Credible Pathways to 1.5 °C

Four pillars for action in the 2020s

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SUMMARY

- Global energy related CO_2 emissions rose 0.9% in 2022, reaching an all-time high of 36.8 billion tonnes (Gt). Land-use related CO_2 emissions remained at around 6 Gt in 2022, while energy related methane emissions rose in 2022 but remained below the record levels of 2019. The window to a credible pathway towards limiting warming to 1.5 °C in 2100 is therefore rapidly closing.
- Declining costs for clean energy technologies and new policies have shaved around 1 °C from projected 2100 warming compared to the pre-Paris baseline. The ambitions that countries have put on the table go a significant way to meeting the 1.5 °C goal. If implemented on time and in full, countries' net zero pledges would be sufficient to hold warming to around 1.7 °C in 2100. The key question is therefore what needs to be done now to strengthen near-term action to put the world on a credible pathway consistent with the 1.5 °C goal. Four pillars are key:
- **In the energy sector, decarbonising electricity, accelerating energy efficiency and electrification are the critical tools**. Capacity additions of renewables need to triple from 2022 levels by 2030, reaching around 1 200 GW annually, representing on average 90% of new generation capacity each year. Electric car sales should reach a market share of around 60% by 2030, while zero emissions medium and heavy freight trucks should reach a market share of around 35% by the same year.
- **Reducing deforestation to net zero by 2030** – in line with The Glasgow Leaders' Declaration on Forests and Land Use – provides the largest share of CO_2 emissions reductions from the land-use sector.
- **Tackling non-CO_2 emissions** is vital to limiting peak warming. Assuming strong action on CO_2, meeting or exceeding commitments like the Kigali Amendment on HFCs and the Global Methane Pledge, and acting on non-CO_2 emissions from agriculture, could make the difference between a scenario which substantially overshoots 1.5 °C, risking triggering irreversible climate tipping points, and one which does not.
- Even in a low overshoot scenario, **carbon capture and storage and atmospheric carbon dioxide removal** will be required to mitigate and compensate hard-to-abate residual emissions. Projects capturing around 1.2 Gt CO_2 by 2030 need to be implemented, against the roughly 0.3 Gt CO_2 currently planned for 2030.
- A credible pathway to the 1.5 °C goal needs strong, immediate action on each of these four pillars, to deliver immediate and rapid emissions reductions; strong contributions from all countries, especially advanced and major economies; and clear policy signals to enable actors to anticipate and achieve change.

Introduction

Global energy-related CO_2 emissions rose 0.9% in 2022, reaching a new all-time high of 36.8 Gt (IEA, 2022a).[1] Land-use related CO_2 emissions remained at around 6 Gt in 2022. At the same time, record high fossil energy and electricity prices in many markets and new policies pushed energy efficiency and clean energy technology investments to new heights. Solar PV and wind generation each increased by around 275 TWh, a new annual record. Taken together, renewables covered more than 90% of electricity demand growth in 2022. Electric cars also surged, reaching 14% of global sales, up from 4% in 2020.

Despite the continued growth of emissions in 2022, countries have increased their ambitions on climate change. According to analysis by the *International Energy Agency* (IEA), if countries implement in full and on time their nationally determined contributions (NDCs) and net zero pledges, as well as sectoral pledges such as the Global Methane Pledge and the Glasgow Leaders' Declaration on Forests and Land Use, the world would be on a pathway to limiting warming to around 1.7 °C by 2100 (IEA, 2022b). This is substantially better than the trajectory implied by current policy settings, which would see warming of about 2.5 °C in 2100. However, it would still not limit warming to 1.5 °C. The *Intergovernmental Panel on Climate Change* (IPCC) has highlighted the significant risks of warming above 1.5 °C (IPCC, 2018; IPCC, 2021a; IPCC, 2022).

