Net Zero Roadmap

A Global Pathway to Keep the 1.5 °C Goal in Reach

2023 Update

International Energy Agency

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The publication of the first Net Zero Roadmap by the International Energy Agency (IEA) in May 2021 was a landmark moment for the energy and climate world, setting out what would need to happen in the global energy sector in the years and decades ahead to limit global warming to 1.5 °C. The interest in the report was huge. The world finally had an authoritative benchmark for what a clear pathway to net zero energy sector CO_2 emissions by 2050 would look like – something against which the proliferation of net zero pledges could be compared.

The significance of the report was reflected by the massive number of readers it attracted online. It quickly became our most viewed and downloaded publication ever, a sign of the strong demand for clear and unbiased analysis, translating the temperature goals of the Paris Agreement into practical milestones for the global energy sector. Our Roadmap became a reference point for governments, companies, investors and civil society, helping inform discussions and decision-making on pursuing secure, inclusive and affordable transitions to clean energy.

Much has happened since its launch two and half years ago: first, the strong and carbon-intensive economic recovery from the Covid crisis; then, the global energy crisis triggered by Russia's invasion of Ukraine. The negative consequences of these major events include the rise of global energy-related carbon dioxide emissions to a new record in 2022 and increased investment in new fossil fuel projects.

However, we have also seen some extremely positive developments, most notably the rapid progress of key clean energy technologies, such as solar PV and electric vehicles, backed by significant policy efforts to advance them further. Recognising the importance of these industries of the future for energy security and economic competitiveness, countries around the world are seeking to boost their clean technology manufacturing capacities, driving a resurgence in industrial policy. Innovation is also accelerating, strengthening the pipeline of technologies that will be needed to complete the world's journey to net zero.

At the same time, the case for climate action is stronger than ever. July 2023 was the hottest month on record – and 2023 as a whole appears likely to become the hottest year. Severe wildfires, droughts, floods and storms further underlined that the climate crisis is with us and that the costs are mounting. Politically, this year is an important test for the Paris Agreement, with the first Global Stocktake at the COP28 Climate Conference providing a comprehensive assessment of where things stand five years on. To succeed, it needs to set a course for all countries to step up to meet the challenge.

With this in mind, the IEA is therefore providing a 2023 update to our Net Zero Roadmap, drawing on the latest data and analysis to map out what the global energy sector would need to do, especially in the crucial period between now and 2030, to play its part in keeping the 1.5 °C goal in reach. The findings are clear: while the global pathway to net zero by 2050 we mapped out previously has narrowed, it is still achievable. It is too soon to give up on 1.5 °C. And I would like to underscore that net zero by 2050 globally doesn't mean net zero by 2050 for every country. In our pathway, advanced economies reach net zero sooner to allow emerging and developing economies more time.

Among the wealth of insights contained in this report, I would like to highlight one message in particular: in an era of international tensions, governments need to separate climate from geopolitics. Meeting the shared goal of preventing global warming from going beyond critical thresholds requires stronger cooperation not fragmentation. Climate change is indifferent to geopolitical rivalries and national boundaries – in its causes and its effects. What matters is emissions, regardless of which country produces them, calling for leadership on collaborative efforts to tackle them. As this Roadmap makes clear, we have the proven technologies and policies to reduce those emissions quickly enough this decade to keep 1.5 °C in reach. All countries need to work together to make that happen or we all lose in the end.

I hope the insights this report offers will inform international discussions going into COP28 and beyond. For the rigorous and incisive analysis it contains, I'd like to thank my colleagues who led the work, Laura Cozzi and Timur Gül, and their excellent teams.

Dr Fatih Birol
Executive Director
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Annexes

In 2021, the IEA published its landmark report, Net Zero by 2050: A Roadmap for the Global Energy Sector. Since then, the energy sector has seen major shifts. Based on the latest data on technologies, markets and policies, this report presents an updated version of the Net Zero Emissions by 2050 (NZE) Scenario; a pathway, but not the only one, for the energy sector to achieve net zero CO_2 emissions by 2050 and play its part, as the largest source of greenhouse gas emissions, in achieving the 1.5 °C goal.

The path to 1.5 °C has narrowed, but clean energy growth is keeping it open

The case for transforming the global energy system in line with the 1.5 °C goal has never been stronger. August 2023 was the hottest on record by a large margin, and the hottest month ever after July 2023. The impacts of climate change are increasingly frequent and severe, and scientific warnings about the dangers of the current pathway have become stronger than ever.

Global carbon dioxide (CO_2) emissions from the energy sector reached a new record high of 37 billion tonnes (Gt) in 2022, **1% above their pre-pandemic level, but are set to peak this decade**. The speed of the roll-out of key clean energy technologies means that the IEA now projects that demand for coal, oil and natural gas will all peak this decade even without any new climate policies. This is encouraging, but not nearly enough for the 1.5 °C goal.

Positive developments over the past two years include solar PV installations and electric car sales tracking in line with the milestones set out for them in our 2021 *Net Zero by 2050* report. In response to the pandemic and the global energy crisis triggered by Russia's invasion of Ukraine, governments around the world announced a raft of measures designed to promote the uptake of a range of clean energy technologies. Industry is ramping up quickly to supply many of them. If fully implemented, currently announced manufacturing capacity expansions for solar PV and batteries would be sufficient to meet demand by 2030 in this update of the NZE Scenario.

We have the tools needed to go much faster

Ramping up renewables, improving energy efficiency, cutting methane emissions and increasing electrification with technologies available today deliver more than 80% of the emissions reductions needed by 2030. The key actions required to bend the emissions curve sharply downwards by 2030 are well understood, most often cost effective and are taking place at an accelerating rate. The scaling up of clean energy is the main factor behind a decline of fossil fuel demand of over 25% this decade in the NZE Scenario. But well-designed policies, such as the early retirement or repurposing of coal-fired power plants, are key to facilitate declines in fossil fuel demand and create additional room for clean energy to expand. In the NZE Scenario, strong growth in clean energy and other policy measures together lead to energy sector CO_2 emissions falling by 35% by 2030 compared to 2022.

Renewables and efficiency are key to drive fossil fuel demand down

Tripling global installed renewables capacity to 11 000 gigawatts by 2030 provides the largest emissions reductions to 2030 in the NZE Scenario. Renewable electricity sources, in particular solar PV and wind, are widely available, well understood, and often rapidly deployable and cost effective. Current policy settings already put advanced economies and China on track to achieve 85% of their contribution to this global goal, but stronger policies and international support are required in other emerging market and developing economies. For all countries, speeding up permitting, extending and modernising electricity grids, addressing supply chain bottlenecks, and securely integrating variable renewables are critical.

Doubling the annual rate of energy intensity improvement by 2030 in the NZE Scenario saves the energy equivalent of all oil consumption in road transport today, reduces emissions, boosts energy security and improves affordability. Although the mix of priorities will differ by country, at the global level energy intensity improvements stem from three equally important actions: improving the technical efficiency of equipment such as electric motors and air conditioners; switching to more efficient fuels, in particular electricity, and clean cooking solutions in low-income countries; and using energy and materials more efficiently.

These two actions reduce fossil fuel demand, enabling continued adherence to a key milestone of our 2021 report: an immediate end to new approvals of unabated coal plants.

Accelerating electrification and cutting methane are also essential

Booming technologies like electric vehicles and heat pumps drive electrification across the energy system, providing nearly one-fifth of the emissions reductions to 2030 in the NZE Scenario. Recent growth puts electric car sales on track to account for two-thirds of new car sales by 2030 – a critical milestone in the NZE Scenario. Announced production targets from car makers underscore that this high share is achievable. Heat pump sales increased by 11% globally in 2022, and many markets, notably in the European Union, are already tracking ahead of the roughly 20% annual growth rate needed to 2030 in the NZE Scenario. China remains the world's largest market for heat pumps.

Cutting methane emissions from the energy sector by 75% by 2030 is one of the least cost opportunities to limit global warming in the near term. Strong reductions in both energy sector CO_2 and methane emissions are essential to meeting the 1.5 °C goal. Without efforts to reduce methane emissions from fossil fuel supply, global energy sector CO_2 emissions would need to reach net zero by around 2045, with important implications for equitable pathways. Reducing methane emissions from oil and natural gas operations by 75% costs around USD 75 billion in cumulative spending to 2030, equivalent to just 2% of the net income received by the oil and gas industry in 2022. Much of this would be accompanied by net cost savings through the sale of captured methane.

Innovation is already delivering new tools and lowering their cost

In the 2021 NZE Scenario, technologies not available on the market at the time delivered nearly half of the emissions reductions needed in 2050 to reach net zero; that number has fallen to around 35% in this update. Progress has been rapid: for example, the first commercialisation of sodium-ion batteries was announced for 2023, and commercial-scale demonstrations of solid oxide hydrogen electrolysers are now underway.

But we still need to do much more, notably on infrastructure

Today much of the momentum is in small, modular clean energy technologies like solar PV and batteries, but these alone are not sufficient to deliver net zero emissions. It will also require: large new, smarter and repurposed infrastructure networks; large quantities of low-emissions fuels; technologies to capture CO_2 from smokestacks and the atmosphere; more nuclear power; and large land areas for renewables.

Electricity transmission and distribution grids need to expand by around 2 million kilometres each year to 2030 to meet the needs of the NZE Scenario. Building grids today can take more than a decade, with permitting a particularly time-consuming bottleneck. The same is true for other kinds of energy infrastructure. Policy makers, industry and civil society need to work together to nurture a "build big" mentality and to expedite decision making, while preserving public engagement and respecting environmental safeguards.

Carbon capture, utilisation and storage (CCUS), **hydrogen and hydrogen-based fuels, and sustainable bioenergy are critical to achieve net zero emissions; rapid progress is needed by 2030.** The history of CCUS has largely been one of underperformance. Although the recent surge of announced projects for CCUS and hydrogen is encouraging, the majority have yet to reach final investment decision and need further policy support to boost demand and facilitate new enabling infrastructure.

Increasing clean energy investment in developing countries is vital

The world is set to invest a record USD 1.8 trillion in clean energy in 2023: this needs to climb to around USD 4.5 trillion a year by the early 2030s to be in line with our pathway. Clean energy investment is paid back over time through lower fuel bills. By 2050, energy sector investment and fuel bills are lower than today as a share of global GDP. The sharpest jump in clean energy investment is needed in emerging market and developing economies other than China, where it surges sevenfold by the early 2030s in the NZE Scenario. This will require stronger domestic policies together with enhanced and more effective international support. Annual concessional funding for clean energy in emerging market and developing economies will need to reach around USD 80-100 billion by the early 2030s.

As clean energy expands and fossil fuel demand declines in the NZE Scenario, there is no need for investment in new coal, oil and natural gas

Stringent and effective policies in the NZE Scenario spur clean energy deployment and cut fossil fuel demand by more than 25% by 2030 and 80% in 2050. Coal demand falls from around 5 800 million tonnes of coal equivalent (Mtce) in 2022 to 3 250 Mtce by 2030 and around 500 Mtce by 2050. Oil declines from around 100 million barrels per day (mb/d) to 77 mb/d by 2030 and 24 mb/d by 2050. Natural gas demand drops from 4 150 billion cubic metres (bcm) in 2022 to 3 400 bcm in 2030 and 900 bcm in 2050.

No new long-lead time upstream oil and gas projects are needed in the NZE Scenario, neither are new coal mines, mine extensions or new unabated coal plants. Nonetheless, continued investment is required in existing oil and gas assets and already approved projects**.** Sequencing the decline of fossil fuel supply investment and the increase in clean energy investment is vital if damaging price spikes or supply gluts are to be avoided.

The drop in fossil fuel demand and supply reduces traditional risks to energy security, but they do not disappear – especially in a complex and low trust geopolitical environment. In the NZE Scenario, higher cost producers are squeezed out of a declining market and supply starts to concentrate in large resource-holders whose economies are most vulnerable to the process of change. But attempts by governments to prioritise domestic production must recognise the risk of locking in emissions that could push the world over the 1.5 °C threshold; and that, if the world is successful in bringing down fossil demand quickly enough to reach net zero emissions by 2050, new projects would face major commercial risks.

The net zero emissions transition must be secure and affordable

Particular attention needs to be paid to bridging the looming supply and demand gap for critical minerals. Announced mining projects for minerals such as nickel and lithium fall short of booming demand in the NZE Scenario in 2030. New projects, innovative extraction techniques, more recycling and material-efficient design can help to bridge this gap.

Extraordinary advances in clean energy technology supply chains have kept the door to net zero emissions open, but have been accompanied by a high degree of geographical concentration. The mining and refining of critical minerals are similarly highly concentrated. This presents an increased risk of disruption, such as from geopolitical tensions, extreme weather events or a simple industrial accident. While more diverse and resilient supply chains are highly desirable, the pace at which clean energy must be scaled up will be even harder to achieve without open supply chains.

As electricity becomes the "new oil" of the global energy system in the NZE Scenario, secure electricity supplies become even more important. The hugely increased need for electricity system flexibility requires massive growth of battery energy storage and demand response; expanded, modernised and cybersecure transmission and distribution grids, and more dispatchable low-emissions capacity, including fossil fuel capacity with CCUS, hydropower, biomass, nuclear, and hydrogen and ammonia-based plants.

By 2030 in the NZE Scenario, total household energy expenditure in emerging market and developing economies decreases by 12% from today's level, and even more in advanced economies. The decrease reflects large energy and cost savings from energy efficiency and electrification. However, policy makers need to support households, particularly low-income ones, to meet the often higher upfront costs of clean energy technologies.

There is no low international co-operation route to limit warming to 1.5 °C and no slow route either

By 2035, emissions need to decline by 80% in advanced economies and 60% in emerging market and developing economies compared to the 2022 level. Current Nationally Determined Contributions are not in line with countries' own net zero emissions pledges, and those pledges are not sufficient to put the world on a pathway to net zero emissions by 2050. COP28 and the first Global Stocktake under the Paris Agreement provide a key opportunity to enhance ambition and implementation.

As part of an equitable pathway to the global goal of net zero emissions by 2050, almost all countries need to bring forward their targeted net zero dates. In the NZE Scenario, advanced economies take the lead and reach net zero emissions by around 2045 in aggregate; China achieves net zero emissions around 2050; and other emerging market and developing economies do so only well after 2050. The NZE Scenario is a global but differentiated pathway: each country will follow its own route based on its resources and circumstances. However, all must act much more strongly than they are today. The net zero pathway achieves full access to modern forms of energy for all by 2030 through annual investment of nearly USD 45 billion per year — just over 1% of energy sector investment.

Our *Delayed Action Case* shows that failure to increase ambition to 2030 would create additional climate risks and make achieving the 1.5 °C goal dependant on the massive deployment of carbon removal technologies which are expensive and unproven at scale. Nearly 5 Gt CO_2 would have to be removed from the atmosphere every year during the second half of this century. If carbon removal technologies fail to deliver at such scale, returning the temperature to 1.5 °C would not be possible. Removing carbon from the atmosphere is costly and uncertain. We must do everything possible to stop putting it there in the first place.

The fierce urgency of now

The energy sector is changing faster than many people think, but much more needs to be done and time is short. Momentum is coming not just from the push to meet climate targets but also from the increasingly strong economic case for clean energy, energy security imperatives, and the jobs and industrial opportunities that accompany the new energy economy. Yet, momentum must be accelerated to be in line with the 1.5 °C goal and to ensure that the process of change works for everyone. Above all, this needs to be a unified effort in which governments put tensions aside and find ways to work together on what is the defining challenge of our time. All of us, and in particular future generations, will remember with gratitude those who act upon the urgency of now.

