C pathways. Most reductions are achieved in the electricity sector, through expansion of renewable energy, followed by the reduction of fluorinated gases, reducing venting and flaring in oil and gas production, and improving industry efficiency. This strengthening of ambition until 2030 implies lower mitigation challenges after 2030 for achievement of the well below 2 or 1.5 °C targets, such as reduced speed, scale, and smaller increases of energy and food prices (reduced requirements for CDR).

Pathways that follow such a gradual phase-in of ambition level are characterised by a less abrupt disruption than both the 2 °C scenarios with immediate cost-optimal policies and those with optimal policies only after following NDC trajectories until 2030 (Kriegler et al. 2018).

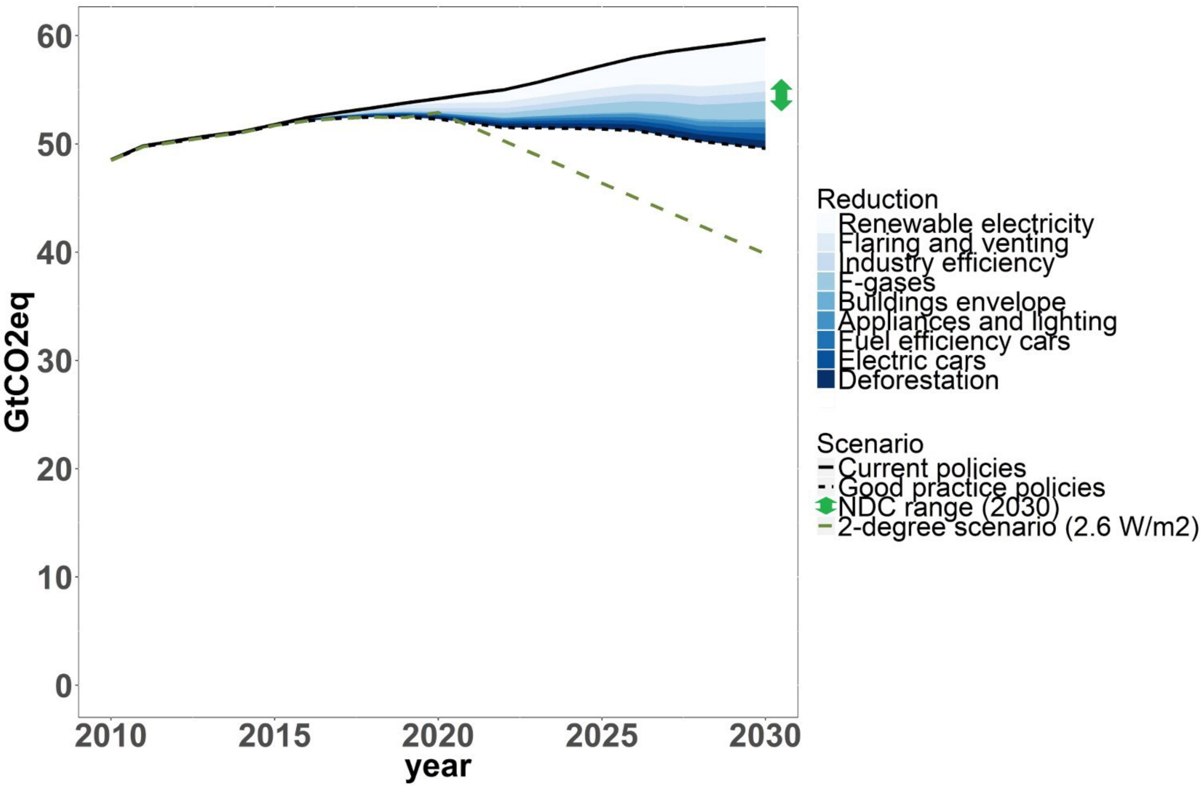


Figure 7: GHG emission levels (including LULUCF) as a result of implementing the selected nine good practice policies together (good practice policies scenario). The emission levels are compared to a 2 °C scenario (Roelfsema et al., 2018).

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Chapter 3: How do get from where we are going to where we want to go?

Dynamics of the transformation

The massive transformation of global energy, industry, and land-use systems required to achieve the 1.5 and well below 2 °C global warming goals depends critically on policies that incentivise changes in investment patterns, uptake of clean energy technologies and household/business behaviour. A number of long-term scenario studies based on integrated assessment models have illustrated the scale of these changes and the sector-specific dynamics underlying the system-wide transformation over the coming decades. This section highlights some of the most robust insights from these studies, pointing also to the successes already achieved by countries with the so-called 'good-practice policies'. One overarching finding from these studies is that aggressive efforts to mitigating greenhouse emissions will have impacts on other, non-climate sustainable development goals - mostly for the better, though not always, thus requiring explicit consideration of the broader context for defining policies. Limiting global average temperatures to 1.5 and well below 2 °C implies a tight limit on cumulative net GHG emissions from today onward (Figure 8). From a cost-optimal perspective, the ideal way to do this would be to strengthen all countries' current NDC pledges prior to 2030 so that global emissions peak by 2020 (thus allowing for the possibility that some countries' emissions are still rising in the 2020s).