The goal of this paper is to highlight the critical areas where accelerated action in the current decade can preserve a reasonable chance of limiting global temperature rise[2] to 1.5 °C by 2100, structured around four key pillars:

- Achieving the substantial near-term emissions reductions from the **energy sector** necessary to put it on a pathway to reach **net zero CO_2 emissions by mid-century**;
- Reducing **deforestation to net zero by 2030** and taking additional mitigation actions in the land-use sector;
- **Cutting non-CO_2 greenhouse gases** (GHGs), especially methane, and other short-lived climate pollutants, which have an outsized impact on lowering peak warming;
- Scaling up the innovation and deployment of **carbon management technologies**.

Strong and coordinated action on these four pillars can put the world on a credible pathway to limiting warming to 1.5 °C. A credible pathway should be built around:

- Immediate and steep reductions in GHG emissions, in order minimise the magnitude and duration of a temperature overshoot above 1.5 °C. This reduces the risks associated

[1] In this paper, energy related CO_2 emissions refers to emissions from fossil fuel combustion and industrial processes.

[2] Unless otherwise stated, temperature rise estimates quoted refer to the median temperature rise, meaning that there is a 50% probability of remaining below a given temperature rise. Changes in temperatures are relative to 1850-1900 and match the IPCC 6th Assessment Report definition of warming of 0.85 °C between 1995-2014.

with: physical hazards and economic costs of warming; irreversible climate tipping points; and the availability and socio-economic trade-offs of technologies to remove CO_2 from the atmosphere.

- A smooth transition achieved through strong and co-ordinated policies and incentives that enable all actors to anticipate and participate in the rapid change required.
- Contributions from all countries, especially advanced and major economies, and international collaboration to lower costs and support emerging market and developing economies in undertaking the transition.

Box 1 ▹ IEA scenarios in the World Energy Outlook 2022

This paper uses the following IEA scenarios[3]:

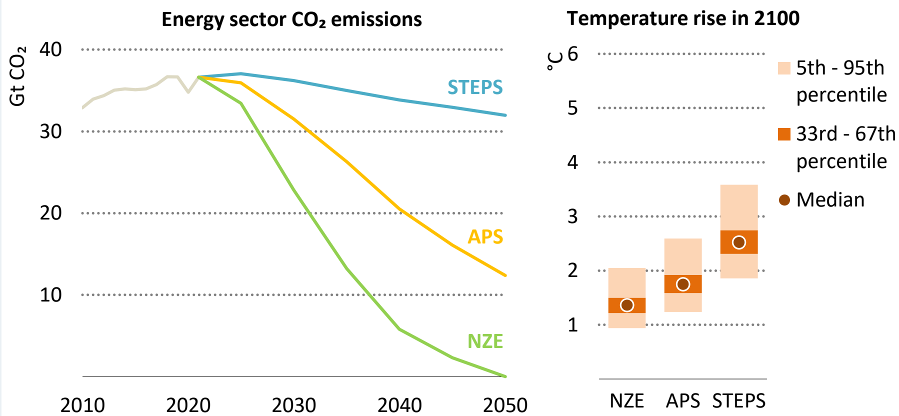
- *Net Zero Emissions by 2050 (NZE) Scenario*: This normative scenario sets out a pathway to the stabilisation of global average temperatures below 1.5 °C above pre-industrial levels by 2100, and avoids high overshoot of the 1.5 °C threshold by limiting peak warming to below 1.6 °C. This scenario reaches net zero CO_2 emissions from the energy sector by 2050, without offsets from outside the energy sector, as well as steep cuts in CO_2 from AFOLU and in other GHGs.
- *Announced Pledges Scenario (APS)*: This scenario assumes that governments will meet, in full and on time, all of the climate-related commitments, goals, and targets that they have announced, including longer-term net zero emissions pledges and NDC targets. Pledges made in international fora and initiatives on the part of businesses and other non-governmental organisations are also taken into account. In this scenario, the temperature increase reaches around 1.7 °C by 2100.
- *Stated Policies Scenario (STEPS)*: This scenario is based on a detailed sector-by-sector review of the policies and measures that are actually in place or under development. In this scenario, temperatures would reach 2.5 °C by 2100 and continue to rise thereafter.