Progress in the clean energy transition

Bending the curve

S U M M A R Y

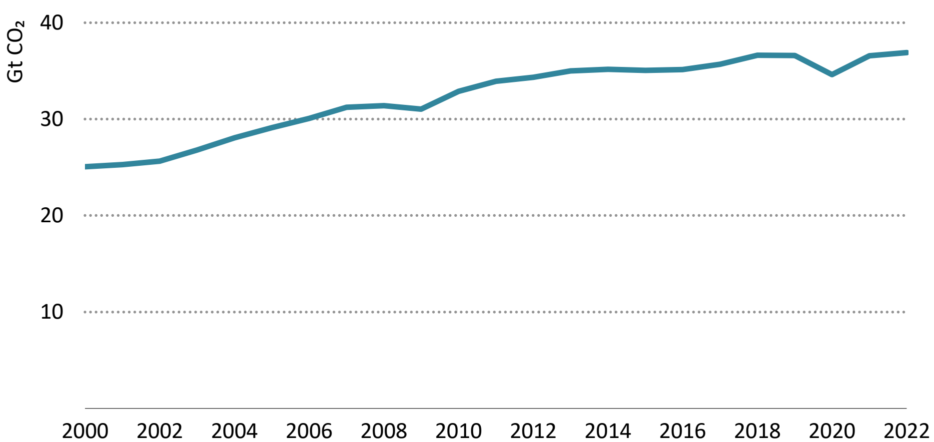
- The IEA's landmark report *Net Zero by 2050: A Roadmap for the Global Energy Sector* was published in 2021. It translates the goal of limiting global warming to 1.5 degrees Celsius (°C) into a concrete roadmap for the global energy sector. In the two years since then, the energy sector has undergone major shifts.
- Energy sector CO_2 emissions remain worryingly high, reaching a new record of 37 gigatonnes (Gt) in 2022. Instead of starting to fall as envisaged in the 2021 report, demand for fossil fuels has increased – spurred by the energy crisis of 2022 after Russia's invasion of Ukraine – and so have investments in supply. Progress on energy access has stalled while millions of people still lack access to electricity and clean cooking, notably in sub-Saharan Africa.
- On a brighter note, clean energy technology adoption surged at an unprecedented pace over the last two years. Solar PV capacity additions increased by nearly 50%, and currently track ahead of the trajectory envisaged in the 2021 version of our Net Zero Emissions by 2050 Scenario (NZE Scenario). Electric car sales expanded 240% and stationary battery installations by 200% since 2020. We now estimate that global manufacturing capacities for solar PV and electric vehicle batteries would be sufficient to meet projected demand in 2030 in the updated NZE Scenario, if announced projects proceed. This progress reflects cost reductions for key clean energy technologies – solar PV, wind, heat pumps and batteries – which fell by close to 80% on a deployment weighted average basis between 2010 and 2022.
- Driven by policies, expanding markets, and falling costs, clean energy technologies are shifting the outlook for emissions even under current policies. In the Stated Policies Scenario, emissions are now projected to be 7.5 Gt lower in 2030 than in our 2015 Pre-Paris Baseline Scenario, of which policy driven expansions of solar PV and wind account for 5 Gt and electric vehicles for nearly 1 Gt. This shift in the outlook means that the projected warming of 2.4 °C in 2100 under current policy settings, through still worryingly high, is now 1 °C lower than before the Paris Agreement in 2015.
- Nearly 90% of countries have updated their first Nationally Determined Contribution (NDC) under the Paris Agreement. If countries deliver in line with their revised NDCs, emissions in 2030 will be around 5 Gt lower than under the first round of NDCs. But more needs to be done to be on course by 2030 to deliver announced longer-term net zero pledges or our NZE Scenario. Both advanced economies and emerging market and developing economies need to strengthen ambition. Fair and effective international co-operation is urgently needed to unlock clean energy investment in emerging market and developing economies other than in China.

1.1 The context

Net Zero by 2050: A Roadmap for the Global Energy Sector was published in 2021 (IEA, 2021a). It translates the goal of limiting global warming to 1.5 °C into a concrete roadmap for the global energy sector. It describes *a* pathway, not *the* definitive pathway, to the goal of net zero emissions by 2050. It takes into account countries' varying circumstances and challenges.

An update of that roadmap is the focus of this report. It is based on recent developments in technologies, markets, policies and investment, and identifies what governments and other stakeholders need to do to keep alive the goal of net zero emissions by 2050. The importance of that goal has been underlined by a number of recent climate-related disasters, with 2023 seeing the hottest July and hottest August ever recorded.

Figure 1.1 ▷ Global energy sector CO_2 emissions, 2000-2022



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Global energy sector emissions have not fallen in the last two years, as envisaged in our 2021 roadmap, but instead have risen to record levels

The energy sector has undergone major shifts in the two years since the release of our 2021 report. Energy sector emissions have remained stubbornly high, reaching a new record of 37 gigatonnes (Gt) of carbon dioxide (CO_2) in 2022, 1% above the 2019 level (Figure 1.1).[1] Even with the very strong economic rebound in advanced economies since the Covid-19 pandemic, their emissions in 2022 were around 4% below the pre-pandemic level. By contrast, in emerging market and developing economies emissions were around 4.5% (roughly 1 Gt) above the 2019 level. This rise was largely driven by the People's Republic of

[1] Unless otherwise specified, energy sector emissions in this report refer to CO_2 emissions from fossil fuel combustion, industrial processes, and fugitive and flaring CO_2 from fossil fuel extraction.

China (hereinafter China), where emissions increased 7% between 2019 and 2022, relative to a 2% increase in other emerging market and developing economies.

Since the publication of the original *Net Zero by 2050* report, concerns about energy security have become more acute, in large part due to the invasion of Ukraine by the Russian Federation (hereinafter Russia) in 2022, which precipitated an unprecedented global energy crisis. Prices for energy commodities surged to five- to ten-times their historical levels in some instances, adding to the inflationary pressures that had been building in the wake of the Covid-19 pandemic. The crisis spurred an increase in clean energy deployment and investment, but also in investment in fossil fuel supply. Concerns about energy security will remain an important consideration in the development of policy frameworks that shape investment decisions.

Increasing geopolitical fractures have also stoked energy security concerns about the pronounced concentration in a small number of countries of both mining and processing of critical minerals and clean energy technology manufacturing. In response, several countries introduced measures that aim to promote the development of domestic supply chains. Such measures should help to scale up the supply of clean energy technologies but could also put at risk the benefits of global supply chains. More broadly, increased geopolitical fragmentation highlights the need for fair and effective international co-operation to achieve the clean energy transition.

Although fossil fuel demand has not yet started to fall, deployment and investment in some clean energy technology supply chains has risen very rapidly since the 2021 *Net Zero by 2050* report. This is partly thanks to stronger policy support in post-Covid-19 economic recovery packages and partly due to policy responses to the global energy crisis. Recent rates of growth for solar photovoltaics (PV) adoption and electric vehicles (EVs) sales have been particularly impressive. If all announced projects are realised, manufacturing capacity for solar PV will exceed the level required in 2030 in our 2021 Net Zero Emissions by 2050 (NZE) Scenario, and capacity for EV batteries will come very close to requirements. Progress in technologies such as wind power and carbon capture, utilisation and storage (CCUS) has been less rapid. Overall, recent progress on clean energy technologies has been encouraging, although much more remains to be done to get the world on track with the roadmap in the NZE Scenario.

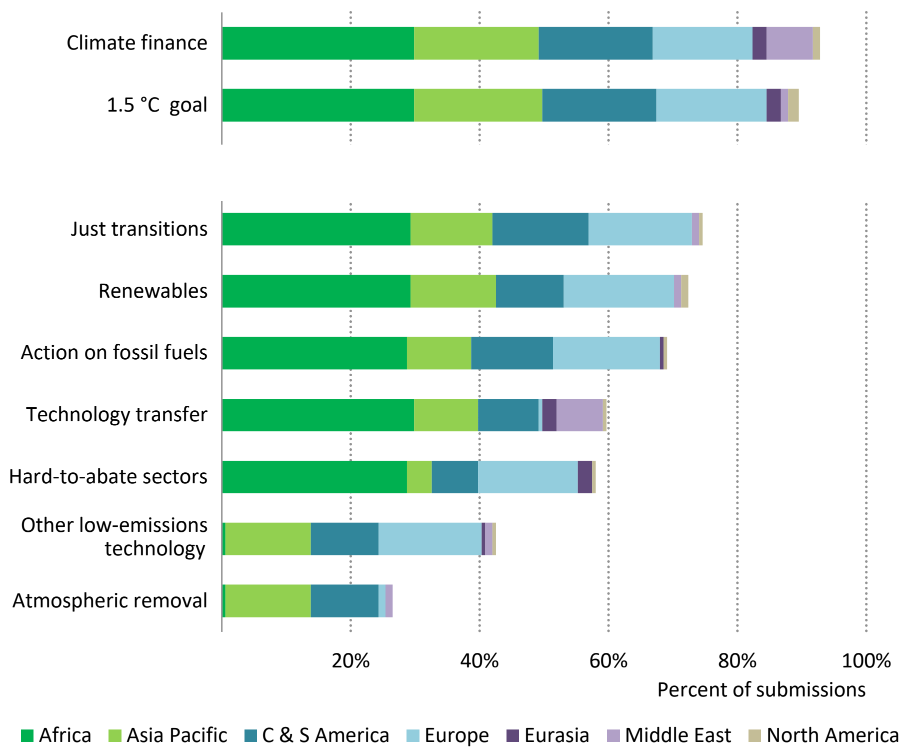
This report is being published in an important year for global climate change diplomacy. The sixth assessment cycle of the Intergovernmental Panel on Climate Change (IPCC) recently set out with greater clarity than ever before both the dangers of exceeding the 1.5 °C limit and the availability and cost effectiveness of a range of emissions reduction options. Alongside the IPCC scientific stocktaking, a political review of the progress towards internationally agreed climate goals concludes this year in the form of the first Global Stocktake under the Paris Agreement (see Spotlight).

SPOTLIGHT

First global stocktake under the Paris Agreement

The Global Stocktake (GST) is a process under the Paris Agreement designed to provide a regular assessment of collective progress towards the long-term goals of the Agreement in order to inform subsequent updates of Nationally Determined Contributions and enhance international co-operation on climate action. The first stocktake (GST1) started at 26th Conference of the Parties (COP) in 2021 and is expected to conclude at COP28 in 2023. Countries and other stakeholders have submitted more than 170 000 pages of input to the GST1. The 1.5 °C goal is a central priority of country submissions, as is the enhancement of climate finance (Figure 1.2).

Figure 1.2 ▷ Key aspects of energy transition mentioned in Global Stocktake submissions by region



Just transitions, renewables and action on fossil fuels are priority topics in the first global stocktake, alongside climate finance and the 1.5 °C goal

Note: C & S America = Central and South America; Europe = the geographical region, not the European Union.

The energy sector is a central component of the GST1 country submissions: 96% of the 181 countries included in our analysis indicate that mitigation action in the energy sector is a priority. Around 65% of countries, representing around 60% of global CO_2 emissions, indicate that just transitions, renewables and action on fossil fuels are priority topics for the energy sector. Other areas such as atmospheric removals are not yet perceived as priority for the GST1 by all countries.

At COP28, the GST1 will move to the final, political phase. How the outcomes of the GST1 process influence the ambition of the next round of NDCs, expected in 2025 ahead of COP30, will be the acid test of its success.

This report presents an updated NZE Scenario that takes account of an in-depth, sector-by-sector assessment of developments since 2021. It enhances the detail of what is needed to make the NZE Scenario a reality by region and technology. The analysis is presented in four chapters.

- Chapter 1 provides an overview of key developments in the energy sector in recent years. It takes stock of progress in the energy transition and development of clean energy technologies.
- Chapter 2 presents an updated NZE Scenario. It sets out some of the key differences with the 2021 version and provides high level "dashboards" to show how each sector and technology needs to contribute.
- Chapter 3 assesses in more depth how key sectors and technologies can make the progress assumed in the updated NZE Scenario and looks at the implications of not reaching the ambitious milestones set out for 2030.
- Chapter 4 focusses on the critical importance of energy security, equity and enhanced global co-operation for the pathway set out in the NZE Scenario.

1.2 Bending the emissions curve

Considerable progress has been made in deploying clean energy technologies and lowering their cost, which is altering the emissions outlook for the energy sector. IEA projections for global CO_2 emissions from the energy sector in the Stated Policies Scenario (STEPS) have been progressively revised downward compared with our Pre-Paris Baseline Scenario (IEA, 2021b). The Pre-Paris Baseline Scenario considered government policies in place in 2015 when the Paris Agreement on climate change was negotiated. On the basis of these policies, it projected a rise in average global temperature of 3.5 °C by 2100. In the latest version of the STEPS, the equivalent figure is 2.4 °C. This reflects progress made in the transition to a lower emissions energy system since 2015, although it still falls far short of what is needed to meet the temperature goals of the Paris Agreement.

Box 1.1 ▷ IEA scenarios

This report is based on an updated and revised **Net Zero Emissions by 2050 Scenario** (NZE Scenario), which sets out a pathway for the global energy sector to achieve net zero CO_2 emissions by 2050. (Chapter 2 provides a description of the design of the NZE Scenario.)

Three other scenarios are employed as benchmarks against which the NZE Scenario is compared:

- The **Stated Policies Scenario** (STEPS) projects energy demand and supply and their implications for emissions taking account of established and planned policies and regulations. It incorporates the most recent available data and projections on technology costs, manufacturing capacity and the industrial strategies of countries and companies operating in the energy sector.
- The **Announced Pledges Scenario** (APS) assumes that all climate commitments made by governments around the world, including all those set out in NDCs and long-term net zero emissions pledges, are met in full and on time.
- The **Pre-Paris Baseline Scenario** was produced in 2015. It is based on the policies that were in place at the time; it does not incorporate additional policy intentions and targets since then. It corresponds to the Current Policies Scenario set out in the 2015 edition of the *World Energy Outlook*.

Detailed projections and analysis of the updated STEPS and APS will be included in the *World Energy Outlook 2023*, to be released in October.

World

Global energy sector emissions were 37 gigatonnes (Gt) in 2022 – a record high and a 5% increase from 2015. Nonetheless, progress since the 2015 Paris Agreement means that the outlook in the STEPS sees emissions peak by the middle of this decade and fall to around 35 Gt by 2030, which is well below the level of around 43 Gt projected in the Pre-Paris Baseline Scenario (Figure 1.3). To put this in perspective, this 7.5 Gt difference is equal to the current combined energy sector emissions of the United States and European Union.

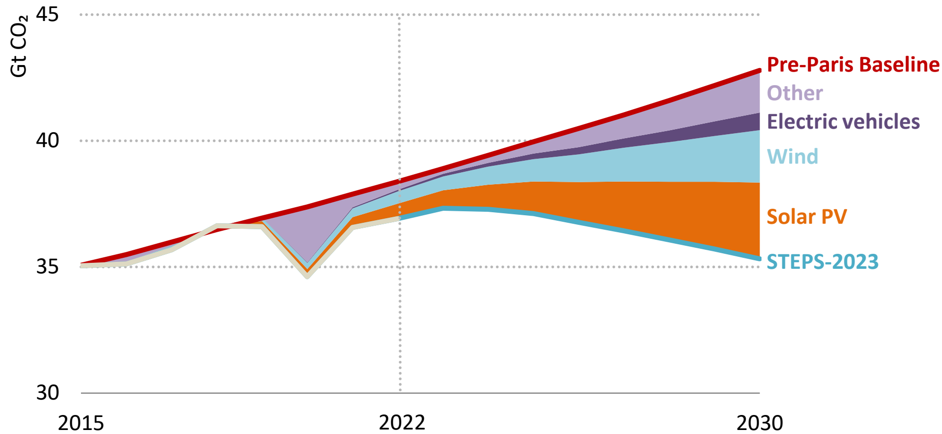
Three technologies contribute the bulk of the emissions reductions in the STEPS relative to the Pre-Paris Baseline Scenario: solar PV, wind and EVs.[2] Solar PV is projected to reduce emissions by around 3 Gt in 2030, roughly equivalent to the emissions from all the world's cars on the road today. Wind power reduces emissions by around 2 Gt in 2030 and EVs by around 1 Gt.[3] The latter reflects replacement of internal combustion engine (ICE) vehicles by

[2] STEPS refers to the 2023 version of the scenario in this report unless otherwise specified.

[3] The decomposition analysis in this section is based on direct emissions, with indirect emissions allocated to the electricity sector.

EVs which are increasingly powered by lower emissions electricity generation sources. Together numerous other smaller changes across all sectors reduce emissions by a further 1.5 Gt.

Figure 1.3 ▷ Global energy sector CO_2 emissions in the Pre-Paris Baseline Scenario and STEPS, 2015-2030



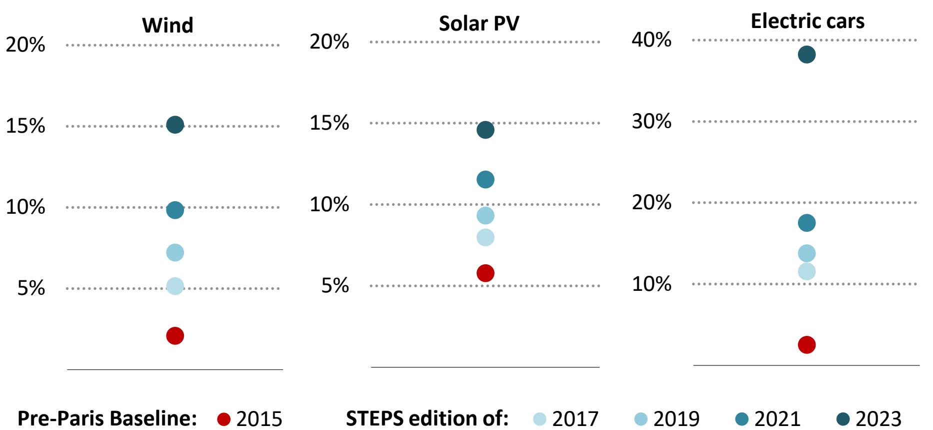
Solar PV, wind power and EVs reduce emissions by 6 Gt in 2030 in the STEPS relative to the Pre-Paris Baseline Scenario

Note: Other includes all other levers with downward or upward effects on the emissions difference between the Pre-Paris Baseline Scenario and the 2023 STEPS projections, as detailed in Figures 1.5-1.8.