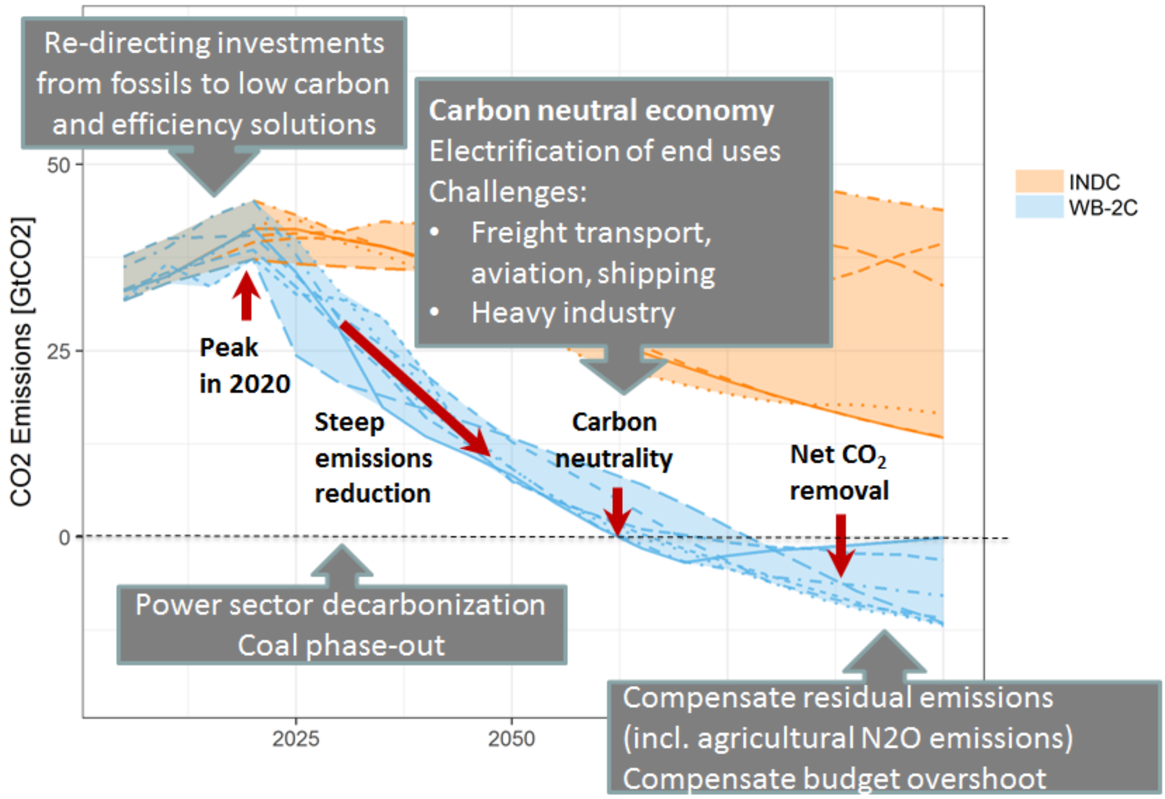

Figure 8: Key characteristics of decarbonisation pathways, based on Luderer et al. (2018). WB-2C: well below 2 °C scenario.

In both the well below 2 °C and 1.5 °C scenarios, the emission peak in 2020 is followed by a steep emissions reduction. There are different sectors that contribute to rapid emissions reductions.

- *This is initially realised by a rapid decarbonisation of the power supply sector, spearheaded by a phase-out of unabated coal power plants (i.e., those not equipped with carbon capture and storage: CCS).* Electricity supply offers large and low-cost emission reduction potentials and considerable flexibility due to the substantial variation in technology choice across models. As a result, near-carbon neutrality is expected to be reached in 2050. As the power sector turns essentially carbon-free (or carbon-negative with deployment of BECCS) in the second half of the century, its cumulative fossil fuel CO_2 emissions depend mostly on the pace at which emissions decline before mid-century. The additional emission reductions in the 1.5 °C scenario are therefore largely achieved by a faster phase-out of conventional coal-fired power, and quicker ramp-up of carbon-free electricity.
- *Demand-side emission reductions are, in most scenarios, less deep than those achieved in power generation*. Demand side emissions are defined here as the emissions from the combustion of fossil fuels directly in the industry, buildings and transport sectors, thus excluding upstream emissions from energy conversion processes. Demand-side emissions reduction efforts can be broadly categorised into energy demand savings, replacing combustible fuels by electricity or hydrogen (electrification), and moving toward very low carbon intensities of these advanced energy carriers. In the 1.5 °C scenario, final energy demand savings of 36% (range [2–40]%) are realised in 2050 relative to 2010 levels, equivalent to an annual efficiency increase of 2.1[1.8–2.9]% per year over 2010–2050. These policy-induced energy demand reductions are around 50% greater than those observed in the 2 °C case (Luderer et al. 2018). Still, some scenarios exist that more specifically target the demand-side sector.
- *Reaching high electrification shares in transportation requires a more fundamental transformation than in the other sectors.* Electric vehicles can contribute substantially to future transport-sector emissions abatement. However, the share of combustible fuels (including biofuels) in useful energy for transportation is projected to remain at 55[52–74]% in 2050 in the 1.5 °C scenario, as electrification is substantially more challenging for freight, aviation and shipping transport segments.

Aside from much greater electrification of end-use sectors, a key role in the reduction of fuel carbon intensities is bio-energy. Bioenergy is, however, subject to considerable sustainability concerns, and its overall potential is constrained by the competition for food production and other land uses. Models therefore exhibit considerable differences in the future role of bioenergy globally. For instance, by 2050 biomass accounts for 86[66–100]% of solid final energy for the industry and buildings sectors in the 1.5 °C scenario, while 28[20–35]% of liquids, mostly for transportation, are biofuels.