Figure 1 shows the energy sector CO_2 emissions and temperature outcomes of the three scenarios.

The IEA will update these scenarios as part of its World Energy Outlook 2023, and will place a particular focus on the updated NZE Scenario in a Special Report on Climate Change to be published in the second half of 2023.

[3] These scenarios are the same as those included in the IEA's World Energy Outlook. (IEA, 2022b))

Figure 1 ▷ **Energy sector CO_2 emissions by scenario, 2010 – 2050, and temperature rise by scenario, 2100**



If implemented fully, net zero pledges see warming of 1.7 °C in 2100, an improvement compared to the trajectory of current policies, but still not in line with the 1.5 °C limit

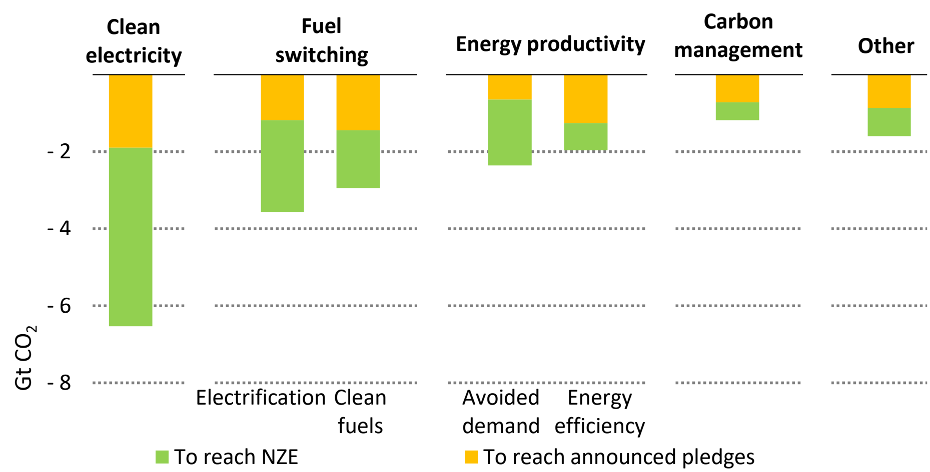
Pillar 1: net zero CO_2 emissions from energy by 2050

There is no credible pathway to limiting warming to 1.5 °C without steep and immediate reductions in energy related CO_2 emissions. The low-overshoot 1.5 °C scenarios assessed by the IPCC reach net zero CO_2 emissions from the energy sector by around mid-century (Byers et al., 2022). Achieving this pathway requires rapid and profound transformation of the global energy sector, structured around four types of key actions (Figure 2):

- **Scaling up the deployment of clean electricity**. Another record year for renewables was achieved in 2022, with renewables meeting 90% of electricity generation growth. Solar PV and wind generation each increased by around 275 TWh, a new annual record.
- Scaling up the deployment of clean electricity - including renewables, nuclear power, fossil fuel power plants with carbon capture, storage and use (CCUS), and plants firing hydrogen and ammonia - is one of the most critical actions needed to reduce emissions in line with a credible 1.5 °C pathway (Figure 2). Annual capacity additions of renewables need to quadruple from historical levels (or roughly triple from levels achieved in 2022) and reach 1 200 GW annually by 2030, representing on average more than 90% of new generation capacity each year.
- Fuel switching to electricity and low-emissions fuels such as sustainable bioenergy, hydrogen and hydrogen-based fuels enable deep emissions cuts in industry, transport and buildings. In 2022, electric vehicles reached 14% of global car sales. Spurred on by

high natural gas prices and government incentives, heat pump sales were very strong in 2022, with global sales increasing 11% from 2021 levels and sales in the EU alone rising almost 40% (IEA, 2023a).

Figure 2 ▹ Reduction in energy related CO_2 emissions by broad category of measure, 2035



Reaching NZE levels of emissions reductions requires strong action across all levers, but clean electricity and electrification provide the largest absolute reductions to 2035

Note: To reach current pledges refers to the reduction in emissions from STEPS to APS. To reach NZE refers to reduction in emissions from APS to the NZE Scenario. Other includes energy supply measures and other fuel switches.