In the Pre-Paris Baseline Scenario, only modest deployment of clean energy technologies was projected to 2030, based on the policies in place in 2015 (Figure 1.4). Wind power and solar PV were projected to account for less than 10% of global electricity generation in 2030, nearly four times lower than in the STEPS. EVs are projected to continue recent spectacular growth, accounting for more than one-third of car sales in 2030 in the STEPS compared with a small fraction in the Pre-Paris Baseline Scenario.

A significant strengthening of government policies in major economies is at the heart of this improvement. For example, successive five-years plans in China have progressively raised ambitions for solar PV and driven down global costs. Offshore wind deployment in Europe kick-started a global industry. EV targets, and fuel-economy and CO_2 emissions standards in the European Union and China – and more recently in the United States – have driven a major transformation in the industrial strategies of car and truck manufacturers. Similarly, electric two/three-wheelers and buses have seen significant uptake in India and other emerging market and developing economies thanks to policy support, increasing economic competitiveness and limited infrastructure needs. The United States, through the Inflation Reduction Act (IRA) adopted in 2022, has provided unprecedented funding to support deployment and reduce costs for a range of low-emissions technologies, notably CCUS and hydrogen. Progress across all sectors in other regions has also helped bend the global emissions curve. The following sections focus on key developments in selected economies which together account for over 60% of energy-related emissions today.

Figure 1.4 ▹ Wind power and solar PV in electricity generation, and electric cars in car sales, Pre-Paris Baseline Scenario and STEPS, 2030



IEA. CC BY 4.0.

Key clean energy technologies by 2030 in the STEPS have increased progressively since 2015 reflecting stronger policies and technological advances

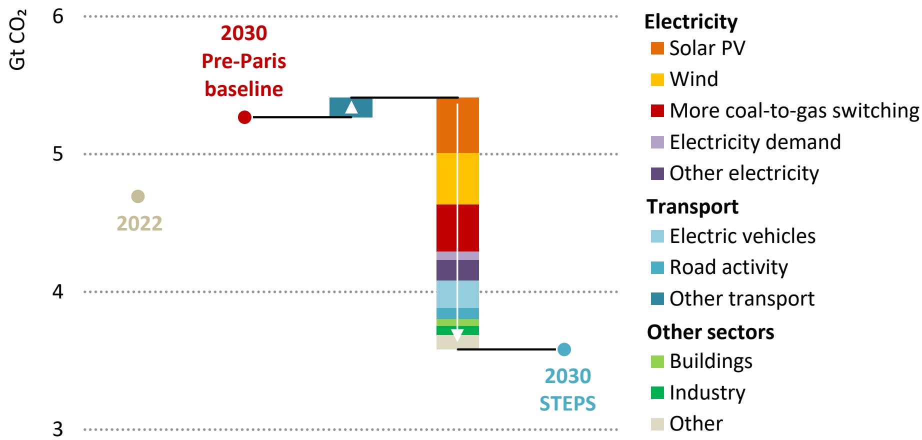
Notes: Wind and solar PV refer to the share of total electricity generation. Electric cars refer to the share of passenger light-duty vehicle sales.

United States

In the United States, CO_2 emissions in 2030 are 1.7 Gt lower in the outlook in the current STEPS than in the Pre-Paris Baseline Scenario, with solar PV and wind together accounting for around 0.8 Gt of the reduction (Figure 1.5). A larger switch from coal to natural gas for electricity generation accounts for around an additional 340 million tonnes (Mt) of CO_2 emissions reductions by 2030. The increased renewables projections reflect federal government subsidies, post Covid-19 recovery spending, carbon-free electricity targets in an increasing number of states, and large-scale support provided for a range of clean energy technologies by the IRA. Among others, the IRA includes substantial funding for energy efficiency measures in the buildings sector, manufacturing of low-emissions technologies and CCUS projects.

In the transport sector, the projected share of electric cars in total car sales in 2030 increases from less than 10% in the Pre-Paris Baseline Scenario to 50% in the STEPS. This upward revision reflects public charging infrastructure funding under the Infrastructure Investment and Jobs Act, new eligibility requirements for EV tax credits under the IRA, more stringent national fuel-economy standards, and more aggressive electrification strategies of car and truck manufacturers. Increased deployment of EVs accounts for 200 Mt of additional CO_2 emission reductions by 2030. However, these reductions are partially offset by an increase in the market share of sports utility vehicles (SUVs), which are less fuel efficient than standard passenger cars.

Figure 1.5 ▷ Energy sector CO_2 emissions in the United States in the Pre-Paris Baseline Scenario and STEPS, 2030



Nearly half of the emissions reductions in 2030 between the Pre-Paris Baseline Scenario and the 2023 STEPS are due to accelerated deployment of renewables in the power sector

Notes: Other electricity includes nuclear, hydropower, emissions intensity of heat generation and electricity sector efficiency. Other transport includes changes in the fuel economy of ICE vehicles and the deployment of biofuels. Buildings and industry refer to direct emissions in these sectors.

European Union and United Kingdom

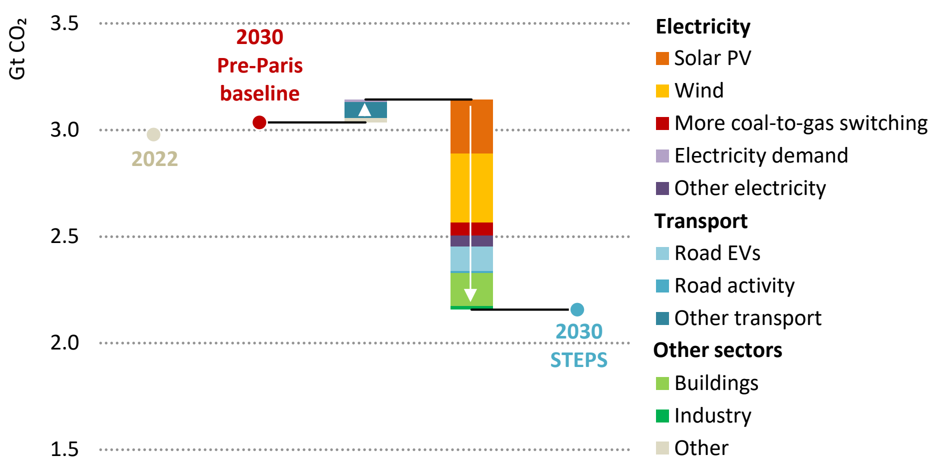
In the European Union and United Kingdom, CO_2 emissions projections in the STEPS are around 0.9 Gt lower than in the 2015 Pre-Paris Baseline Scenario (Figure 1.6). Two-thirds of the difference in 2030 are due to increased shares of wind and solar PV in electricity generation, driven by a range of new incentives and targets. A number of coal phase-out targets introduced in major European countries such as Germany, Italy and the United Kingdom between 2018 and 2020 also contribute to lower projected emissions in the electricity sector in the STEPS.

The buildings sector makes a big contribution to lower emissions, with CO_2 emissions 150 Mt lower in the STEPS than in the pre-Paris Baseline Scenario in 2030 thanks in part to the revised EU Energy Performance of Buildings Directive as well as new and expanded incentives for energy efficiency retrofits. An accelerated deployment of heat pumps under the REPowerEU Plan and a range of fossil fuel boiler bans also contribute to a smaller share of fossil fuels in heating demand in buildings, which is nearly 10 percentage points lower in 2030 in the STEPS than in the Pre-Paris Baseline Scenario.

The transport sector contributes through accelerated deployment of EVs, which reduce emissions by more than 100 Mt in 2030 compared with the 2015 projections. From a small fraction of annual cars sales by 2030 in the Pre-Paris Baseline Scenario, the projected share of electric cars increases to nearly two-in-three new cars in the STEPS, driven by new CO_2 standards, forthcoming bans on new ICE vehicles, EV incentives and investment in charging infrastructure. As in the United States, however, slower improvements in road transport fuel economy due to increasing SUV sales partially offset this gain.

In industry, strengthening of the European Union Emissions Trading Scheme is projected to lead to larger savings from energy-intensive industries in 2030 than previously projected, though much of this is outweighed by higher projections for industrial activity.

Figure 1.6 ▻ Energy sector CO_2 emissions in the European Union and the United Kingdom in the Pre-Paris Baseline Scenario and STEPS, 2030



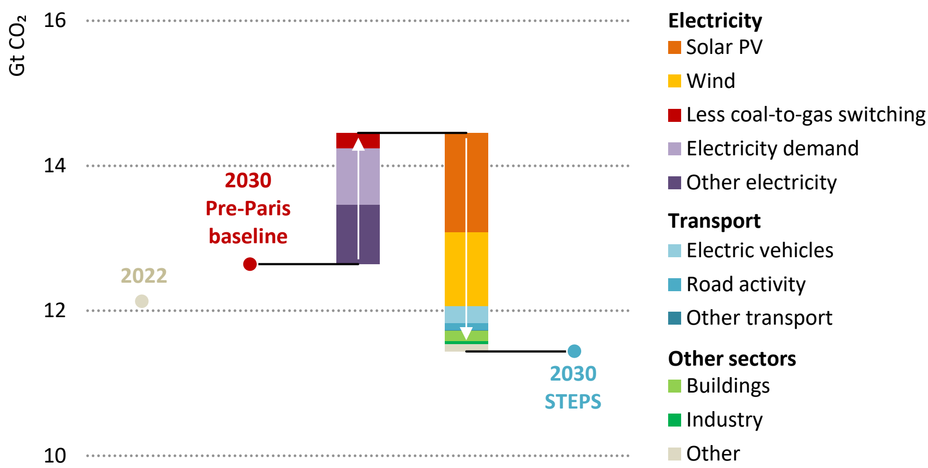
Two-thirds of the emissions reductions in 2030 between the Pre-Paris Baseline Scenario and the STEPS in Europe are due to accelerated deployment of wind and solar PV

Notes: Other electricity includes nuclear, hydropower, emissions intensity of heat generation and electricity sector efficiency. Other transport incudes the fuel economy of ICE vehicles and the deployment of biofuels. Buildings and industry refer to direct emissions in these sectors.

China

CO_2 emissions in China are projected to be around 1.2 Gt lower in 2030 in the STEPS than in the Pre-Paris Baseline Scenario (Figure 1.7). Solar PV and wind are the main drivers. In the Pre-Paris Baseline Scenario, wind and solar PV account for slightly less than 10% of total electricity generation in 2030; in the STEPS they account for more than one-third. This change reflects more ambitious renewables deployment goals in successive five-year plans and an increase from 20% to 25% in the updated NDC in the planned share of non-fossil fuel sources in primary energy by 2030.

Figure 1.7 ▷ Energy sector CO_2 emissions in China in the Pre-Paris Baseline Scenario and STEPS, 2030



Emissions in China in 2030 in the STEPS are projected to be 1.2 Gt lower than in the Pre-Paris Baseline Scenario, though rising coal demand partially offsets reductions from renewables

Notes: Other electricity includes nuclear, hydropower, emissions intensity of heat generation and electricity sector efficiency. Other transport incudes the fuel economy of ICE vehicles and the deployment of biofuels. Buildings and industry refer to direct emissions in these sectors.

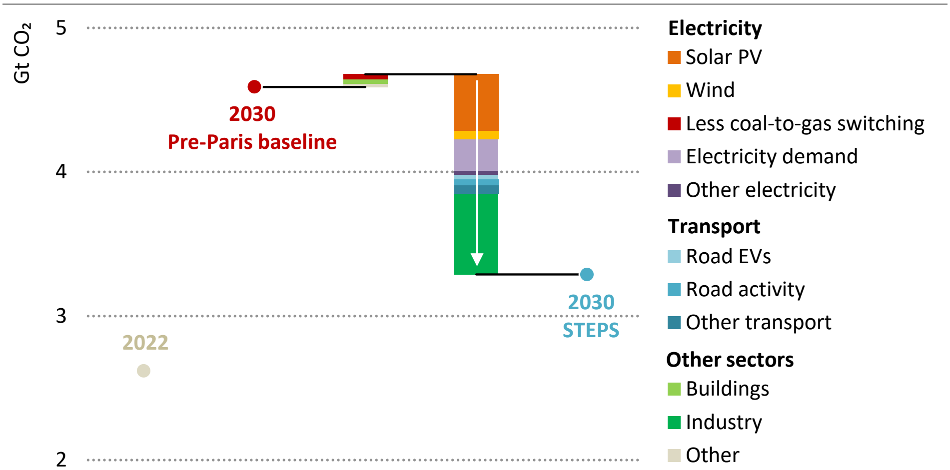
EVs are projected to reduce CO_2 emissions by around 250 Mt by 2030 in China in the STEPS relative to the Pre-Paris Baseline Scenario. Electric cars account for a tiny share of total car sales by 2030 in the Pre-Paris Baseline Scenario, but for two-thirds of all new car sales in the STEPS. In 2016, the government set a planning target for New Energy Vehicles (largely EVs) to reach 12% of total vehicle sales in 2020. In 2020, it set a new target of 20% of new vehicle sales in 2025 supported by large purchase subsidies and tax exemptions. These measures, together with continued policy support to promote EV manufacturing and high levels of EV sales in recent years, have led to successive upwards revisions in the STEPS projections of the EV share in total vehicle sales in 2030.

China's drive to increase electrification in the transport, buildings and industry sectors, together with strong demand growth in the manufacturing and residential sectors, has led to rapidly rising electricity demand. Between 2015 and 2022, China's electricity generation increased at more than 6% per year, faster than the rate of GDP growth. The massive expansion of China's low-emissions electricity generation during this period was not sufficient to meet demand, leading to an increase in coal-fired power generation. As a result, China's share in global coal-fired power generation increased by 10 percentage points during these years. This growth in coal-fired electricity generation moderates the emissions reductions in the STEPS relative to the Pre-Paris Baseline Scenario by 2030. In the longer term, however, China's early electrification of energy consumption will also bring lower CO_2 emissions in end-use sectors as power generation continues to decarbonise.

India

Projected CO_2 emissions in India in 2030 are 1.3 Gt lower in the STEPS than the Pre-Paris Baseline Scenario (Figure 1.8). The share of solar PV in power generation increases eightfold, saving nearly 400 Mt of emissions in 2030 in STEPS. In the Pre-Paris Baseline Scenario, wind and solar PV account for less than 10% of total generation in 2030; in the STEPS, this rises to around 25%. A key reason is the adoption in 2021 of a 500 gigawatt (GW) target for non-fossil fuel capacity by 2030. Compared with solar PV, wind power has made less progress, with projections for capacity deployment by 2030 in the STEPS only slightly larger than expected in Pre-Paris Baseline Scenario. This reflects a lack of progress in resolving land acquisition and tariff setting issues related to wind power developments.

Figure 1.8 ▷ Energy sector CO_2 emissions in India in the Pre-Paris Baseline Scenario and STEPS, 2030



India sees major emissions reductions from solar PV; lower GDP growth in STEPS as a result of the pandemic also reduces projected emissions

Notes: other electricity includes nuclear, hydropower, emissions intensity of heat generation and electricity sector efficiency. Other transport incudes the fuel economy of ICE vehicles and the deployment of biofuels. Buildings and industry refer to direct emissions in these sectors.

Changes in macroeconomic assumptions account for part of the difference in emissions between the Pre-Paris Baseline Scenario and the STEPS. India's GDP took a significant hit in the Covid-19 pandemic, and the subsequent growth projected in the STEPS is not sufficient to recover lost ground. Therefore, GDP in 2030 is slightly lower in the STEPS than in the Pre-Paris Baseline Scenario. As a result, industrial production and electricity demand are also somewhat lower, as are projected emissions in both the industry and electricity sectors.

1.3 Nationally Determined Contributions and Net Zero Emissions Pledges

Despite the progress in recent years, national commitments to reduce emissions collectively fall short of what is required by 2030 to bring global emissions down to a level in line with achieving net zero emissions by 2050. In addition, the various commitments are not yet underpinned by sufficiently strong and comprehensive policies to give confidence that they will be successfully delivered. Both advanced economies and emerging market and developing economies need to strengthen their implementation of pledges and to raise their level of ambition, including through the submission of stronger NDCs at the international level (see Chapter 4).