Most scenario studies point to the need for large scale carbon dioxide removal (CDR) in the power sector in the second half of the century, mainly in the form of the combination of bioenergy with carbon capture and storage (BECCS). Such a strategy is required to compensate for the residual greenhouse gas emissions in the demand sectors. This is true for the 2 °C case, but even more so in the 1.5 °C scenario. Even when strengthened pre-2030 mitigation action is combined with very stringent long-term climate policies, cumulative residual CO_2 emissions from fossil fuels remain at 850–1,150 $GtCO_2$ during 2016–2100, despite carbon prices of US$130–420 per tCO_2 by 2030. Thus, 640–950 $GtCO_2$ removal is required for a likely chance of limiting end-of-century warming to 1.5 °C.

Box 1: Is carbon dioxide removal absolutely necessary for reaching the 1.5 and well below 2 °C targets?

Some of the newest scenario literature explicitly deals with the controversial topic of 'negative emissions' (or 'carbon-dioxide removal') - a mitigation strategy wherein CO_2 emissions are pulled directly out of the air then permanently stored somewhere else. There are different technological options for doing this. Afforestation ('planting trees') is an age-old strategy known to be effective. Another one that has achieved much prominence in integrated modelling studies in recent years is BECCS (bioenergy combined with carbon capture and storage).

Both Grubler et al. (2018), Bertram et al. (2018) and Van Vuuren et al. (2018) illustrate with alternative scenarios that the scale of carbon dioxide removal can be significantly reduced, or perhaps eliminated beyond afforestation, if a number of other mitigation options are dramatically scaled up. These include options such as additional reduction of non-CO_2 greenhouse gases and more rapid electrification of energy end-use sectors based on renewable energy. But on top of this, a conclusion of these studies is that major changes on the energy and food demand side offer the biggest lever for reducing the need for carbon dioxide removal technologies on the supply side: i.e., substantial boosts in energy efficiency across all demand sectors, combined with changes in consumer lifestyles and preferences to speed the uptake of disruptive innovations and practices (e.g., vehicle sharing, ICT, low-meat consumption diets, and so on).

The scenarios show how changes in the quantity and type of energy services drive structural change in intermediate and upstream supply sectors (energy and land use). Or put differently, a down-sizing of the global energy system dramatically improves the feasibility of a low-carbon supply-side transformation, allowing the 1.5 °C climate target to be met with little or no net negative emissions beyond afforestation.

Another key facet of these low-demand, limited carbon dioxide removal scenarios is that they bring with them many synergies and co-benefits for a number of other sustainable development goals (Bertram et al., 2018; Grubler et al., 2018).

Energy investments required for the transformation

Low-carbon investments can act as the vehicle for the needed deep energy system transformation. Put differently, rapid shifts from fossil energy technologies to renewables and energy efficiency will require dramatic changes in global energy investment patterns. As illustrated in a multi-model study by McCollum et al. (2018a), the impact of future energy and climate policies on total energy (supply and demand) investments depends on the nature and extent of those policies. Meeting the most recent suite of countries' climate pledges ('NDC' scenario) would likely only necessitate a marginal increase in total future investments globally, relative to a continuation of current trends ('current policies'). In contrast, more aggressive policies promoting deep decarbonisation through a global energy system transformation ('2 °C' and '1.5 °C' pathways) would, according to most models, require a marked increase in energy-related investment. As a share of global GDP, the total energy investments projected by the models do not rise significantly from today in any of the scenarios, hovering just over 2% (model range: 1.5–2.6%) in current policies and NDC and growing to 2.5% [1.6–3.4%] and 2.8% [1.8–3.9%] in the 2 °C and 1.5 °C pathways, respectively. Regional results can diverge widely though, with wealthier countries showing per-GDP investment costs lower than the global average and emerging economies showing higher costs driven by the higher abatement effort for developing countries projected in cost-optimal global decarbonisation scenarios.

More important than total capital flows is how the energy investment portfolio might be expected to evolve over time in different scenarios. That portfolio continues to look very similar to today in the current policies baseline, and to a large extent also in the NDC case. In contrast, the transformational 2 °C and 1.5 °C pathways exhibit a shift from fossil (especially coal) to low-carbon and energy efficiency investments (Figure 9). Declines in unabated coal, gas, and oil investments imply increases in renewables, nuclear, and demand-side energy efficiency (and to a lesser extent fossil fuels equipped with CCS), especially in the more transformative 2 °C and 1.5 °C pathways. Additionally, several models provide evidence of significantly increased investment requirements for electricity transmission and distribution (T&D) and storage to complement expansion of intermittent variable renewable energy (solar and wind). This highlights the greater demands for delivering electricity to the end-use sectors (buildings, industry, and transport) in a deeply decarbonised energy system, as well as needs for large-scale electricity storage when the contribution from intermittent sources of electricity (solar, wind) is substantially greater.