- By 2030, the share of electric cars in global annual car sales needs to reach around 60% to be in line with the NZE Scenario, enabling significant emissions reductions as the stock of vehicles progressively becomes dominated by EVs, in tandem with the deployment of clean electricity. Similarly, the share of zero-emission medium and heavy freight trucks in global sales should reach around 35% by 2030. In the buildings sector, the share of electricity in residential and commercial buildings demand grows almost fifteen percentage points to 2030 in the NZE Scenario, driven by the electrification of end-uses through technologies such as heat-pumps. Global production of low-emissions hydrogen has to grow exponentially, reaching around 90 million tons (Mt) by 2030, enabling emissions reductions in industry and heavy-duty transport applications. The deployment of such low-emissions fuels enables reductions to start in sectors such as shipping, which sees CO_2 emissions decrease from 0.8 Gt in 2021 to 0.7 Gt in 2030 in the NZE Scenario, as the share of fossil fuels in the sector's consumption falls from essentially 100% in 2021 to around 80% in 2030.

- **Improving energy productivity**, or the ratio of economic output to energy input, is critical to reducing the required scale-up of low-emissions energy sources. In 2022, global energy productivity improved by 2%, a significant acceleration from the levels seen in 2020 and 2021. However, in the NZE Scenario, the annual rate of energy productivity improvement nearly triples to 2030 compared to average historical rates, reaching an annual rate of greater than 4% per year by 2030. Without this improvement in energy productivity, the size of the global energy system would be 20% larger in 2030 – equivalent to adding the energy consumption of China today.
- **Carbon management** via CCUS is a critical for the energy sector to reach net zero emissions by 2050. In 2022, around 44 million tons (Mt) of CO_2 were captured globally. To be in line with net zero emissions by 2050, global CO_2 capture in the energy sector needs to increase to 1.2 Gt by 2030. CCUS plays three important roles: providing a solution for hard-to-abate sectors such as cement process emissions; contributing to the production of low-emissions fuels including synthetic fuels; and removing carbon from the atmosphere (see Pillar 4 dedicated to this topic).

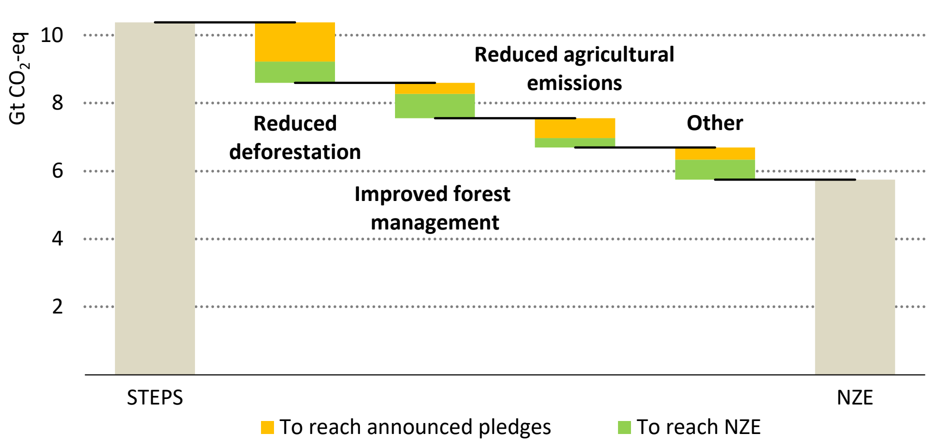
To achieve net zero CO_2 emissions by mid-century, countries need to strengthen both policy implementation and ambition. If policies were strengthened sufficiently to put all countries on a path to reaching their NDCs and net zero pledges, energy sector CO_2 emissions would start to decline decisively in this decade and would end the decade at 31.5 Gt, compared to 36 Gt in a scenario under today's policy settings. To limit the temperature rise to below 1.5 °C in 2100 would require steeper reductions in the near term. By 2030, energy related CO_2 emissions in the median low-overshoot 1.5 °C scenario assessed by the IPCC are around 22 Gt; in high-overshoot scenarios they are around 30 Gt. Delaying the enhancement of policy implementation and ambition would likely make reaching net zero emissions by 2050 infeasible.