1.3.1 Nationally Determined Contributions

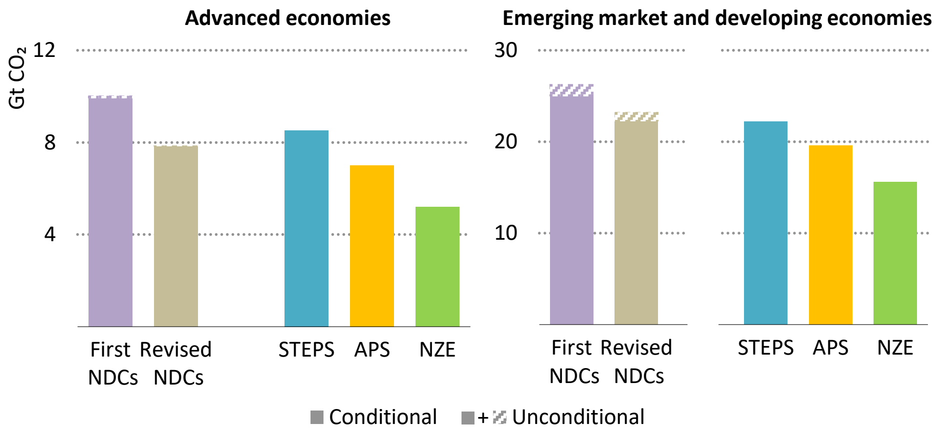
The Paris Agreement requires all countries to submit Nationally Determined Contributions (NDCs) that set out their climate targets. As of July 2023, 168 NDCs had been submitted, covering 195 Parties to the United Nations Framework Convention on Climate Change (UNFCCC).[4] Successive Conferences of the Parties (COPs) have encouraged countries to update their first NDCs to increase their ambition. So far, nearly 90% of NDCs have been updated since the first submission.

The revisions have led to a significant reduction in targeted emissions in 2030 totalling around 5 Gt, if all targets conditional on international support are reached (Figure 1.9).[5] According to IEA analysis, advanced economies were projected to emit slightly less than 10 Gt of CO_2 emissions from fuel combustion in 2030 under the first round of NDCs; revised NDCs have lowered this by around 2.1 Gt, or around 20%. Full implementation of NDCs in advanced economies would still see emissions of around 5.5 tonnes per capita in 2030, about 1 tonne per capita more than the current world average, but about 2 tonnes less than in China today. In emerging market and developing economies, the picture is somewhat different. In aggregate, revised NDCs in emerging market and developing economies lowered emissions compared to their first NDCs by 2.8 Gt, mostly driven by revisions unconditional on financial support.

[4] 194 countries and one region, the European Union, whose member states submit a joint NDC.

[5] The analysis in this section refers to emissions from fuel combustion and excludes industrial process emissions and international bunkers. It considers that conditional mitigation pledges put forward by some developing economies in their NDCs are fully achieved.

Figure 1.9 ▷ CO_2 emissions from fuel combustion implied by NDCs and in IEA scenarios by region, 2030



Revised NDCs boost the reduction in targeted emissions by around 5 Gt CO_2 in 2030, this is far short of what is needed to be on track for net zero emissions by 2050

However, IEA analysis suggests that planned energy policies in emerging market and developing economies are already more ambitious in the aggregate than their NDCs indicate, particularly in the case of conditional NDCs. Their emissions in the STEPS in 2030 are accordingly lower, by 1 Gt, than under their revised unconditional NDCs. The picture is reversed in advanced economies, where emissions in 2030 are nearly 0.7 Gt higher in the STEPS than in revised NDCs, implying that the policies currently in place are inadequate to meet stated NDCs, let alone longer-term net zero emissions pledges.

1.3.2 Net zero emissions pledges

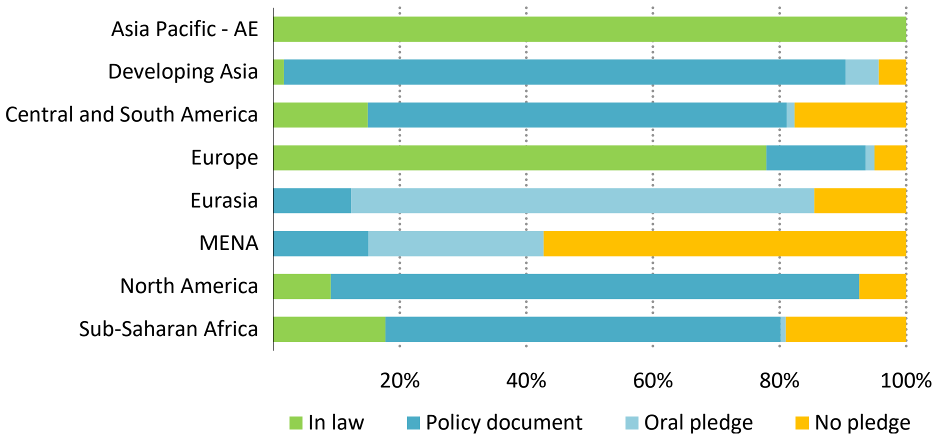
As of September 2023, net zero emissions pledges[6] cover more than 85% of global energy-related emissions and nearly 90% of global GDP. To date, 94 countries and the European Union have pledged to meet a net zero emissions target. Some countries have also communicated their net zero emissions pledges to the UNFCCC in the form of long-term low-emissions strategies. These strategies do not have the same legal force under the Paris Agreement as NDCs, but they are important as they provide a signal of country ambitions to contribute to the collective goal of net zero emissions.

Increasing numbers of countries have adopted a net zero emissions target in national law. Collectively, they currently account for about one-fifth of global energy sector emissions. The

[6] Net zero emissions pledges and targets here include climate neutrality (all greenhouse gases) and carbon neutrality (CO_2 only) objectives. As of August 2023, out of the 88 net zero emissions pledges formulated by countries, 83% have a target comprising all greenhouse gases and 17% a target on only CO_2 emissions.

advanced economies in Asia Pacific and Europe are the leaders in this regard: 100% of energy-related emissions are covered by a net zero emissions target in national law in advanced economies in the Asia Pacific region and about 80% in Europe, including through the EU Climate Law (Figure 1.10).[7]

Figure 1.10 ▷ Energy-related CO_2 emissions covered by a government net zero emissions pledge by type and by region



The bulk of emissions are covered by some form of net zero emissions pledge in all regions except the Middle East and North Africa

Note: Asia Pacific - AE includes Australia, Korea, Japan and New Zealand; MENA includes the Middle East and North Africa country groups.

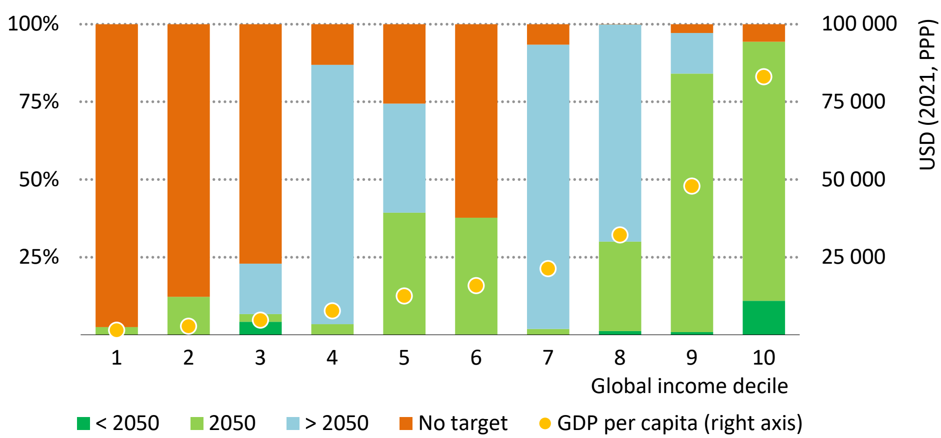
The majority of emissions in emerging market and developing economies in Central and South America, Eurasia, North America and sub-Saharan Africa are covered by net zero emissions pledges, but mostly in a non-legally binding policy document or in an oral pledge. In the Middle East and North Africa (MENA), 11 countries out of 17 have yet to adopt a net zero emissions target: if Egypt, Iran and Algeria adopted such a target, they would collectively cover almost 90% of CO_2 energy-related emissions in the MENA region.

The overwhelming majority of net zero emissions pledges cover all sectors of an economy, and all cover the energy sector. However, as many countries include the land use, land-use change and forestry sector in their projections, and account for this as an emissions sink, the pace of emissions reduction in the energy sector is usually slower than in the IEA scenarios. Setting more transparent net zero emissions targets, for instance by specifying the absolute level of emission reductions foreseen by the goal year and, separately, the level of emission removals, would help bring more clarity and trust to the process.

[7] This 80% coverage refers to the geographical region of Europe, not just the European Union.

Countries have varying starting points and levels of responsibility and capabilities. Consequently, they have adopted various timeframes for their net zero emissions pledges. In general, advanced economies have put forward net zero emissions pledges with the earliest target years. About 30% of current global energy-related CO_2 emissions are covered by net zero emissions pledges by 2050 or sooner, but the share is close to 95% in those countries in the highest decile of global income distribution, e.g. Finland (climate neutral by 2035), Iceland and Austria (climate neutral by 2040), and Germany and Sweden (climate neutral by 2045) (Figure 1.11).

Figure 1.11 ⊳ Energy sector CO_2 emissions covered by net zero emissions targets by net zero year and per capita income group



Ambition of net zero emissions target dates tends to correlate with development levels; almost all countries would need to bring the date forward to align with the NZE Scenario

Note: GDP = gross domestic product; PPP = purchasing power parity.

The picture is more mixed in other deciles. Some countries in the top 30-40% of the global income distribution have net zero emissions targets after 2050 or no target at all, such as Kuwait and Qatar (no target), and Bahrain and Saudi Arabia (climate neutral by 2060). Some countries moved their target year forward. For instance, in 2021 Germany advanced its climate neutrality goal from 2050 to 2045 and Brazil from 2060 to 2050. In its updated NDC, China pledged to peak its emissions before 2030 and to target carbon neutrality by 2060 at the latest.

1.4 Clean energy technologies

1

Development and deployment of clean energy technologies have progressed significantly since the adoption of the Paris Agreement in 2015, boosted recently by stimulus spending related to the Covid-19 pandemic, the response from governments and investors to the global energy crisis, and growing commercial and geopolitical competition for markets and supply chains.

1.4.1 Deployment

Mass manufactured technologies are leading the way

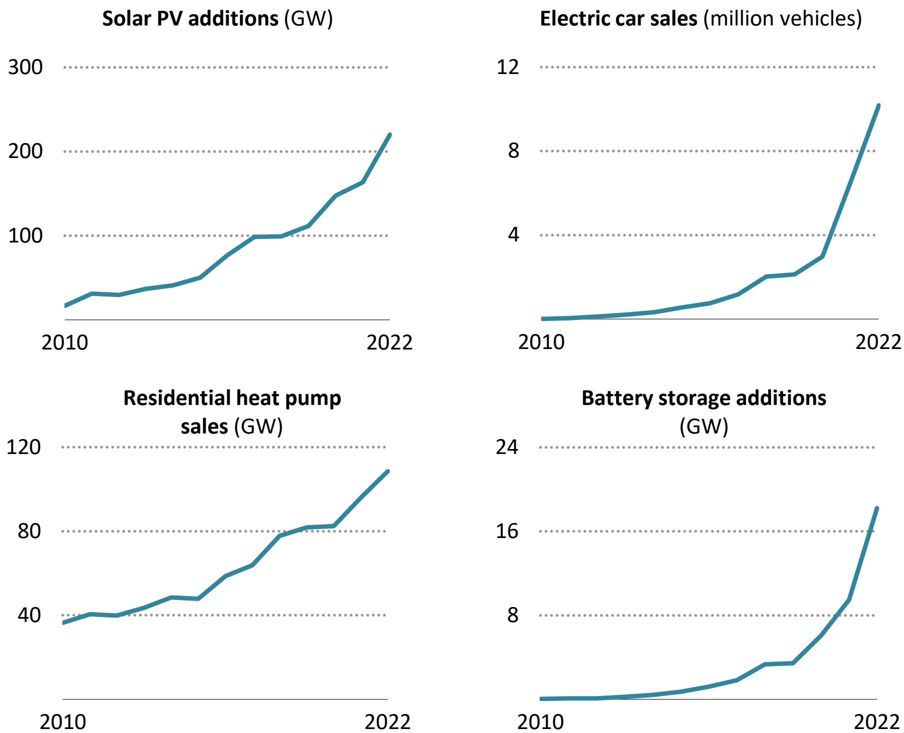
The deployment of many clean energy technologies has accelerated markedly since 2015 (Figure 1.12) (IEA, 2023a). Mass manufactured technologies have seen the fastest growth, benefiting from standardisation and short lead times. For example, between 2015 and 2022:

- *Solar PV* capacity additions increased by more than 400%, with almost 1 terawatt (TW) of capacity added, nearly equivalent to the total installed electricity capacity in the European Union.
- *Electric car* sales increased by nearly 2 000%, with over 25 million sold over the period, equivalent to more than all the cars on the road in Canada.
- *Residential heat pump* sales increased by 225%, with approximately 600 GW sold, approximately equivalent to the entire residential heating capacity in Russia.
- *Stationary battery storage* capacity additions increased by 2 500%, with nearly 45 GW installed, approximately equivalent to the total installed electricity capacity in Argentina.

The acceleration in clean technology deployment has been particularly strong in the last two years. Around one-third of all PV solar deployment to date took place in 2021 and 2022, and the figures are even higher for some other clean energy technologies: about 60% for both electric car sales and for the installation of stationary batteries. Actual installations for solar PV in 2022 and estimated installations for 2023 track ahead of the level projected in the IEA Net Zero by 2050 report in 2021 (IEA, 2021a). Emerging technologies such as electrolysers for hydrogen production are also moving forward, with total global installed electrolyser capacity more than doubling in the last two years, reaching nearly 700 megawatts (MW) in 2022. Manufacturing capacity for clean energy technologies is scaling up quickly, suggesting that deployment will continue to increase strongly in the coming years.

Important and impressive as this progress is, there is much more to be done. The slow pace of the turnover of the stock of most types of energy-related equipment means that there is a considerable lag between a technology becoming dominant in new deployments and that technology becoming dominant in the overall operating stock, underlining the urgent need for continued action to further boost deployment in the near term to be on track to reach net zero emissions by 2050 (see Chapter 3).

Figure 1.12 ▷ Global installations of selected clean energy technologies, 2010-2022

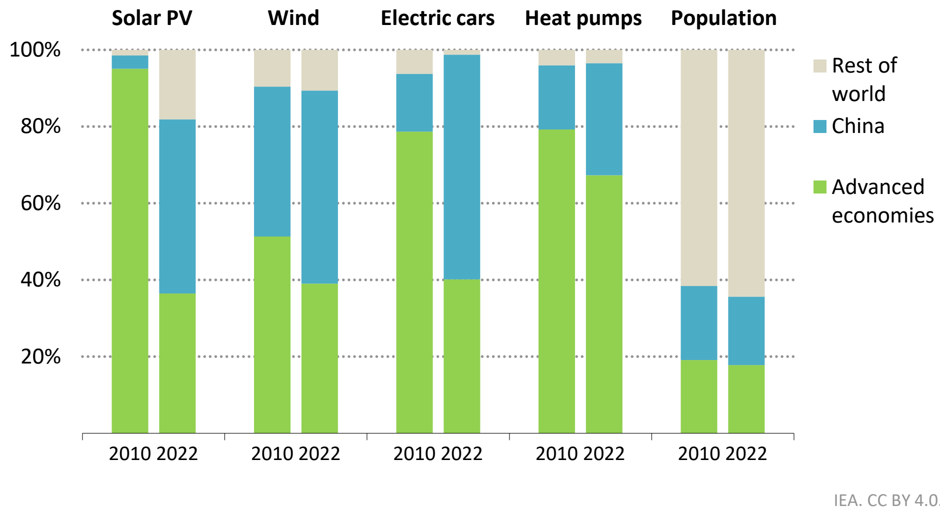


Deployment of a number of key clean technologies has accelerated significantly since the Paris Agreement in 2015

Moreover, deployment has been uneven across regions, with the strongest progress in regions with supportive policy environments, and strong financial and technical capabilities. From 2015 to 2022, advanced economies and China together accounted for over 95% of global electric car and heat pumps sales and nearly 85% of combined wind and solar capacity additions (Figure 1.13). Nevertheless, some technologies have expanded strongly in some other countries. For instance, India has seen particularly rapid progress in solar PV deployment.