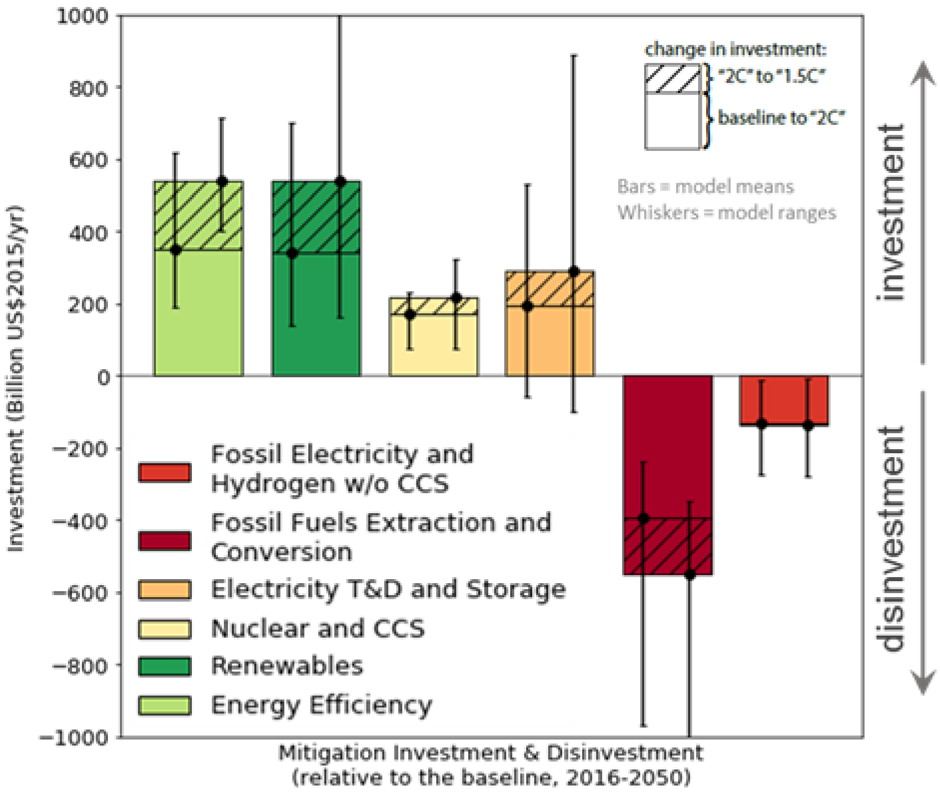

Figure 9. Projected global average annual investments and disinvestments by category from 2016 to 2050 according to different models. Source: McCollum et al. (2018a)

A substantial low-carbon energy and energy efficiency investment gap exists between "Paris Pathways" and current policies. According to our calculations, achieving the current NDC pledges of countries implies that a global near-term (to 2030) LCEI-Gap of approximately 130 billion US$/year (model mean), accounting for around 7% of all energy investments worldwide in 2015, needs to be filled over the next several years. If the aim is instead to keep global temperatures below 2 °C or 1.5 °C in the long term, then this near-term LCEI-Gap quickly escalates to 300 or 460 billion US$/year, respectively (or 17-26% of 2015 investments). Looking toward mid-century, the global LCEI-Gap reaches far higher levels in all mitigation scenarios, with the relative up-scaling of investment effort being particularly strong in the 2 °C and 1.5 °C futures (1050 and 1560 billion US$/year in 2050, respectively). The world's largest economies have already agreed that spurring low-carbon energy investments should be placed high on their collective priority list and G20 countries have 'reemphasised' the previously agreed commitment of wealthy countries to jointly mobilise 100 billion $/year (during the period

2020-2025) for mitigation actions in developing countries. This would go a long way toward fulfilling the NDC commitments; however, it would not nearly close the investment gap for a 2 °C- or 1.5 °C-consistent future.

Policy needs to incentivise the transformation

There has been a strong increase in the formulation of national-level (or subnational) climate mitigation policies and strategies over the past decade. This appears to be due to the political momentum driven initially by the Copenhagen Climate Conference in 2009 and then later by the Paris Agreement in 2015. At present, nearly 90% of global GHG emissions are covered by some sort of climate policies at the national level (Figure 10). More specifically, the number of countries with renewable energy targets has seen a steady increase in recent years, with 79% of the global GHG emissions covered in 2017 compared to just 45% in 2007. Developing countries have been the main driver of this increase. The fact that the Copenhagen and Paris UNFCCC COP events helped to motivate such a flurry of activity underscores the importance of the international climate policy process in maintaining national-level momentum.

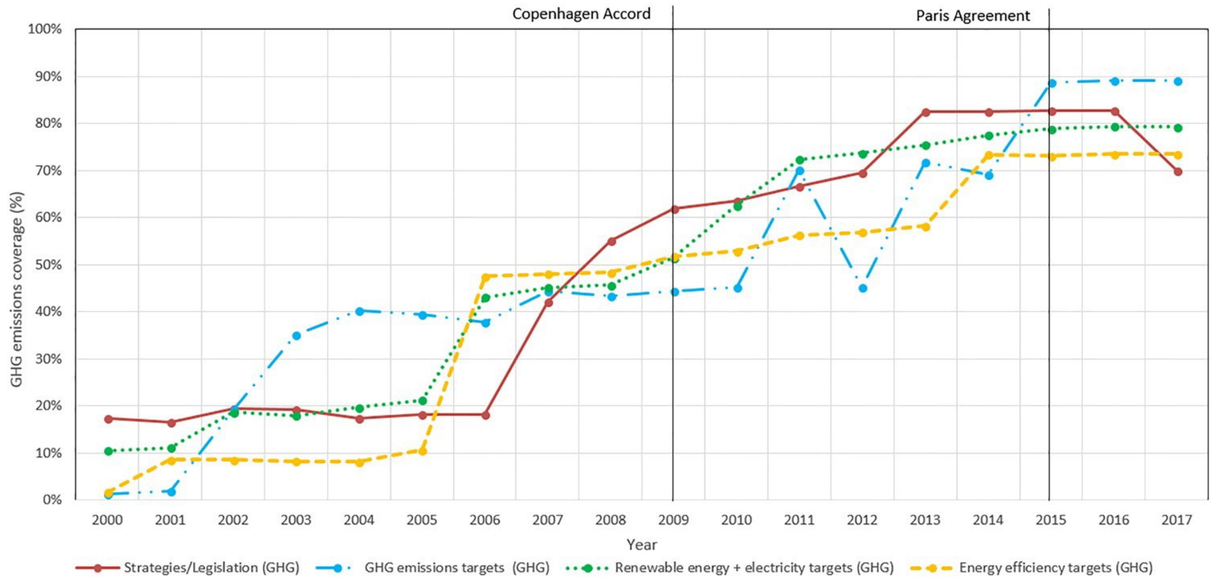

Figure 10: GHG emissions coverage by climate strategies, legislation and targets in total GHG emissions or only energy emissions (for renewables and energy efficiency targets) in the period 2000 to 2017 (Iacobuta et al., 2018).