The transformation of the global energy sector needs to be led above all by a huge scale-up of investment in clean energy technologies. In the NZE Scenario, global investment in clean energy technology deployment almost quadruples by 2030, from a recent annual average of USD 1.2 trillion to USD 4.2 trillion. The needed increase in clean energy investment is most stark in emerging market and developing economies outside China, where clean energy investment needs to increase almost seven-fold by 2030. Achieving this will require a combination of scaled-up international public support, international private capital and domestic investment, facilitated by stronger and more effective policies.

Pillar 2: zero net deforestation by 2030 and other land use actions

Agriculture, forestry and other land use[4] (AFOLU) is responsible for around one-fifth of global anthropogenic GHG emissions. Around one-half of AFOLU-related GHG emissions is from CO_2, one-third from methane, and the remainder from nitrous oxide (N_2O). Addressing these emissions therefore plays an integral role in limiting warming to 1.5 °C. For example, in low-overshoot 1.5 °C scenarios considered by the IPCC, GHG emissions from AFOLU fall by 30-63% between 2020 and 2030, with CO_2 emissions reaching net-zero around 2030. In these scenarios, the land sector also plays a key role in offsetting remaining GHG emissions from other sectors (e.g., from the energy sector, industrial processes and waste) by *removing* on average around 2.6 Gt CO_2 per year between 2050 – 2100. AFOLU methane and N_2O emissions are discussed in more detail in in Pillar 3.

Figure 3 ▷ Reduction in greenhouse gas emissions from AFOLU by measure in 2030



Stopping deforestation has the biggest impact in reducing GHG emissions to align with the NZE pathway

Note: Other = Afforestation and other land use changes, including short rotation plantations and reforestation of other natural land.

Analysis carried out for the IEA by the International Institute for Applied Systems Analysis (IIASA) indicates that GHG emissions[5] from AFOLU would fall from around 12 Gt CO_2-eq per year in 2021 to around 10 Gt CO_2-eq by 2030 under stated policies. The Glasgow Leaders'

[4] Other land use refers to land not covered by the following categories: forest land, cropland, agriculture, grassland, and settlements.

[5] Here and subsequently CO_2-eq values are quoted based on GWP100.

Declaration on Forests and Land Use and other announced pledges related to AFOLU would reduce net GHG emissions in 2030 by a further 2.4 Gt CO_2-eq. However, this falls short of what would be needed to put the world on a 1.5 °C pathway. In the IEA's NZE Scenario, GHG emissions from AFOLU in 2030 are about 2 Gt CO_2-eq lower than if all currently announced pledges were to be met in full and on time.

Alongside stopping deforestation, the majority of the additional abatement must come from improved management of existing forests, reduction of agricultural non-CO_2 emissions (for example through improvements in enteric fermentation and manure management), and measures related to other land use changes such as the establishment of forest plantations (Figure 3). In the NZE Scenario, early action on afforestation is also crucial for long-term emissions reductions after 2030. For example, around 50 million hectares (equivalent to twice the size of the United Kingdom) of additional forests are planted to 2030, which starts to pay significant dividends in terms of CO_2 removals only after 2050.

Pillar 3: mitigation of non-CO_2 emissions

In addition to cutting CO_2, rapid reductions in emissions of other GHGs are required in all scenarios which limit warming to 1.5 °C. These reductions of non-CO_2 GHGs, particularly of methane, have an outsized impact on global temperatures in the short term, as many of them are short-lived climate forcers[6] with powerful warming potentials but short atmospheric lifetimes (IPCC, 2021b). Cutting these emissions quickly can limit the duration and magnitude of the temperature overshoot above 1.5 °C.