The rapid growth in clean energy technologies has occurred in parallel with a trend towards declining deployment of new fossil fuel-based equipment in several areas. Fossil fuel-based electricity capacity additions peaked in 2012 and declined to less than half their peak level by 2022, while sales of ICE vehicles peaked in 2017 with a 25% decline from this peak by 2022. As a result, clean energy technologies have expanded in both absolute terms and market share.

Figure 1.13 ▷ **Share of the global deployment of selected clean energy technologies in advanced economies and China, 2010 and 2022**



Deployment of clean energy technologies remains highly concentrated in China and advanced economies

Notes: Solar PV and wind indicate capacity additions. Electric cars and heat pumps indicate sales.

Box 1.2 ▷ **Comparative pace of the clean energy transition**

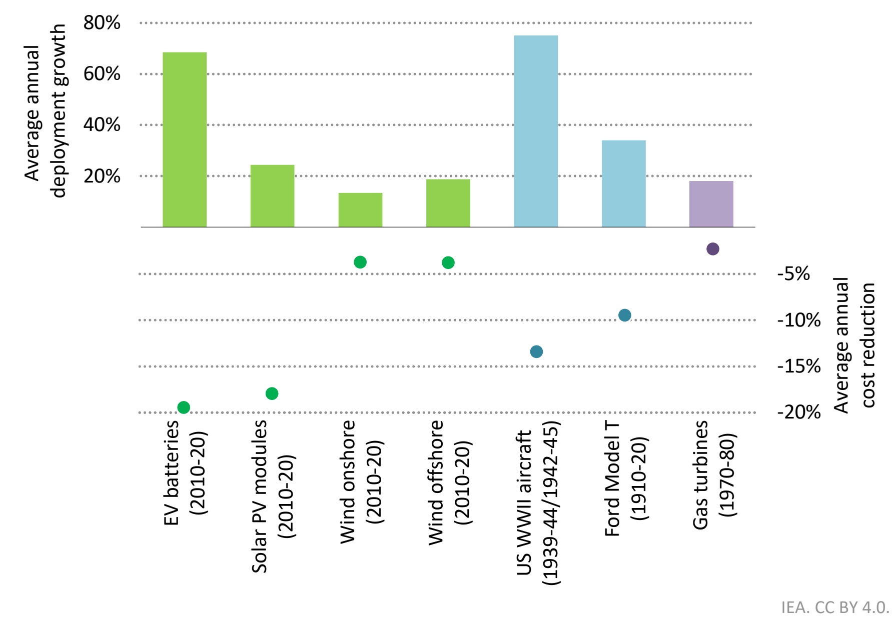
Comparing current events to what happened in the past is not without pitfalls, as no historical analogy is a perfect fit. Nonetheless, looking at how technologies went from niche to mass deployment in the past is a useful way to contextualise the changes underway for clean energy technologies.

Some technologies experienced remarkably rapid growth in the past (Figure 1.14). For instance, US aircraft production rose by an annual average of 75% between 1939 and 1944, driven by a seismic shift to a wartime economy. The Ford Model T achieved an annual average production growth rate of 34% in the 1910s, thanks to innovation in mass production and the assembly line. These transitions were truly transformational, kick-starting the commercial aviation industry and the advent of affordable cars.

EV batteries and solar PV have also experienced rapid deployment growth by historical standards. Average annual deployment growth of EV batteries between 2010 and 2020 was 70%, with solar PV at 24%. Although this level of deployment growth is slightly less than achieved in the case of US aircraft production between 1939 and 1944, the annual average cost reduction for both EV batteries (19%) and solar PV modules (18%), powered by high levels of standardisation in manufacturing, outstrip the average cost declines seen in both US aircraft production from 1942-1945 and the Ford Model T in the 1910s.

There have been even faster examples of technology transitions, though arguably less comparable. For example, computer memory prices reduced each year by an average of about 35% between both 1980-1990 and 1990-2000 (McCallum, 2023).

Figure 1.14 ▷ Deployment growth and cost reduction of clean energy technologies, 2010-2020 relative to selected historical technology transitions



Batteries and solar PV have progressed at rates comparable to some of the most rapid historic technology transitions

Note: The datasets for US Aircraft production in WWII runs from 1939 to 1944 for average annual deployment growth and from 1942 to 1945 for average annual cost reduction.

Sources: Lafond, Greenwald and Farmer (2022); Zeitlin (1995); Abernathy and Wayne (1974); Grubler Nakicenovic and Victor, (1999).

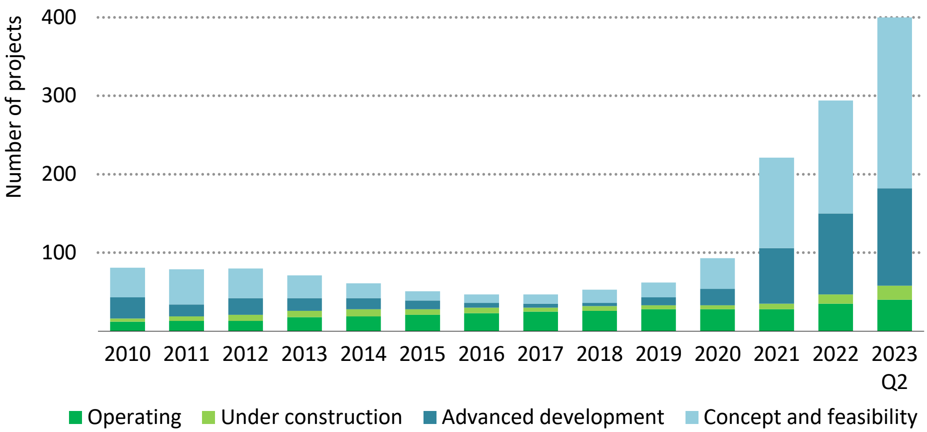
Other technologies such as wind so far have followed a somewhat slower average deployment trajectory, comparable to past transitions such as the introduction of gas turbines in the 1970s, while still exhibiting annual growth rates of 10-20%.

Although progress on some clean technologies compares favourably to historic transformational examples, the example of US WWII aircraft production in particular suggests that even faster deployment could be achieved through more research and development (R&D) funding and more concerted government action.

Plans for large-scale technology projects are starting to increase rapidly

Large-scale technologies, such as CCUS, liquid biofuel or hydrogen-based steel production, have seen slower deployment over the last decade than smaller mass manufactured and modular technologies. For example, less new CO_2 capture capacity was added between 2015 and 2022 than between 2010 and 2015. Large-scale technologies usually need to be tailored to site-specific conditions and, due to their large unit sizes, offer fewer opportunities for learning-by-doing advances than smaller and more modular technologies. This tends to mean slower cost improvements. Some large-scale technologies are not yet available on the market, which also hinders immediate commercial deployment.

Figure 1.15 ▷ Global CO_2 capture project pipeline, 2010-2023



There has been strong growth in the project pipeline for CO_2 capture in recent years, implying that installed capacity is set to rise significantly

Notes: Includes all facilities with a capacity larger than 0.1 Mt CO_2 per year. Q2 = second quarter. Under construction = a final investment decision has been announced and construction is ongoing or imminent. Advanced development = project is at front-end engineering and design stage and/or engineers have been contracted and/or engineering, procurement, and construction have been announced.

In recent years, however, the number of announced projects for large-scale technologies has increased significantly. For example, the number of CCUS projects in the pipeline nearly tripled in 2021 and have nearly doubled again since then (Figure 1.15), driven by stronger policy support, particularly in the United States (IEA, 2023b). If all projects in the pipeline were realised, CO_2 capture capacity would expand more than eight-fold, rising from about 45 Mt today to reach nearly 400 Mt per year in 2030, and CO_2 storage capacity would increase to comparable levels (see Chapter 3). However, so far only about 5% of announced projects have reached the final investment decision stage. Rapid acceleration of the deployment of large-scale, site-specific technologies will require additional policy support, including through measures to encourage investment in key enabling infrastructure such as

CO_2 storage facilities, to facilitate the demonstration and commercialisation of emerging technologies, and to create larger and more international markets for low-emissions products.

Box 1.3 ▷ Clean Technology Deployment Index

It can be hard to grasp the nature and extent of the changes taking place in the global energy system and benchmark them against what needs to happen to meet the goals of the Paris Agreement. The difficulty is increased by the size and complexity of the system and by the slow rate of turnover of the huge stocks of often long-lived energy-related infrastructure and equipment.

In order to provide a succinct and high-level summary of the rate of change, this report has created a **Clean Technology Deployment Index** (CTDI). The CTDI has been developed by:

- Gathering data on the historical annual deployment of clean energy technologies and providing an estimate of expected deployment in 2023.
- Indexing the historical annual values for each technology to the annual average deployment of that technology in the NZE Scenario in the period 2028-2032.
- Weighting each technology according to its share in global emissions reductions in the NZE Scenario in 2030 (see Chapter 2, section 2.1.3).

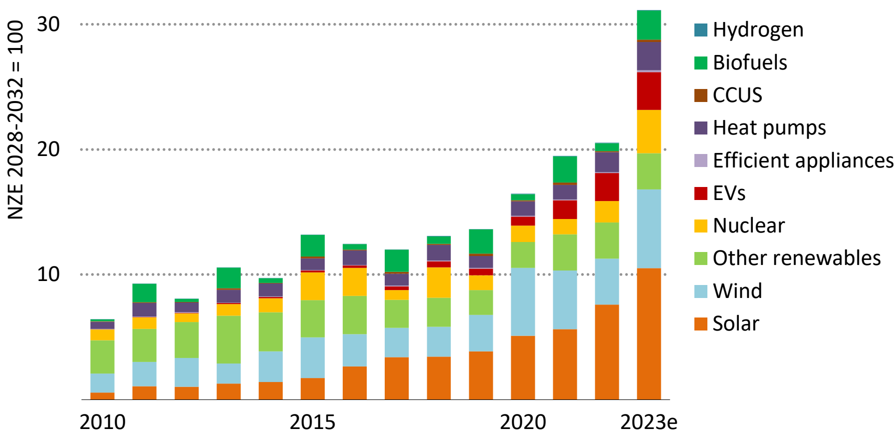
This methodology means that the CTDI gives an aggregate measure of how far current clean energy deployment levels are from the level required in 2030 in the NZE Scenario. An index value of 100 would mean that clean energy deployment captured in the index collectively reaches the level required in 2030. The estimated index value for 2023 of just over 30 implies that current levels of deployment of clean energy technologies are about one-third of the level required in 2030 in the NZE Scenario (Figure 1.16).

Between 2010 and 2023, deployment of clean energy technologies as measured by the CTDI rose at an average annual rate of around 13%, leading the index value to increase by 5-times over the period. There has been a clear acceleration in recent years, with clean energy technology deployment more than doubling between 2019 and the 2023 estimate, achieving an average annual growth rate of over 20%. This compares to an average annual growth rate of just under 20% needed from 2023 to 2030 to align with the NZE pathway.

The CTDI needs to be interpreted with a degree of caution. One reason is that the composition of clean energy technology deployment matters as much as the rate. Surging ahead on one technology and falling behind on another might lead to a short-term boost in the CTDI score without putting the energy system as a whole on a pathway to net zero emissions by mid-century. In addition, the NZE Scenario is one pathway to net zero emissions by 2050, and benchmarking current clean technology deployment against the needs of alternative pathways would yield somewhat different results. Nonetheless, the

CTDI has value in showing the acceleration in deployment seen in recent years, as well as in giving an indication of the levels of deployment needed over the course of this decade to be on track to reach net zero emissions by mid-century.

Figure 1.16 ▷ Clean Technology Deployment Index



Deployment of clean technologies has increased significantly since 2010

Notes: CCUS = carbon capture, utilisation and storage. 2023e = estimated values for 2023 based on the latest available data by technology and project pipeline data.

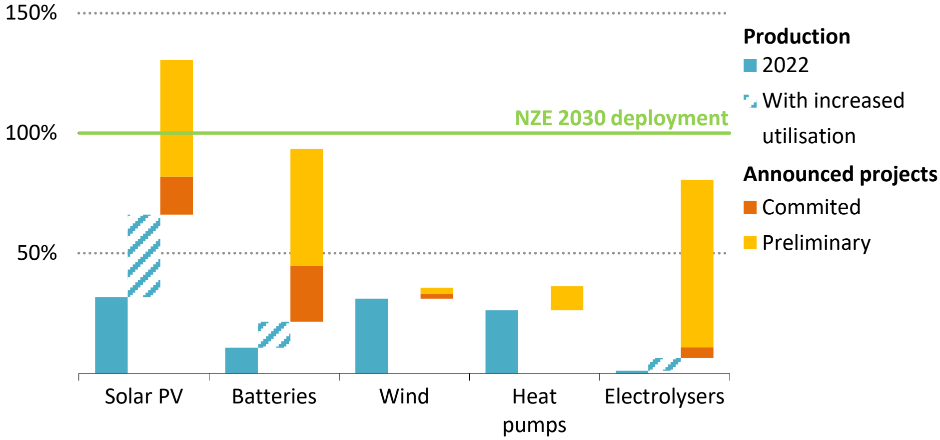
1.4.2 Supply chains

Clean energy technology supply chains have been scaling up rapidly in recent years. Progress has been particularly fast in the manufacturing segment, where countries are competing to secure a place in the new global energy economy. For example, the nascent manufacturing sectors of solar PV in the early 2000s and of batteries in the 2010s have become vast industries (IEA, 2023c). The speed of expansion has exceeded what was expected just a few years ago, which has boosted hopes of getting the energy transition as a whole on track for net zero emissions by 2050 (see Chapter 2).

Manufacturing capacity for some critical technologies is expanding rapidly

Clean technology manufacturing capacity posted strong year-on-year growth rates in 2022 for batteries (+72%), solar PV (+39%), electrolysers (+26%) and heat pumps (+13%). This momentum shows no sign of slowing in the near term given the pipeline of announced manufacturing projects continuing to expand rapidly (Figure 1.17). In the first quarter of 2023 alone, new announcements of solar PV manufacturing projects would increase projected output by around 60% in 2030; the projected increase for batteries would be around 25% and for electrolysers around 30% (IEA, 2023d).

Figure 1.17 ⊳ Announced manufacturing project throughput and deployment of key technologies in the NZE Scenario, 2030



If all announced projects proceed, solar PV manufacturing would exceed and batteries manufacturing would get very close to the 2030 levels required in the NZE Scenario

Notes: 2022 production values reflect actual utilisation rates. A utilisation rate of 85% is used for both existing and announced manufacturing capacity in 2030. Increased utilisation indicates that utilisation of existing manufacturing capacity increases from current rates, which can be relatively low in some cases, to 85%. Committed refers to projects that either have reached a final investment decision or are under construction. Announced projects indicate announcements through first-quarter 2023. Note that data is available for announced electrolyser manufacturing projects as of second-quarter 2023 in the Global Hydrogen Review 2023 (IEA, 2023e).

If all announced solar PV module manufacturing projects are realised, their combined output, together with that from the increased utilisation of existing manufacturing capacity would exceed the deployment needs of the updated NZE Scenario in 2030 by around 30%. EV and grid storage battery needs for 2030 would also be almost fully met under the same considerations. Caution is needed however as many announced projects have not yet reached a final investment decision or started construction. Only around 25% of the announced projects for solar PV manufacturing capacity worldwide can be considered committed. The equivalent figure for batteries is around 30% and about 5% for electrolysers.

Growth in manufacturing capacity for key wind turbine components – nacelles, towers and blades – was much slower at around 2% in 2022. Some wind manufacturers are struggling to boost output due to supply chain disruptions and higher costs resulting from the effects of the Covid-19 pandemic and Russia's invasion of Ukraine. This follows a period of falling costs and rapid expansion in the wind industry prior to 2020. Additional policy support would help the wind power sector to overcome these challenges and play the critical role envisaged for it in the NZE Scenario.

While the clean technology manufacturing base is expanding rapidly, it remains highly concentrated geographically; the majority of current and announced manufacturing projects are in China. Yet, recent policy changes are beginning to expand project pipelines elsewhere. There have been notable increases in the project pipeline for battery production facilities in the United States, driven in large part by the incentives provided by the IRA. Meanwhile the Production Linked Incentive (PLI) programme in India is providing a boost to domestic manufacturing, including through the provision of nearly USD 2.4 billion under the second phase of the High Efficiency Solar PV Modules PLI that began in October 2022 and USD 2.5 billion under the Advanced Chemistry Cell Battery Storage PLI announced in late 2021. Among key measures in the European Union, the Net Zero Industry Act (NZIA), announced in March 2023, proposes measures to strengthen clean technology manufacturing in the European Union.