Despite this progress, a dramatically more stringent policy environment is necessary to achieve the 1.5 and well below 2 °C goals, particularly during the period from 2020 to 2030. Hence, in the spirit of 'How do we get there?' the following question needs to be answered: What examples of 'good-practice' policies exist, and how can these various actions be scaled up over the short term to align countries collectively with the longer-term 1.5 and well below 2 °C goals? One way to support ratcheting-up of the current portfolio of policies is to look back at past low-carbon successes and learn from them. Countries could share insights of success and causes of failure in policy implementation, for example in the Talanoa Dialogue (Roelfsema et al, 2018b). Successful policies from other countries that led to substantial reductions can be replicated, or adjusted to take into account local circumstances as country context matters. The potential impact of such collective efforts was recently illustrated by a scenario modelling exercise, wherein a selection of successful policies in nine policy areas was implemented after translating key aspects of the policies into model parameters (see Table 1). The aggregate result of this good practice policies scenario resulted in projected annual GHG reductions of about 10 $GtCO_2e$ by 2030, compared to the 60 $GtCO_2e$ in the current policies scenario (Roelfsema et al, 2018a). Three examples of successful policies that can be replicated elsewhere and with potentially large benefits include: the German feed-in tariff for renewable energy, the carbon tax in Norway to reduce flaring and venting, and the

Action Plan for Deforestation in Brazil. If the impact of such policy actions were to be achieved in all countries, global emissions by 2030 would be reduced relative to current policies by around 4 $GtCO_2e$ in the electricity sector, 1 $GtCO_2e$ in the oil and natural gas production sector, and 0.7 $GtCO_2e$ in the forestry sector (see Table 1).

Table 1: Overview of nine selected good practice policy actions with corresponding country policy instruments and translation to policy impact (Roelfsema et al., 2018a)

Main sector	*Policy action*	*Successful policy instrument*	*Policy impact*
Energy supply	Increase renewables in electricity production	Renewable portfolio standard, feed-in-tariff in the UK and Germany	+1.35% points growth in share of renewable electricity generation per year
	Reduce flaring and venting in oil and gas production	Regulation and carbon tax in Norway	4.4% annual reduction of oil/gas intensity ($ktCO_2e$/Mtoe) until 2030
Industry	Enhance energy efficiency of industrial production	Energy agreements in Ireland	1% annual energy savings improvement above current efforts until 2030
	Reduce fluorinated emissions	North American Proposal to the Montreal protocol	70% reductions of F-gas emissions below 2010 levels by 2030
Buildings	Enhance efficiency of residential building envelope	EU regulation	Energy intensity of 0 kWh/m² by 2030 (space heating)
	Set efficiency standards for appliances and lighting	Appliance standards in EU countries	Average efficiency improvement of 1.8% per year until 2030
Transport	Improve fuel efficiency of cars	Fuel economy standard in the EU	Fuel economy standard of 26 km/l in 2030
	Increase number of electric cars (charged with renewable electricity)	Tax levies and investments in infrastructure in Norway	25% share of new electric vehicles in 2020, 50% in 2030
LULUCF	Reduce deforestation	Regulations and enforcements in Brazil	Decreasing deforestation rate relative to 2010 by 22% in 2020, 44% in 2030.

A global roll-out of regionally-specific policies could ease the implementation challenge of reaching the 1.5 and well below 2 °C global warming goals. This conclusion can, for instance, be based on the analysis of Kriegler et al. (2018). The policies analysed by Kriegler et al. (2018) comprise a bundle of near-term regulatory actions in energy supply (increased expansion of renewables and phase out of coal power), transport (increasing Electric Vehicle share, vehicle fuel efficiency, enhanced aviation efficiency), buildings (retrofit, improving energy efficiency of appliances), industry (energy efficiency improvement, CCS), and land use (nitrogen use efficiency, anaerobic digesters, ending deforestation, promoting afforestation), and moderate, regionally differentiated carbon pricing. See Kriegler et al. (2018) for current levels of policy ambition globally and the scaled up ambition that would be needed to be considered either 'good practice' or 'strengthened', especially with a view toward the eventual achievement of net-zero emissions for energy and land-use systems.

A global roll-out of very ambitious sector-specific policies based on good practice ("net-zero") could reduce global CO_2 emissions by an additional 10 $GtCO_2eq$ in 2030 relative to what they would otherwise be under current plans. Figure 11 based on Kriegler et al. (2018) shows that an enhanced policy scenario would lead to emissions trajectories by 2030 that are much closer to those of cost-effective pathways toward 2 °C, thereby reducing implementation challenges post-2030. This study confirms the insights from Roelfsema et al. (2018). That being said, while a gradual phase-in of a portfolio of good-practice policies might be less disruptive than immediate cost-effective carbon pricing, it would perform worse in other dimensions. In particular, phasing-in such policies would lead to higher economic impacts over the long term, which could become a major obstacle for the energy system transformation further into the future. Hence, such good-practice policy packages should not be viewed as alternatives to carbon pricing, but rather as complements that provide entry points to achieve the Paris climate goals.