The temperature rise in recent years stands at around 1.2 °C above pre-industrial levels. In the STEPS scenario, the temperature rise reaches around 1.9 °C by 2050, whereas in the NZE scenario, it is just over 1.5 °C by that time. About 40% of the additional warming in STEPS is caused by non-CO_2 emissions, with methane accounting for about 30% of the warming, nitrous oxide (N_2O) for around 5%, and the other gases for around 5% (Figure 4).

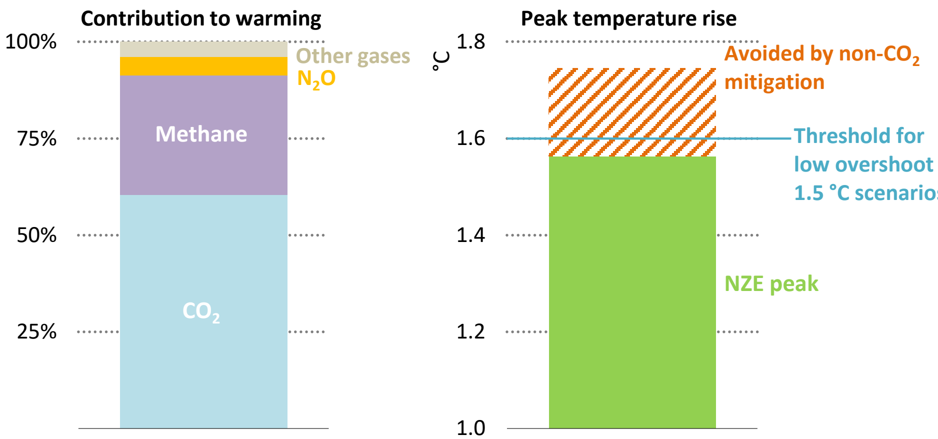
Our analysis[7] suggests that without the strong mitigation of non-CO_2 GHGs in the NZE Scenario, the peak temperature rise would be around 0.2 °C higher. This is sufficient to take the NZE Scenario from a low- to high-overshoot 1.5 °C scenario (as defined by the IPCC). Lack of action on non-CO_2 GHGs would also result in the temperature rise surpassing 1.5 °C for much longer than the 20-year overshoot that happens in the NZE — meaning that CO_2 removals after 2050 would likely need to be larger to return to below 1.5 °C by 2100. The physical hazards and consequential risks associated with global warming of this duration would pose severe threats to societies, economies and eco-systems. Higher peak temperatures over longer periods of time also increase the likelihood of inducing irreversible

[6] Short-lived climate forcers include methane, nitrogen oxides, aerosols and some halogenated compounds. Over 10 - 20 years, the global temperature response resulting from a single year of current emissions of short-lived climate forcers is at least as large as that from a single year of current CO_2 emissions (IPCC, 2021a).

[7] This analysis is based on a future pathway for non-CO_2 GHG emissions as in the STEPS Scenario.

climate tipping points, such as the collapse of the Greenland and West Antarctic ice sheets or widespread abrupt permafrost thaw.

Figure 4 ▻ Contribution to warming by GHG in STEPS vs NZE, 2022 – 2050 and temperature rise avoided by mitigation of non-CO_2 GHGs.



CO_2 is responsible for just 60% of the warming to 2050; mitigation of non-CO_2 GHGs is essential to keep peak temperatures below the low overshoot threshold of 1.6 °C.

Note: Other gases = F-gases and Montreal Protocol GHGs. Source: IEA analysis based on outputs of MAGICC 7.5.3.

Methane is responsible for around 30% of the rise in global temperatures since the Industrial Revolution, and cutting methane emissions in the NZE Scenario has the single biggest impact after CO_2 on limiting the temperature rise to 2050. One hundred and fifty countries have now joined the Global Methane Pledge, which was launched at COP26 in 2021 and aims to reduce methane emissions from human activity by at least 30% from 2020 levels by 2030. The energy sector accounts for around 40% of total methane emissions attributable to human activity, second only to agriculture. In the NZE Scenario, methane emissions from the energy sector fall by around 75% between 2020 and 2030 and total methane emissions from human activity fall by around 45%. The IEA's latest update of its Global Methane Tracker found that methane emissions from oil and gas alone could be reduced by 75% with existing technologies. Around $100 billion in total investment is needed over the period to 2030 to achieve this reduction—equivalent to less than 3% of oil and gas net income in 2022. To address methane emissions from fossil energy production and consumption, countries covering over half of global gas imports and over one-third of global gas exports released a Joint Declaration from Energy Importers and Exporters on Reducing Greenhouse Gas Emissions from Fossil Fuels at COP27 calling for minimizing flaring, methane, and CO_2 emissions across the supply chain to the fullest extent practicable.