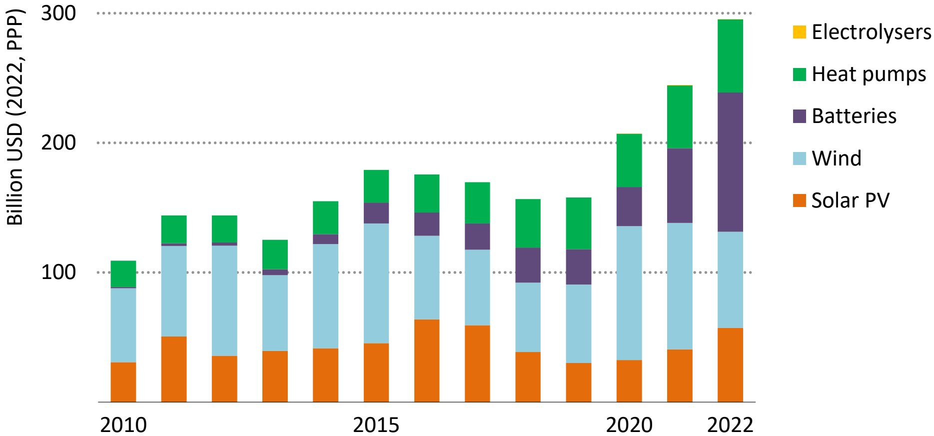
In addition, other countries are providing support to promote clean technology manufacturing. Recent initiatives include USD 1.8 billion in subsidies for battery manufacturing in Japan's Green Transformation (GX) initiative; a refundable tax credit for 30% of investment cost in new manufacturing equipment for key clean technologies in Canada's 2023 Budget; USD 5 billion in loans and guarantees from the Export-Import Bank of Korea and state-owned Korea Trade Insurance to advance domestic battery manufacturing: and in Australia, USD 2 billion for domestic clean technology manufacturing via the National Reconstruction Fund. More diverse and resilient supply chains will help strengthen security.

Clean technology markets are booming

The combined global market for five key clean energy technologies – solar PV, wind, batteries, electrolysers and heat pumps – surged to just under USD 300 billion dollars in 2022, a nearly 20% increase over the previous year. This was fuelled by rapid growth in capacity and sales, though it also reflects unit cost increases for some technologies in 2022 resulting from supply chain disruptions and energy and commodity price inflation. Sales were concentrated in major markets, notably China, North America and the European Union. EV batteries and stationary storage applications contributed 65% of the market growth in 2022, mainly due to the huge global increase in electric car sales from almost 7 million in 2021 (9% of global car sales) to over 10 million in 2022 (14% of global car sales).

The market size of these five technologies has almost tripled since 2010, a period during which their unit costs declined on a combined deployment weighted average basis by around 80% (Figure 1.18). Absent these cost declines, an extra USD 1 trillion in spending would have been needed in 2022 to achieve the level of deployment in that same year.

Figure 1.18 ⊳ Global market size of selected clean energy technologies, 2010-2022



The global market for five key clean technologies – solar PV, wind, batteries, electrolysers and heat pumps – has almost tripled over the past decade

Progress in expanding supply chain capacity has been uneven

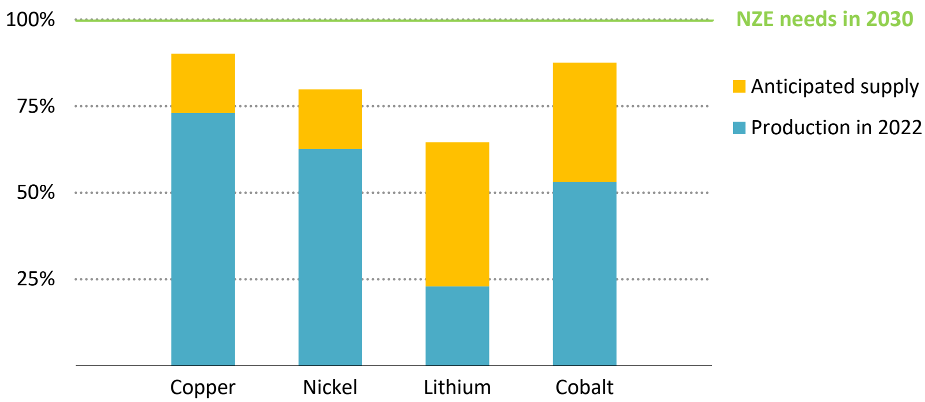
Large quantities of critical minerals are required for clean energy technologies and their supporting infrastructure, ranging from wind turbines and EV batteries to CO_2 pipelines and power grids. Since clean energy technologies already account for high shares of total demand of these minerals (between about 15-55% for lithium, cobalt, nickel and copper today), continuing growth in the deployment of these technologies hinges on rapid expansions in secure and sustainable critical mineral supply chains.

Critical minerals extraction and processing capacity has increased significantly over the last decade in response to rising clean energy and other demands. Between 2010 and 2022, lithium mining output rose by a factor of five, and nickel and cobalt by a factor of two. Growth has been particularly strong in recent years, with lithium mining output expanding by about 80% between 2020 and 2022, and output of nickel increasing by about 35% and cobalt by about 40% over the same period (IEA, 2023f). Despite this growth in supply, markets have been tight as a result of rapid demand growth, especially for batteries. Lithium prices have shown the largest volatility, with international price markers increasing more than five-fold between the first half of 2020 and 2022.

Investors are responding to these price spikes. The pipeline of announced projects for the extraction and processing of key critical minerals points to continued expansion in supply this decade. For example, announced projects to expand lithium extraction capacity increased by 14% for lithium between the end of 2022 and the second quarter of 2023. Anticipated supply based on announced extraction projects would meet approximately 90% of demand levels in

2030 in the updated NZE Scenario for copper, 80% for nickel, 65% for lithium, and 85% for cobalt (Figure 1.19).[8] (Chapter 4 explores critical minerals supply and demand in more detail in the context of the needs of the NZE Scenario).

Figure 1.19 ▷ Production from existing and announced extraction projects for key critical minerals relative to NZE Scenario requirements in 2030



Anticipated supply from the current pipeline of announced projects for key critical minerals would provide at least 65% of 2030's NZE Scenario requirements

Notes: This figure shows primary demand and supply of critical minerals, excluding secondary production. 'Anticipated supply' is expected future production based on expert judgement from third-party data providers. Expectations in commodity prices can have a large impact on the expected supply; a higher price might lead to more supply coming online. At the same time, unexpected delays in financing, permitting or construction could delay projects and yield lower supply. The value is therefore lower than the sum of all announced projects.

One risk arises from the way that global supply is set to remain highly concentrated among a small number of countries and companies. More diverse supply chains would increase supply resilience. A different kind of risk comes from lengthy project lead times for new supplies. Mining projects, including exploration, permitting and construction, can often take more than a decade. Yet, the fastest mining developments can have a lead time of five years or less from discovery to the start of production, e.g. the Nova-Bollinger mine in Australia which produces nickel, cobalt and copper, even though ramping up production to full capacity typically takes up to another three to four years when using established techniques. This suggests that there is still enough time to further scale up supply to meet NZE Scenario needs by 2030, even if the timelines are becoming very tight. Meanwhile continued R&D could help to reduce the need to use critical minerals for which supplies are constrained.

[8] Mineral processing tends to follow similar trends as extraction.

Further increases in investment are urgently needed in the near term, as are government efforts to diversify supply chains, reduce lead times and reduce material demand by promoting recycling and innovation (see Chapter 4).

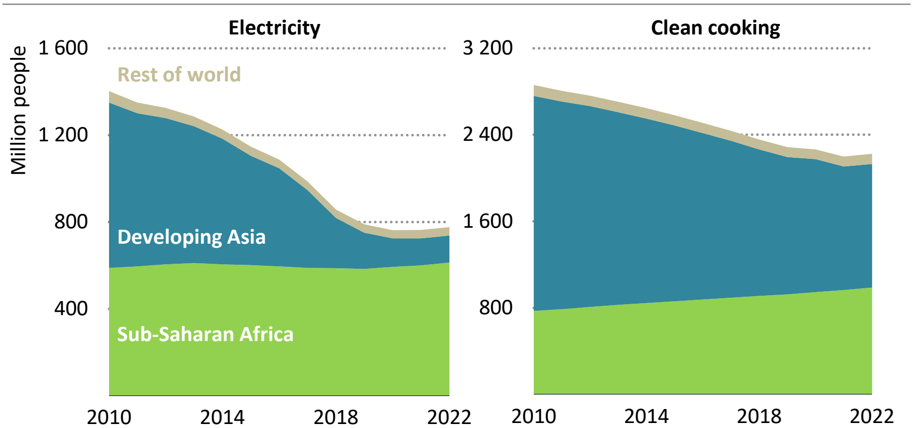
S P O T L I G H T

Energy access and energy security

Energy access

The Sustainable Development Goals (SDGs) were adopted in 2015, alongside the Paris Agreement. We are now halfway between the year the goals were adopted and their 2030 target year. For the energy sector, the SDGs set the objective of achieving full energy access by 2030 both for electricity and clean cooking.[9] In 2015, about 15% of the global population did not have access to electricity and about 35% did not have access to clean cooking (Figure 1.20). In 2022, those numbers had fallen to 10% and around 30% respectively.

Figure 1.20 ▷ Population without access to modern energy by region, 2010-2022



Today nearly one-in-ten people worldwide do not have access to electricity and nearly one-in-three still lack access to clean cooking technologies

Yet progress has been very uneven among regions. In developing Asia, the population without access to electricity has fallen from about 20% in 2010 to less than 5% in 2022 (though this is still more than 120 million people). The large increase in access to

[9] Clean cooking is defined here as cooking facilities that use modern fuels and technologies, including natural gas, liquefied petroleum gas (LPG), electricity and biogas, or improved biomass cookstoves (ICS) that have considerably lower emissions and higher efficiencies than traditional three-stone fires.

electricity that this represents was led particularly by India and Indonesia, which together have seen the number of people without access to electricity fall by more than 300 million since 2015. On the other hand, sub-Saharan Africa has been going in the wrong direction, despite some individual countries making progress earlier in the decade until the Covid-19 pandemic and 2022 energy crisis, and the total population without access to electricity has slightly increased in recent years.

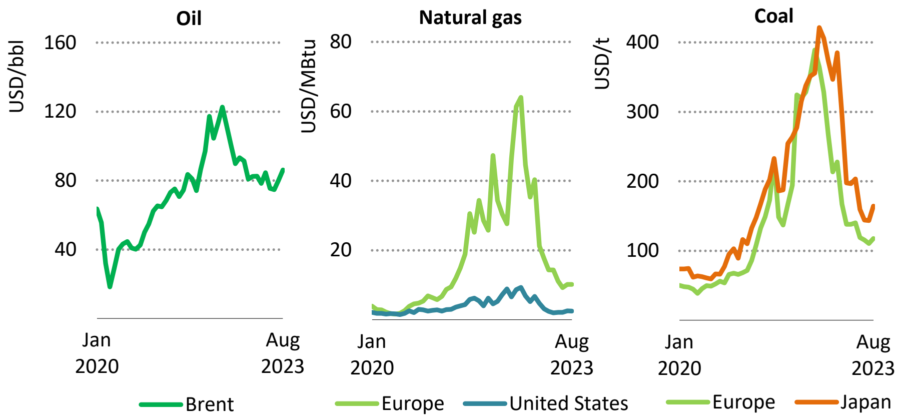
Substantial gains in clean cooking are evident in developing Asia, where the share of the population without access to clean cooking solutions has declined from more than 40% to less than 30% since 2015. This has been led by strong gains in India, China and Indonesia, where nearly half a billion people gained access to clean cooking technologies in the last seven years (equivalent to about 7 000 people per hour). In sub-Saharan Africa, however, population growth has outpaced progress: while the share of the population without access to clean cooking has been gradually falling, the absolute number of people without access has been steadily climbing due to rapid population growth. Nearly 1 billion people in Africa still cook with dirty and dangerous fuels that have severe negative consequences for health and livelihoods.

The pandemic and the global energy crisis of 2022 were a major setback to progress on energy access. With energy prices skyrocketing, we estimate that in 2022 some 75 million people who recently gained access to electricity lost the ability to pay for it, and that almost 100 million people worldwide may have been pushed back into reliance on firewood and charcoal for cooking instead of cleaner, healthier alternatives.

Energy security

Russia's invasion of Ukraine in early 2022 triggered a surge in energy prices (Figure 1.21). Natural gas prices on the European benchmark briefly reached an all-time high of USD 99 per million British thermal units (MBtu), almost 20-times higher than their 2016-2020 average (the highest monthly average reached in 2022 was USD 64/MBtu). Buyers with little capacity to pay were priced out of the market, and countries such as Bangladesh and Pakistan experienced blackouts due to fuel shortages. Prices for coal also climbed to unprecedented levels, reaching monthly averages as high as USD 350-420/tonne, or five-to six-times the 2016-2020 EU average. In some cases, power plants and regions dependent on imported coal were forced to curtail purchases. These high prices fed into electricity prices in many markets. Governments around the world spent more than USD 500 billion in 2022 to mitigate the impact of high prices on consumers. The energy crisis exacerbated existing inflationary pressures, and the world experienced a synchronized inflationary upswing unprecedented since the energy crises of the 1970s (IEA, 2022a).

Figure 1.21 ▷ Benchmark international fossil fuel prices, 2020-2023



Fossil fuel prices skyrocketed on international markets during the 2022 energy crisis, feeding into high electricity prices and further inflaming inflation

Notes: bbl = barrel. Prices shown are monthly averages.

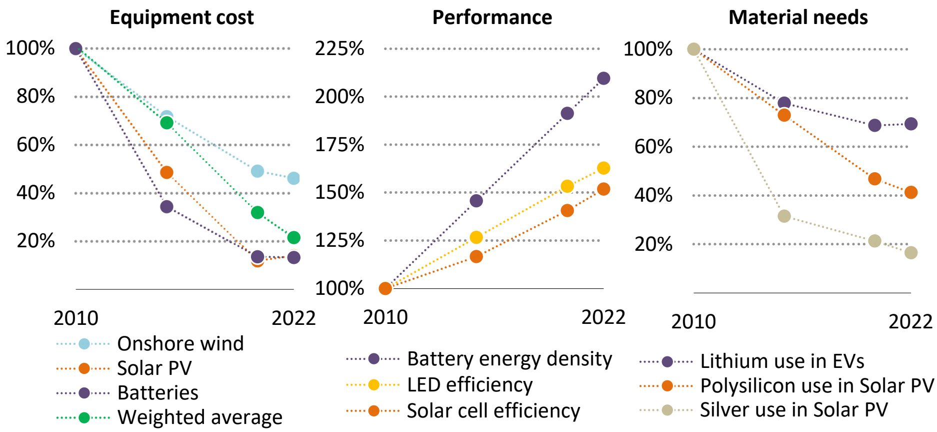
The energy crisis accelerated both clean energy deployment and investment, as well as investment in fossil fuel in response to concerns about the availability and affordability of energy supplies. Clean energy investment increased by about 15%, to reach around USD 1.6 trillion in 2022 and is set to continue to rise rapidly. At the same time, investment in fossil energy climbed by nearly 10%, to reach around USD 1 trillion and looks set to increase again in 2023.

Disruptions in recent years have put the spotlight on the security of critical mineral and clean energy manufacturing supply chains. Prompted by rapid demand growth and significant supply concentration, governments have been taking action such as legislation that aims to increase domestic supply of key clean energy technologies and related inputs such as the Inflation Reduction Act in the United States and the Net Zero Industry Act in the European Union, and through programmes such as the Production Linked Incentives in India. This has had the positive effect of significant increases in the potential supply of clean energy technologies, while at the same time raising concerns about potential market distortions and the extent of public fiscal commitments.

1.4.3 Costs and performance

Over the last decade, considerable advances in clean energy technologies have cut costs, improved performance and reduced material input requirements. Costs for selected mass manufactured clean energy technologies – including solar PV, wind, heat pumps and batteries, have fallen by close to 80% in aggregate (Figure 1.22).

Figure 1.22 ▷ Equipment cost, performance and material needs per unit for selected clean energy technologies, 2010-2022



Deployment boosted cost reductions and improved the performance of clean energy technologies in a virtuous cycle

Notes: Index values in 2010 = 100%. Equipment cost excludes engineering, procurement, construction and installation costs, and is in real terms. Weighted average equipment cost compares the costs of the annual deployment of selected mass manufactured clean energy technologies, i.e. solar PV, onshore and offshore wind, heat pumps and batteries in aggregate to the costs as if there had been no cost reductions since 2010.