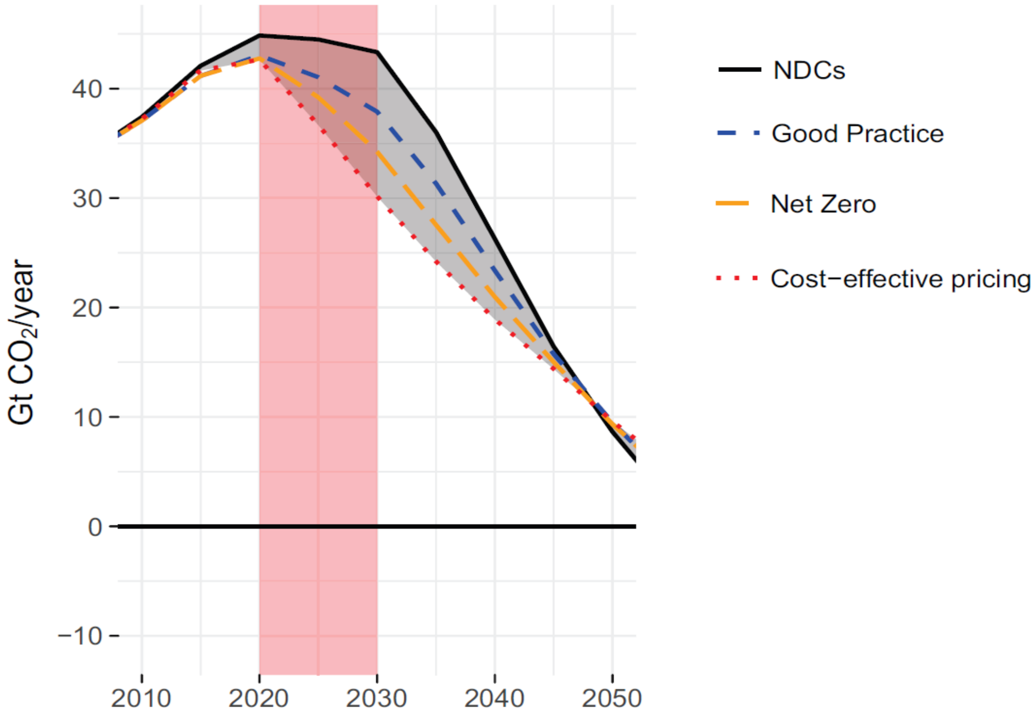

Figure 11: Global net CO_2 emission trajectories towards the well below 2 °C target with full CDR availability (centre) and towards the 1.5 °C target with full CDR availability (right). The blue and yellow trajectories illustrate the extent to which a world-wide but differentiated roll-out of good-practice and additional policies can reduce the gap to least-cost pathways. Source: Kriegler et al. 2018.

Benefits of deep decarbonisation efforts for other sustainability objectives

Climate policies need to be integrated with broader sustainable development policies. Scenarios from the integrated assessment literature point to the value of taking an integrated approach to policy development and implementation. More specifically, from the perspective of climate policy, a number of recent studies have found that strong mitigation actions leading to a transformation of global energy, industry and land-use systems over the long term will simultaneously lead to numerous co-benefits over the short term. In other words, an integrated strategy ensures there are synergies between the UNFCCC climate policy process and the implementation of the United Nations' Sustainable Development Goals (SDGs), both at the global and national levels (McCollum et al., 2018b, Fuso Nerini et al., 2018, Roy et al., 2018) (see Figure 12).