Government-led actions have also been put forward to tackle other GHGs. For example, in 2016, the Kigali Amendment to the Montreal Protocol called for a phase-down of hydrofluorocarbon (HFC) production and consumption by 80-85%, to be reached in advanced economies by 2036 and in emerging market and developing economies by 2047 to tackle the climate impacts of HFC emissions. As of March 2023, parties representing over 80% of global GHG emissions have joined the amendment. There are significant opportunities for even further benefits from countries taking early action and pairing their HFC phase-down schedules with more energy efficient appliances that require lower amounts of refrigerants or other HFCs (IEA, 2022c).

Tackling emissions of nitrous oxide (N_2O) is also important to achieve climate goals. The agricultural sector is responsible for about four-fifths of anthropogenic N_2O emissions. In the STEPS, agricultural N_2O emissions rise by around 8% to 2030 compared to 2021 levels, whereas in the NZE Scenario they fall by around 2% over this period, mainly due to efficiency gains in crop management and fertilizer use. The majority of energy-related N_2O emissions today are associated with the industry sector and road transport. In the NZE Scenario, energy-related N_2O emissions fall by around 30% between 2021 - 2030, almost entirely associated with reductions in coal and oil use.

Sustainable development goals related to tackling air pollution or providing clean energy access can also mitigate non-CO_2 GHGs as a co-benefit. For example, achieving universal access to clean cooking by 2030 in the NZE scenario cuts GHG emissions by almost 900 Mt CO_2-eq due to the avoided release of methane and N_2O from traditional use of biomass, and it also reduces emissions of black carbon.

Pillar 4: carbon management

Carbon management refers to technologies and processes enabling the capture, use and storage of carbon, both from point sources like power plant and industry smokestacks but also from the atmosphere. As net atmospheric removals from the land-use sector were dealt with under Pillar 2, the discussion here focuses on energy sector carbon management. Essentially all scenarios that limit warming to 1.5 °C make use of energy sector carbon management to play three roles:

- Carbon capture and storage (CCS) avoids emissions to the atmosphere in sectors where alternative clean energy technologies are expensive or lacking, such as industrial process emissions, and from existing electricity or industrial facilities, many of which were built in the past decade.
- Carbon capture and use (CCU) provides a carbon feedstock for the production of synthetic fuels critical to decarbonising sectors like aviation. If the source of this carbon feedstock is atmospheric[8], the resulting fuel is climate neutral.

[8] An atmospheric source of carbon can include direct capture of CO_2 from atmosphere (direct air capture) or indirect capture mediated by plant photosynthesis.

- Carbon dioxide removal (CDR) can also compensate for continued emissions in sectors where reductions are hardest, and – if removals exceed gross emissions – can additionally provide net negative emissions to draw down carbon from the atmosphere and thereby reduce global temperatures. CDR can occur directly through direct air capture and storage (DACS) or indirectly through the process of atmospheric carbon uptake in the process of biomass growth, in the case of bioenergy with carbon capture and storage (BECCS).