Sources: IEA analysis based on BNEF, (2022); VDMA, (2021) (2023); IEA,(2022a); IEA, (2023a); SPV Market Research, (2022); RTS, (2021); PV InfoLink, (2022).

Notably, solar PV demonstrates impressive cost declines. Typically, as deployment increases, the learning rate for a given technology (defined as the fall in unit cost associated with a doubling of cumulative deployment) tends to decrease. For solar PV modules, however, the learning rate since 2006 of around 40% is actually higher than the average since the 1970s of around 25%, largely thanks to economies of scale in manufacturing and efficiency improvements (VDMA, 2023) (IEA, 2020a) (Kavlak, McNerney and Trancik, 2018).

Costs declines have been more modest for other technologies. For example, heat pump unit costs fell by only around 5% on average over the 2010-2022 period, partly because the manufacturing process was already mature. Large-scale site-tailored technologies, such as carbon capture, also exhibit slower cost declines. Slower deployment has provided fewer opportunities for learning. Furthermore, the site-specific and bespoke nature of large-scale projects means that knowledge and experience gained may not always be applicable to other projects. This limits the potential for standardisation such that cost declines are likely to be more modest even in the longer term.

Costs have started to increase rather than decrease in the last two years for some clean technologies such as solar PV and batteries, reflecting inflationary pressure and, in particular, surging costs for critical minerals (IEA, 2023g). This period of cost increases is likely to be temporary, as was the case for a similar period of inflation and high material costs in 2007-2009 and given that the critical mineral supply project pipeline has begun to rapidly expand in response to increased demand. The risk of future volatility in raw material prices can be mitigated by continuing to develop resilient and secure supply chains (see Chapter 4).

Considerable technology performance improvements have contributed to increase the attractiveness of technologies for consumers and reduce critical mineral requirements. For example, driven in part by changes in composition and chemistries, the sales weighted average energy density of batteries doubled since 2010 from around 90 Watt hour per kilogramme (Wh/kg) to around 190 Wh/kg in 2023 (BNEF, 2023). This has enabled increased driving ranges for EVs and a reduced use of lithium by about 30% per kilowatt-hour (IEA, 2023h).

Solar PV cells are another example of technology performance improvements. In 2010, on average 14% of the solar energy hitting a solar panel was converted to electricity; by 2022, that figure had risen by half to 21% efficiency. This gain helped bring about a 60% reduction in the use of polysilicon and an 80% reduction in the use of silver in the average solar PV cell since 2010. Since polysilicon and silver make up around 20-30% of solar PV module costs, this level of improved efficiency and the related material savings have been an important contributor to declining costs. With more advanced cell designs and tandem technologies such as silicon perovskites entering the market, average efficiency is expected to improve even more in the coming years.

1.4.4 Innovation

Innovation has a critical role to play in reaching net zero emissions, especially in sectors such as heavy industry and long-distance transport where emissions are hard to abate because low-emissions technologies or processes are not yet readily available. Considerable progress has been made in recent years to address pressing innovation gaps, and this has resulted in upgrades in the technology readiness level of some critical clean energy technologies (Figure 1.23). Selected illustrative examples of innovation progress in recent years include the following areas.

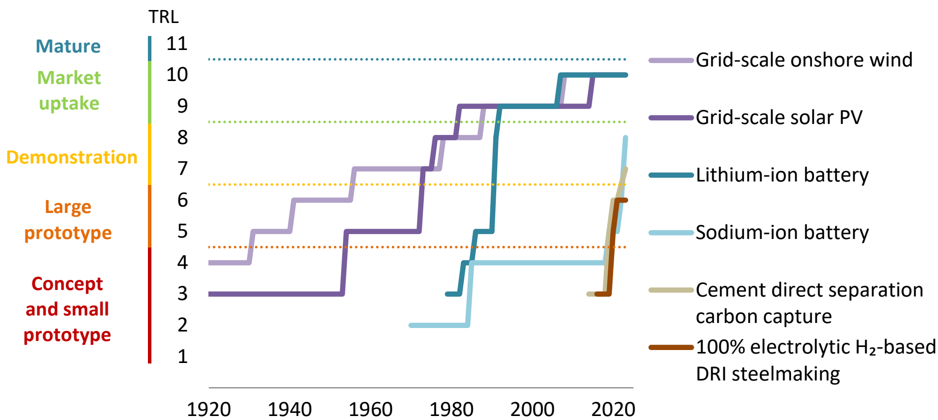
- **Power generation**: New commercial-scale designs of small modular nuclear reactors are expected to come online this decade in China, Europe and North America; floating offshore wind parks are getting bigger than ever with parks of several hundred MW announced for 2025-2026, also announced are a 1 GW offshore installation in China for 2027 and a 6 GW project in Korea for 2030; perovskite solar cells are nearing 30% efficiency, with several firms in China, Europe and the United States competing to commercialise the first modules.
- **Low-emissions hydrogen supply**: Commercial-scale demonstrations of solid oxide electrolysers are underway. The two large demonstrators started operating in 2023.
- **Road transport**: Sodium-ion batteries for EVs are being scaled up, moving from prototypes pre-2021 to first-of-a-kind commercial production in China in 2023.

- **Heavy industry**: Scaling up carbon capture via direct separation in cement production is underway (a final investment decision taken for LEILAC-2 with production of 100 kilotonnes [kt] of CO_2 per year); 100% electrolytic hydrogen-based direct reduced iron production could soon be demonstrated at industrial scale (HYBRIT, the most advanced project for this technology, produced fossil-free steel for the first time in Sweden in November 2021); small-scale use of carbon-free aluminium in consumer goods is moving ahead (ELYSIS, Canada, expects first-of-a-kind demonstration of commercial production by 2026 before moving to industrial production).
- **Critical minerals**: Bioleaching for electronic waste recycling and metal recovery is moving to first-of-a-kind commercial operation (this technique has been used in the mining industry for years and now is being considered to recover critical minerals from batteries); direct lithium extraction from geothermal brine is at the pre-commercial demonstration stage.
- **Direct air capture**: In Iceland, a first-of-a-kind 4 kt CO_2/year project has begun capturing CO_2 from the air and storing it underground with plans to expand to 36 kt CO_2/year as part of a broader effort to demonstrate multi-megatonne capacity by 2030. A 0.5 Mt/year plant is under construction in the United States and aims to begin operations in 2025.
- **Aviation**: Regional electric planes with up to 30 passengers are being designed with commercial flights expected before 2030; electric vertical take-off and landing models are being demonstrated; hydrogen-powered aircraft designs are being developed, though they are at an earlier stage and operations are not expected to begin until after 2030.
- **Shipping**: The first industrial plant that converts biogas into low-emissions bio-liquefied natural gas for use as drop-in fuel to replace heavy fuel oil is set to begin operations in 2023 (FirstBio2Shipping, Netherlands, which received funding from the European Union Innovation Fund). Several major ship engine makers are in the final stages of developing ammonia two-stroke engines for commercialisation by 2025; large methanol-powered container ships are being delivered for the first time in 2023 just as electrolytic hydrogen-based methanol commercial production starts; and small-scale hydrogen fuel cell ferries began operating in Norway and the United States in 2023.

For a comprehensive overview of the full suite of technologies and projects related to clean energy innovation, see the IEA Clean Energy Technology Guide.[10]

[10] The IEA Clean Energy Technology Guide contains information on more than 550 individual technology designs and components that can contribute to getting on track with the NZE Scenario, with indications of technology maturity and major R&D and demonstration activities (https://www.iea.org/articles/etp-clean-energy-technology-guide).

Figure 1.23 ▹ Evolution of technology readiness levels for selected clean energy technologies



Significant advances in clean energy technology development have been made in recent years, but much remains to be done to put the world on a net zero emissions pathway

Notes: TRL = Technology Readiness Level; H_2 = hydrogen; DRI = direct reduced iron. For 100% electrolytic H_2-based DRI steelmaking, R&D related to using hydrogen in steelmaking has been taking place for decades, including at one commercial plant in the 1990s relying largely on hydrogen. In this figure, the focus is specifically on 100% electrolytic H_2.

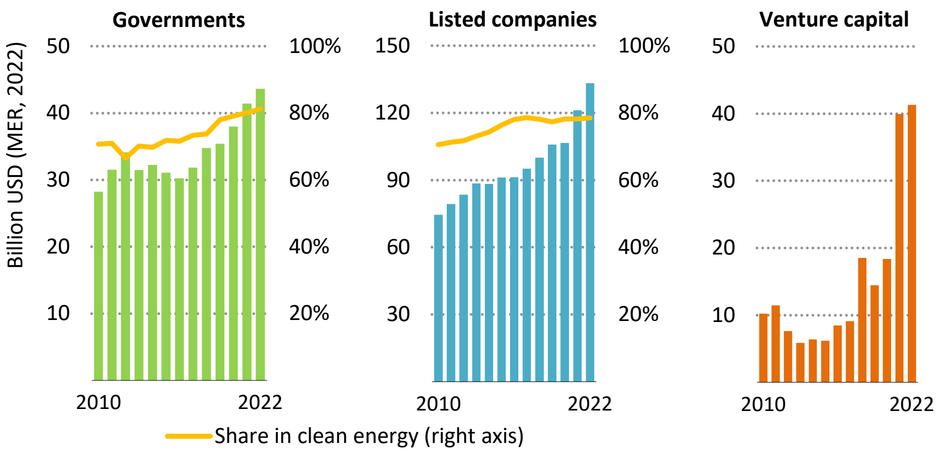
Public and corporate spending on energy R&D has been increasing despite the pandemic and macroeconomic crises (IEA, 2023g) (Figure 1.24). Governments allocated nearly USD 44 billion to energy R&D in 2022, more than 80% of which was earmarked for clean energy, compared with around USD 30 billion in 2015, when 70% of the total was for clean energy. Much of the increase in public energy-related R&D over the last few years is in China, which is now the largest spender in this area. Advanced economies account for most of the rest. The emerging market and developing economies excluding China together accounted for just 5% of the global total in 2022.

Energy R&D spending by globally listed companies exceeded USD 130 billion in 2022, an increase of 25% from 2020. Spending by companies developing renewables increased on average by 25% each year between 2020 and 2022 compared with 5% per year over the 2010-2020 period. The R&D budgets of major oil and gas companies have remained more or less flat since 2010. Aviation, rail and shipping were badly hit by the Covid-19 crisis and their R&D spending has not increased much since. By contrast, R&D spending recovered quickly in chemicals, cement and iron and steel, although a relatively low share of energy R&D budgets in industrial sectors is directed to clean energy, indicating further opportunities to increase spending.

The role of start-ups in clean energy innovation is also growing and has shown impressive resilience in the face of recent macroeconomic crises (IEA, 2023g). Clean energy venture capital investment nearly doubled between 2010 and 2020 and has more than doubled again since then. Total investment reached USD 7 billion for early-stage start-ups and USD 35 billion for growth stage start-ups in 2022, with notable growth in investment in EVs and batteries, hydrogen, renewables and energy efficiency.

The number of global patents in low-emissions energy technologies has been rising over the last two decades, while for fossil fuels it has been declining since 2015 (IEA, 2021c). Between 2005 and 2018, for example, patenting in batteries increased 14% annually on average, four times faster than the average of all technology fields (IEA, 2020b). Clean technologies accounted for nearly 80% of all patents related to hydrogen production in 2020 (IEA, 2023i).

Figure 1.24 ▷ Global public and corporate spending on energy R&D and venture capital investment in clean energy start-ups, 2010-2022



Energy R&D spending by governments and corporations, and clean energy venture capital investment have grown substantially

Note: MER = market exchange rate.

A renewed pathway to net zero emissions

Net zero emissions guide

SUMMARY

- The Net Zero Emissions by 2050 Scenario (NZE Scenario) relies on the deployment of a wide portfolio of low-emissions technologies and emissions reduction options to reach net zero CO_2 from the energy sector by 2050, but it also depends on a high degree of global co-operation and collaboration. Advanced economies take the lead and reach net zero emissions by 2045 in aggregate in the NZE Scenario, China by 2050 and other emerging market and developing economies after 2050. The comprehensive NZE Scenario update presented here reflects real-world progress since our *Net Zero by 2050: A Roadmap for the Global Energy Sector* report in 2021 and a continuous assessment of feasibility across sectors and technologies, but it is not the only pathway to reach the goal of net zero emissions by 2050.
- Taken together, solar photovoltaics (PV) and electric vehicles (EVs) provide one-third of the emissions reductions to 2030 in the updated NZE Scenario. The share of electric cars in total car sales soars to more than 65% by 2030, and solar PV capacity increases fivefold from today. The announced manufacturing pipeline for solar PV and batteries is projected to be sufficient to meet the NZE Scenario deployment needs to 2030. Demand for oil and gas declines by around 20% by 2030 – fast enough that no new long lead time conventional oil and gas projects need to be approved for development. Low-emissions electricity rises so rapidly that no new unabated coal plants beyond those under construction at the start of 2023 are built.
- Technologies under development are essential to achieve net zero emissions. Progress in clean energy innovation over the past two years, such as on battery chemistries, and the even stronger market momentum of commercial technologies such as solar PV, have had a tangible impact. In our 2021 report, the share of emissions reductions in 2050 from technologies under development was almost half: that figure has now fallen to around 35% in our updated NZE Scenario.
- The extraordinary surge in global manufacturing capacity for solar PV and batteries underpins their more significant role in the period to 2030. Capacity additions of wind have been revised downwards relative to the 2021 NZE Scenario, but wind is still critical to reach net zero emissions; further policy support is required to help overcome challenges in wind power deployment. The role of nuclear power has been revised upwards given recent policy support.
- Hydrogen and hydrogen-based fuels and carbon capture, utilisation and storage (CCUS) have an important part to play to reduce emissions in heavy industry and long-distance transport. In the 2023 NZE Scenario, they provide one-fifth of all emissions reductions between 2030 and 2050. But the part they play is smaller than in the 2021 version, particularly in the near term. This reflects slower technological and market development progress than envisaged in 2021 and stronger electrification prospects.

2.1 Overview of the NZE Scenario

2.1.1 Scenario design

This report sets out an updated NZE Scenario – referred to as the 2023 NZE Scenario – that takes into account the key changes that have occurred since 2021 in energy policies, technologies, markets and supply chains. It reflects the latest IEA data that track energy policies; developments in the deployment and innovation of more than 550 clean energy technologies; supply chain capacities for critical minerals and clean energy technology manufacturing; and progress towards the more than 400 milestones presented in the 2021 *Net Zero by 2050* report (IEA, 2021a). The NZE Scenario pathway achieves net zero CO_2 emissions from the energy sector by 2050, leading to limited overshoot of the 1.5 °C limit set out in the 2015 Paris Agreement, but the increase in global average temperature falls below 1.5 °C by 2100.[1]

The 2023 NZE Scenario:

- Describes a pathway for the global energy sector to reach net zero emissions of CO_2 by 2050 by deploying a wide portfolio of clean energy technologies and without offsets from land-use measures. Decisions about technology deployment are driven by costs, technology maturity, market conditions, available infrastructure and policy preferences. Building on the IEA 2021 NZE roadmap analysis, this report evaluates the balance of technology deployment taking into consideration progress and setbacks over the last two years (Spotlight). It also provides an in-depth analysis of the current trajectory of key technologies and mitigation options, and what it would take to put the world on track for the NZE Scenario (see Chapter 3).
- Prioritises an orderly transition that aims to safeguard energy security through strong and co-ordinated policies and incentives that enable all actors to anticipate the rapid changes required, and to minimise energy market volatility and stranded assets. Rapid deployment of clean energy technologies and energy efficiency is at the core of this transition. The NZE Scenario is underpinned by detailed analysis of project lead times for minerals supplies and clean energy technologies as part of efforts to ensure the feasibility of the deployment. There is, however, inevitably a risk of bottlenecks emerging for some technologies, which underscores the importance of measures to enhance material reuse and recycling and to drive down the material intensity of clean energy technologies.
- Recognises that achieving net zero energy sector CO_2 emissions by 2050 depends on fair and effective global co-operation. The pathway to net zero emissions by 2050 is very narrow. All countries are required to contribute to deliver the desired outcomes; advanced economies take the lead and reach net zero emissions earlier in the NZE Scenario than emerging market and developing economies. Global access to electricity

[1] High overshoot refers to an increase in global average temperature to above 1.6 °C, but below 1.8 °C above pre-industrial levels and a subsequent fall to below 1.5 °C (IPCC, 2023).

and clean cooking is achieved by 2030 in line with established Sustainable Development Goals. Rapid and major reductions in methane emissions from the oil, gas and coal sectors help to buy some time for less abrupt CO_2 reductions in emerging market and developing economies. Without these reductions, global energy sector CO_2 would need to reach net zero by around 2045, with important implications for equitable pathways. Global collaboration facilitates the development and adoption of ambitious policies, drives down clean technology costs, and scales up diverse and resilient global supply chains for critical minerals and clean energy technologies. Enhanced financial support to emerging market and developing economies plays a critical part in this collaboration.