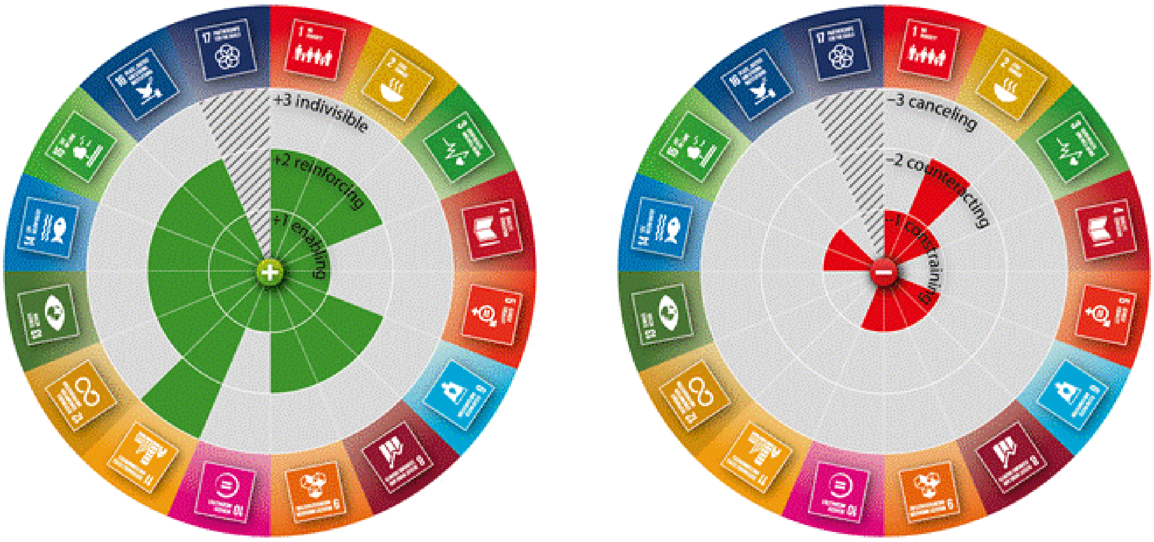

Figure 12: Nature of the interactions between SDG7 (Energy) and the non-energy SDGs. Figure reproduced from McCollum et al. (2018b) with permission. The relationships may be either positive (left panel) or negative (right panel) to differing degrees. See Nilsson et al. (2016) for definitions pertaining to each score from +3 (positive) to –3 (negative) in integer increments. The absence of a coloured wedge in either the left or right panels indicates a lack of positive or negative interactions, respectively; if wedges are absent in both panels for a given SDG, this indicates a score of 0 ('consistent'). Only one positive or negative score is shown per SDG; in instances where multiple interactions are present at the underlying target level (positive and negative treated separately), the individual score with the greatest magnitude is shown. Note that, while not illustrated by this figure, some SDG linkages may involve more than simple two-way interactions (e.g., the energy-water-land 'nexus'). No scoring is done for the "means of implementation" goal, SDG17. Sustainable Development Goals: 1 – No Poverty, 2 – Zero Hunger, 3 – Good Health and Well-being, 4 – Quality Education, 5 – Gender Equality, 6 – Clean Water and Sanitation, 7 – Affordable and Clean Energy, 8 – Decent Work and Economic Growth, 9 – Industry, Innovation and Infrastructure, 10 – Reduced Inequalities, 11 – Sustainable Cities and Communities, 12 – Responsible Consumption and Production, 13 – Climate Action, 14 – Life below Water, 15 – Life on Land, 16 – Peace, Justice and Strong Institutions, 17 – Partnerships for the Goals

The studies identify numerous potential synergies between mitigation activities and other SDGs, including with air pollution and health, water availability, freshwater and marine ecotoxicity, and marine eutrophication. Bertram et al. (2018) and Krey et al. (in review) developed scenarios that track impacts of climate mitigation activities on multiple SDG dimensions. The scenarios include existing climate policies and NDCs, as well as long-term transitions towards 2 °C and 1.5 °C. Vandyck et al. (forthcoming) also show that climate and energy policies in the NDCs bring substantial air quality co-benefits for agricultural productivity and human health, which are further scaled up under more ambitious 2 °C-compatible climate action. On the other hand, there are potential trade-offs of stringent mitigation efforts that Bertram et al. argue should not be ignored (e.g., near-term costs to the economy, access to modern energy services, food prices and hunger risk, biodiversity loss, and mineral resource availability). These risks are amplified in an 1.5 °C pathway relative to 2 °C, given the increased decarbonisation effort of the former (Figure 12). That being said, if mitigation is pursued not only by comprehensive carbon pricing but also by targeted support of more sustainable lifestyles and early support for key mitigation technologies, then most trade-offs related to mitigation can be reduced considerably, and the synergies with other SDGs can be greatly increased. Multi-objective type of policy or other medium to short-term regional objectives might be key to close the gap between the NDCs pathways and a 2 °C or 1.5 °C policy. Importantly, the choice of mitigation policy is found to be of greater importance for the magnitude of trade-offs than the choice for either 2 or 1.5 °C, as the switch to an integrated, holistic sustainability mitigation policy paradigm more than offsets the incremental trade-offs from increasing ambition from 2 to 1.5 °C (Bertram et al. 2018, Figure 13).