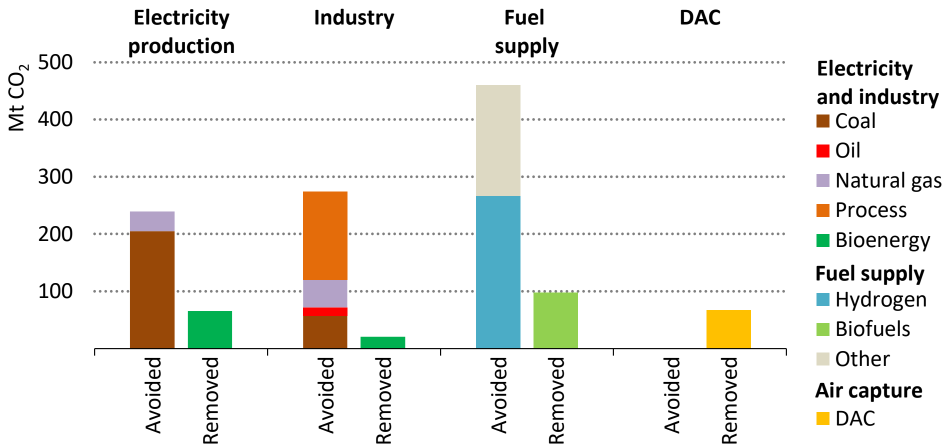
Even if clean technologies outside of carbon management are deployed aggressively, carbon management will be needed to meet climate goals. By 2030, about 1.2 Gt are captured annually across the energy system in the NZE Scenario. This represents almost a 30-fold increase on 2021 levels. Based on current project pipelines, annual carbon capture is projected to reach about 0.3 Gt by 2030. This implies that the current pipeline of projects would need to grow by four times to reach NZE levels by 2030.

Of the 1.2 Gt of carbon management required in the NZE in 2030, about one-third is used to mitigate emissions from fossil fuel combustion in sectors like industry and electricity generation. However, renewables remain the main driver of emissions reductions in the power sector, making up around 60% of total power generation in the NZE in 2030, while fossil plants equipped with carbon capture make up less than 1%. Another one-third avoids process emissions in industrial sectors and hydrogen production. One-fifth relates to removals from the atmosphere. Most of this comes from BECCS in the electricity, industry, and biofuels production sectors. DACS is also scaled up, reaching nearly 70 million tons by 2030 (Figure 5). However, the project pipeline for DAC is growing rapidly. If all announced projects were to advance, DAC deployment would reach NZE Scenario requirements for 2030, although the technology would need to grow very rapidly after 2030 in order to be in line with a 1.5 °C scenario (IEA, 2023).

Carbon management technologies are an important strategic tool in strong mitigation scenarios, but by no means a silver bullet. The scale of deployment required in the NZE Scenario is huge, equivalent to ten new CCUS-equipped facilities commissioned each month between now and 2030.

CDR technologies do not remove the need for deep emissions cuts. In the NZE Scenario, 1.5 Gt of CO_2 per year are removed from the atmosphere with CDR technologies by 2050, balancing residual gross emissions and bringing net CO_2 emissions to zero. However, if the world overshoots the available CO_2 budget for 1.5 °C or if gross emissions aren't reduced as strongly as in the NZE Scenario, additional CDR would be required.

Figure 5 ⊳ Total CO_2 capture by sector and type in the NZE, 2030



Carbon capture technologies play an important role across the whole energy sector, but particularly in mitigating process emissions from industrial and fuel production

Notes: DAC = direct air capture. Not all the carbon dioxide removal shown in the figure (shaded areas) is permanent, as some of the captured atmospheric carbon is used for example for synthetic fuels production.

This additional CDR would have significant trade-offs. For example, high overshoot 1.5 °C scenarios assessed by the IPCC see annually about 7 Gt CO_2 of BECCS and DACS in 2060. Achieving this with a mix of BECCS and DACS could require:

- A land area equivalent to the current cropland of the United States to supply bioenergy[9].
- About 760 GW of additional wind and solar generation capacity (almost equivalent to the current combined capacity of the European Union, United States, India and Japan).
- Thermal energy almost equivalent to the 2021 natural gas consumption of the European Union.

[9] Land area requirements calculated here assume a bioenergy supply similar to that used in the IEA NZE in 2050. Part of the bioenergy supply requires land use in the form of cropland, marginal land, pasture land, and managed forested land, complemented by wastes and residues which do not require land use (IEA, 2021).

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