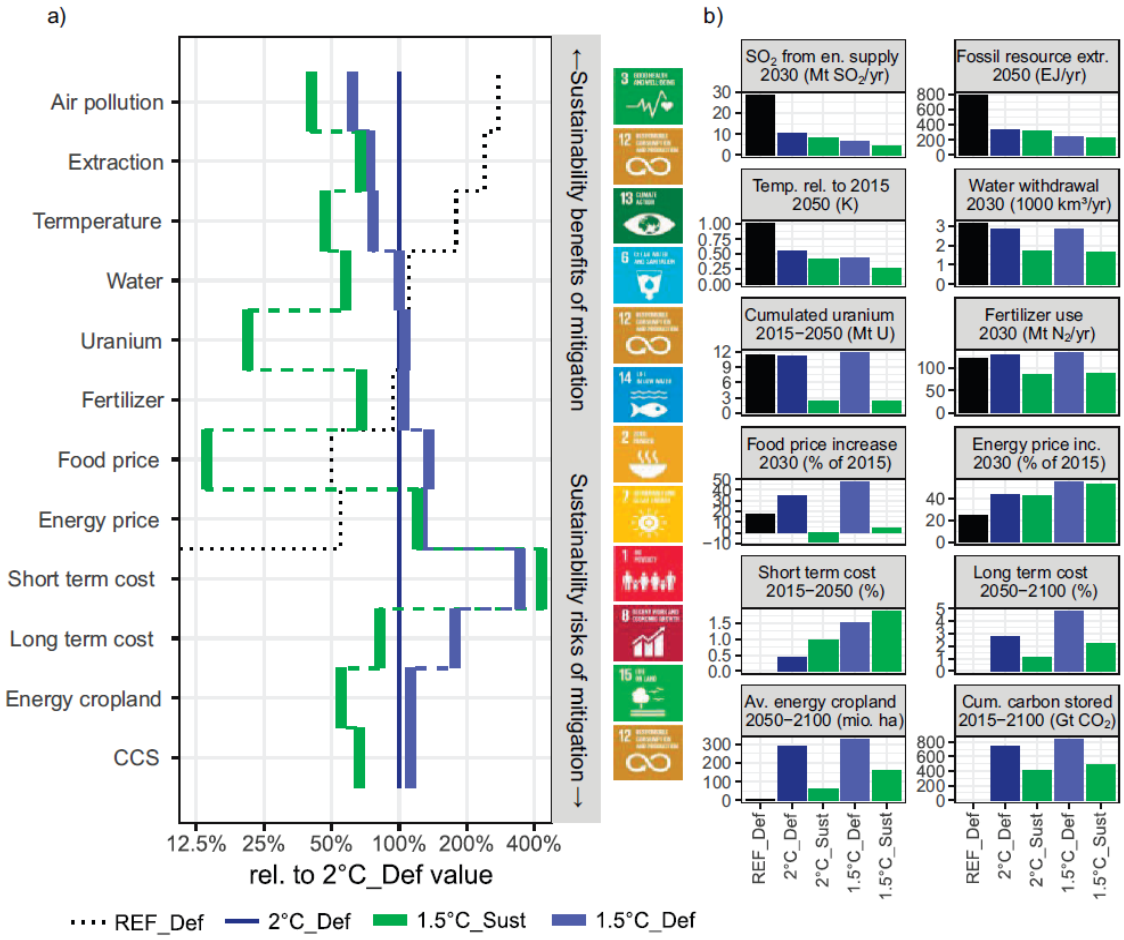

Figure 13: Comparative analysis of sustainability effects of policy approaches and long-term targets. Sustainability indicators for 2 °C and 1.5 °C scenarios with mitigation-only policy (Def) and combined sustainability policy package including lifestyle changes, regulation and increased early action (Sust). Panel (a) shows values relative to the 2 °C_Def scenario in logarithmic scale, panel (b) shows the absolute values for all five main scenarios and additionally indicates the time/timespan shown. All values are global totals or averages. Indicators are arranged such that the most pronounced sustainability benefits of mitigation sit on top, and the most severe sustainability risks at the bottom. This ranking is based on the relative values, and does not imply a normative weighting of the different dimensions which can only emerge from broad public deliberations. Please note that the 2 °C_Sust scenario is only shown in panel (b), in order to provide a clear overview in panel (a). Source: Bertram et al. 2018.

In short, an important conclusion from the growing body of literature looking into climate and development interlinkages is that integrated policies are needed to ensure multiple SDGs are achieved simultaneously. This is also discussed in Box 1. In particular, dealing with undesirable distributional consequences of climate policies is key to avoid negative impacts on the poor. The good news is that, at least for a handful of sustainability dimensions, scenario studies have calculated that such compensatory measures are of moderate cost relative to incremental investments/disinvestments required for transforming the global energy system (McCollum et al., 2018a) (see Figure 14).

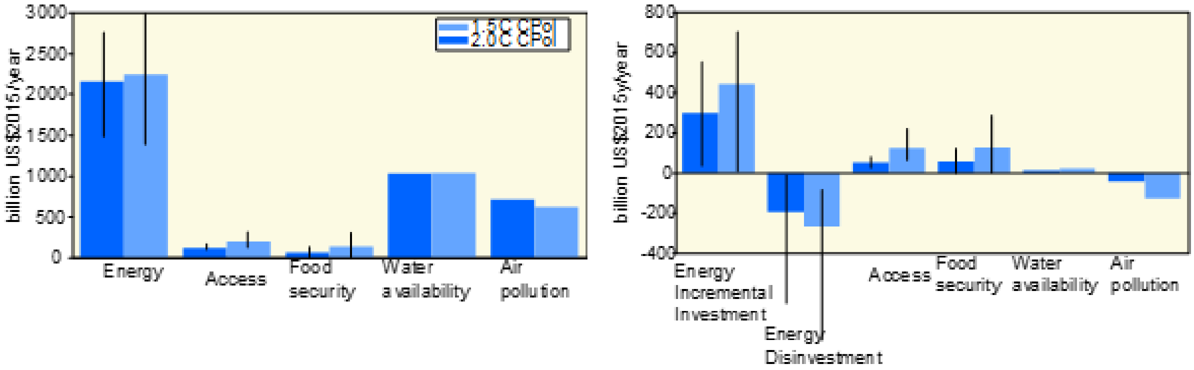

Figure 14. Integrated Policy design needed to steer sustainable investments towards achieving the SDGs: Projected energy investments for climate mitigation (SDG13) and how they relate to four other SDG dimensions (energy access-SDG7, food security-SDG2, water-SDG6, and air quality-SDG3). Total (left panel) and incremental change compared to the baseline (right panel) in average annual investments between 2016 and 2030. Dark blue bars show the median investment in 1.5 °C pathways across results from six different models, and light blue for 2 °C pathways, respectively. Whiskers represent minima/maxima across estimates from six models. Water and air pollution investments are available only for one model. Negative investments reflect reduced investment needs (disinvestments) into fossil fuels (energy sector) or cost savings for air pollution control (synergies). Investments for certain sustainable development dimensions denote the investment needs for complementary measures to avoid trade-offs (negative impacts) of mitigation. For example, energy access reflects policy costs for ensuring 100% clean fuel adoption throughout the world by 2030, via subsidies and microfinance for cook stoves and fuel price support (SDG target 7.1), even in spite of rising energy prices due to stringent climate mitigation. Food security reflects mitigating trade-offs of SDG7 and SDG13 policies on the situation of people at the risk of hunger due to potentially increasing food prices; the costs dot not correspond to completely eradicating hunger (SDG target 2.1). Water includes achieving SDG targets 6.1 to 6.4 and a wide range of municipal water technologies, excl. irrigation costs. Air pollution represents costs to substantially reduce premature deaths from air pollution (SDG target 3.9). All investment values are undiscounted and in US$2015 per year. Source: estimates from CD-LINKS scenarios summarised by McCollum et al. (2018a).

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