SPOTLIGHT

Key changes since the 2021 version of the NZE Scenario

The IEA tracks hundreds of thousands of energy sector datapoints that cover elements ranging from policy developments, technology deployment, investment and supply chains to infrastructure, innovation and costs. This data-driven approach feeds the model used to develop the NZE Scenario, which also factors in the various circumstances of individual countries and regions in great detail. This allows the NZE Scenario to take account of the feasibility of scaling up emissions reduction options at the speed and scale required across various regions, sectors and technologies, and to integrate concerns about equity (Box 2.1).

In the *Net Zero by 2050* report in 2021, we noted that the precise pathway for the transition would be uncertain (IEA, 2021a), stating "… some of these milestones will be met, others will not, and some technologies will fail to deliver and others will surprise us – technology deployment rarely ever follows an idealised trajectory" (IEA, 2021b).

The main differences between this 2023 NZE Scenario and the 2021 version are (Table 2.1):

- While the goal of net zero energy sector CO_2 emissions by 2050 is retained, emissions to 2030 are higher in this edition of the scenario, reflecting the extremely strong rebound in economic activity and emissions in the wake of the Covid-19 pandemic, as well as the failure to act in recent years at the speed envisaged in our original report.
- Total energy demand in 2030 is slightly higher in the 2023 NZE version, reflecting the post-pandemic rebound in economic activity and slower progress than envisaged in implementing strong energy efficiency policies. Energy efficiency continues to play a critical role in the 2023 NZE Scenario (see Chapter 3).
- Near-term use of coal is higher in the 2023 NZE Scenario to reflect both the desire to plot a more equitable pathway for emerging market and developing economies, which dominate global coal use, as well as the energy security concerns around natural gas sparked by Russia's invasion of Ukraine.

Table 2.1 ⊳ Selected indicators in the 2021and 2023 NZE Scenarios

	2021 version		2023 version	
	Peak warming	2100 warming	Peak warming	2100 warming
Median temperature increase (°C)	Consistent with IPCC C1 scenarios	1.4	Consistent with IPCC C1 scenarios	1.4
	2030	2050	2030	2050
Total net energy sector CO_2 emissions (Gt)	21.1	0.0	24.0	0.0
Share of unabated fossil fuels in total energy supply (%)	58%	11%	62%	11%
Total final consumption (EJ)	390	340	410	340
Solar PV capacity additions (GW)	630	630	820	820
Wind capacity additions (GW)	390	350	320	350
Share of EVs in car sales (%)	60%	90%	65%	95%
Total CO_2 capture (Gt)	1.8	7.7	1.0	6.1
Total CO_2 removal (Gt)	0.3	1.9	0.2	1.7
Installed stationary battery capacity (GW)	590	3 100	1 020	4 200
Share of electricity in total final consumption (%)	26%	49%	28%	53%
Share of H_2 and H_2-based fuels in total final consumption (%)	2%	10%	1%	8%

Notes: IPCC = Intergovernmental Panel on Climate Change. Gt = gigatonnes; EJ = exajoules; GW = gigawatts; EVs = electric vehicles; H_2 = hydrogen. IPCC C1 scenarios are scenarios assessed by the IPCC which keep warming below 1.5 °C with no or limited overshoot. Unabated fossil fuels includes fossil fuels used for non-energy purposes.

- Solar PV takes a more prominent role in the 2023 NZE Scenario, though reductions in projected wind capacity additions mean that the combined share of wind and solar PV in total generation is very similar in both NZE Scenario versions, at around 40% by 2030. This reflects the surge in solar PV installations and manufacturing capacity since 2021 report. Correspondingly, the boost in solar PV generation spurs the need for additional stationary battery storage to ensure security of supply.
- Electric vehicles (EVs) also have an even more prominent role in the 2023 NZE Scenario. This reflects both a significant uptick in EV sales and progress in scaling up manufacturing supply chains. This electrification in road transport together with accelerated progress in heat pump deployment in buildings and rising market confidence in technologies such as 100% electrolytic hydrogen-based direct reduced iron production, results in more rapid growth in the share of electricity in final energy consumption.[2]
- Near-term deployment is slower for some technologies in the 2023 NZE Scenario, e.g. wind, hydrogen and carbon capture, utilisation, and storage (CCUS). This reflects

supply chain constraints, delays in scaling up project pipelines and related infrastructure, and sluggish progress in the development of market frameworks for less mature technologies. For some of these technologies, the downward revision is based on recent investment trends from technology manufacturers against other low-emissions alternatives. One example is a reduced role for hydrogen-fuelled trucks.

Some of the changes since the 2021 version of the NZE Scenario are helpful in terms of achieving the objectives while others are not. Overall, the path to achieving net zero emissions by 2050 in the 2023 NZE Scenario is a steeper one than in the 2021 version and requires more to be done after 2030. But the path remains open. The latest Intergovernmental Panel on Climate Change (IPCC) reports underscore the increasing urgency of achieving net zero emissions (IPCC, 2023).

Box 2.1 ▻ Integrating equity into the NZE Scenario design

Reaching net zero emissions by 2050 requires action on the part of all countries. Different countries have varying starting points, capacities, and resource endowments. Differentiated pathways are delineated in the NZE Scenario as an essential design principle (Figure 2.1). Advanced economies take the lead and reach net zero emissions by around 2045 as a group, consistent both with their higher financial capacities and responsibility for historical emissions. With per capita emissions above those of advanced economies today, China achieves net zero emissions around 2050 in the NZE Scenario; other emerging market and developing economies reach it only well after 2050. The global net zero CO_2 emissions target is achieved thanks to net negative emissions in advanced economies, with remaining residual gross emissions concentrated in emerging market and developing economies other than China.

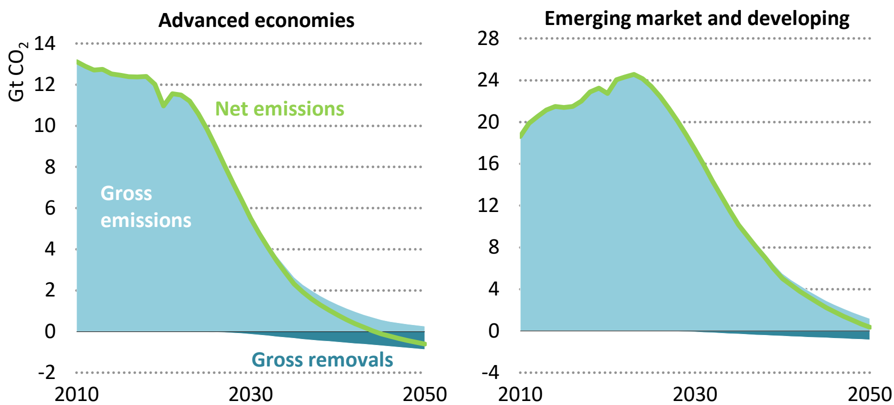
Determined action, particularly in advanced economies and in large oil and gas producing countries, cause oil and natural gas emissions of both CO_2 and methane to fall faster in the NZE Scenario than in comparable scenarios assessed by the IPCC. Emissions from coal fall more slowly in the NZE Scenario than in comparable scenarios assessed by the IPCC reflecting a less abrupt transition in emerging market and developing economies, which today are responsible for more than 80% of global coal use. As a result, emissions in advanced economies fall nearly two-times faster in the current decade than emissions in emerging market and developing economies.

Successful achievement of universal access to electricity and clean cooking by 2030 in line with Sustainable Development Goal 7 is a key pillar of the NZE Scenario. This hinges on both enhanced financial support by the international community and stronger

[2] Final energy consumption reflects the energy form that is brought to an industrial site, which is electricity in the case of captive hydrogen produced onsite at iron and steel facilities to reduce iron ore.

domestic policies in countries that lack full access. In addition to bringing important benefits for health and gender equality, achieving SDG 7 yields a net reduction in greenhouse gas emissions and air pollution, by reducing the incomplete combustion of biomass and deforestation.

Figure 2.1 ▷ Gross emissions and removals, and net emissions by aggregated region in the NZE Scenario, 2010-2050



As a group, advanced economies reach net zero emissions before emerging market and developing economies, and also achieve net negative emissions by 2050

Note: Gt CO_2 = gigatonnes of carbon dioxide; EMDE = emerging market and developing economies.

In emerging market and developing economies other than China, the NZE pathway requires clean energy investment to increase nearly sevenfold by the early 2030s compared to recent averages. Such mobilisation of capital requires frameworks that attract the private sector as well as international public support. Equitable pathways within countries also have a part to play in getting to net zero emissions. These aspects are discussed in Chapter 4.

Key socio-economic assumptions

The NZE Scenario sees the transformation of the energy sector taking place at the same time as a large increase in the global population and economy (Table 2.2). By 2030, the world population is projected to reach over 8.5 billion and almost 10 billion by 2050.[3] Nearly all of the increase is in emerging market and developing economies, including around 1.1 billion more people in Africa by 2050. In parallel, the global economy continues to recover from recent crises. Growth is expected to slow somewhat in the near term, but the size of the global economy is projected to roughly double by 2050.

[3] This is in line with the median variant of the United Nations population projections (UN DESA, 2022).

Table 2.2 ▷ Key socio-economic assumptions in the NZE Scenario, 2022-2050

	2022	2030	2040	2050
World population (million people)	**7 950**	**8 520**	**9 161**	**9 681**
China	1 420	1 410	1 372	1 307
India	1 417	1 515	1 612	1 670
Advanced economies	1 415	1 441	1 461	1 460
Rest of world	3 698	4 154	4 716	5 244
World GDP (USD trillion, 2022, PPP)	164	207	270	339
Energy prices (USD, 2022, MER)				
IEA crude oil (USD per barrel)	98	42	30	25
Natural gas (USD/MBtu)				
United States	5.1	2.4	2.4	2.4
European Union	32.3	4.3	4.2	4.1
China	13.7	5.9	5.3	5.3
Japan	15.9	5.5	5.3	5.3
Steam coal (USD/tonne)				
United States	53	27	24	23
European Union	290	57	45	43
Japan	336	65	51	47
Coastal China	205	64	54	49
CO_2 prices for electricity, industry and energy production (USD/t CO_2)				
Advanced economies		140	205	250
Emerging market and developing economies (with net zero emissions pledges)		90	160	200
Selected emerging market and developing economies (without net zero emissions pledges)		25	85	180
Other emerging market and developing economies		15	35	55

Note: PPP = purchasing power parity; MER = market exchange rate; MBtu = million British thermal units.

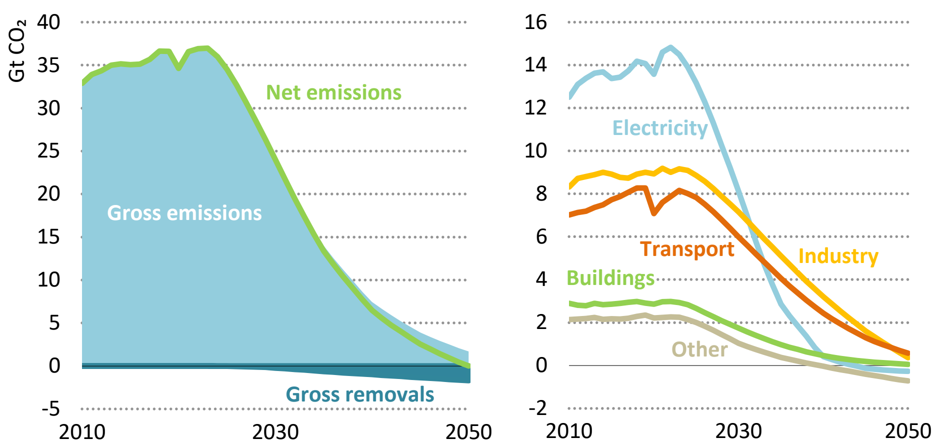
Energy price projections are subject to a high level of uncertainty. In IEA scenarios prices are designed to reflect an equilibrium between supply and demand. In the NZE Scenario, a rapid drop in oil and natural gas demand lowers prices to the operating cost of the marginal project needed to meet demand. As a result, international fossil fuel prices fall significantly, with the oil price dropping below USD 50 per barrel by 2030.

All regions introduce pricing of CO_2 emissions alongside other policies designed to bring about clean energy transitions in the NZE Scenario. Carbon pricing is implemented first in advanced economies, which see prices rise on average to USD 250 per tonne of carbon dioxide (t CO_2) by 2050. Major emerging market and developing economies with net zero emissions pledges, such as China, Brazil and Indonesia, see prices reach USD 200/t CO_2 by 2050. Carbon prices are lower in the rest of the world.

2.1.2 Emissions and temperature trends

CO_2 emissions from the energy sector in the NZE Scenario fall steeply from 37 gigatonnes (Gt) in 2022 to 24 Gt in 2030, a reduction of around 35%. By 2035, emissions fall to around 13.5 Gt, or nearly 65% below the 2022 level (Figure 2.2). Atmospheric removals through direct air capture and storage (DACS) and bioenergy with carbon capture and storage (BECCS) start to scale up rapidly and reach around 0.6 Gt in 2035 and 1.7 Gt in 2050. Total energy sector CO_2 emissions reach net zero in 2050, with residual gross emissions balanced by gross removals from the atmosphere through BECCS and DACS. This is achieved without offsets from land-use measures. Total greenhouse gas (GHG) emissions from all sectors are reduced by around 40% by 2030 and by 60% by 2035.

Figure 2.2 ▹ Energy sector gross emissions and removals, total net CO_2 emissions, and net emissions by sector in the NZE Scenario, 2010-2050



Energy sector CO_2 emissions are reduced 65% by 2035 and reach net zero by 2050, with residual emissions of 1.7 Gt balanced by atmospheric removals of the same magnitude

Total energy-related emissions reach 2.3 gigatonnes of carbon dioxide (Gt CO_2) in advanced economies by 2035, 4.2 Gt CO_2 in China and around 6 Gt CO_2 in other emerging market and developing economies. Advanced economies reach net zero emissions by around 2045, China by 2050 and other emerging market and developing economies only well after 2050.

On a sector basis, electricity sees CO_2 emissions fall the most, with emissions almost halving between 2022 and 2030 as renewables and other low-emissions sources of electricity generation are deployed rapidly and unabated fossil fuel-based generation declines. Other sectors, where low-emissions options are still being developed or ramped up, are slower to decrease emissions. Nevertheless, emissions from all sectors peak in the near term. Sectoral emission decreases between 2022 and 2030 are 20% in industry, around 25% in transport and around 40% in buildings.

Between 2030 and 2040, the electricity sector reaches very low levels of emissions in the NZE Scenario, with advanced economies reaching net zero emissions from the sector in aggregate in 2035. This milestone is reached in 2045 in emerging market and developing economies, which is five years later than in the 2021 version of the NZE Scenario. Many technologies still being developed today, such as those that support the electrification of heavy industry or zero emissions ships, begin to be deployed quickly in the 2030-2040 decade which leads to replacement or retrofitting of existing assets.

Though emissions in the industry and transport sectors both shrink by over 60% between 2022 and 2040, these two sectors remain responsible for close to 90% of residual emissions in 2040. Even by 2050, residual CO_2 emissions from fuel combustion are concentrated in the industry (0.2 Gt) and transport (0.6 Gt) sectors.

By 2050, the electricity, buildings, and other transformation sectors account for 0.4 Gt of residual emissions, and industrial processes for around a further 0.4 Gt. These emissions are counteracted by atmospheric carbon dioxide removal through BECCS and DACS, which account for 1 Gt and 0.7 Gt of removals respectively.

The IEA models the consequences of its scenarios for climate change using the MAGICC climate model, which is widely used in IPCC assessments.[4] The global mean temperature rise[5] above pre-industrial levels stands today at around 1.2 °C. In the NZE Scenario, this rises to a peak of just below 1.6 °C around 2040, and then gradually falls to around 1.4 °C in 2100 (Figure 2.3). This reduction in temperature from the peak is caused by two effects. First is strong reductions in methane emissions to 2050. Second is that temperatures are also reduced after reaching net zero CO_2 emissions as the land and oceans draw down atmospheric carbon in line with the latest generation of Earth system models (MacDougall et al., 2020). These effects are consistent with the Working Group I contribution to the IPCC's Sixth Assessment Report and each contribute about 0.1 °C of cooling between 2040-2100.

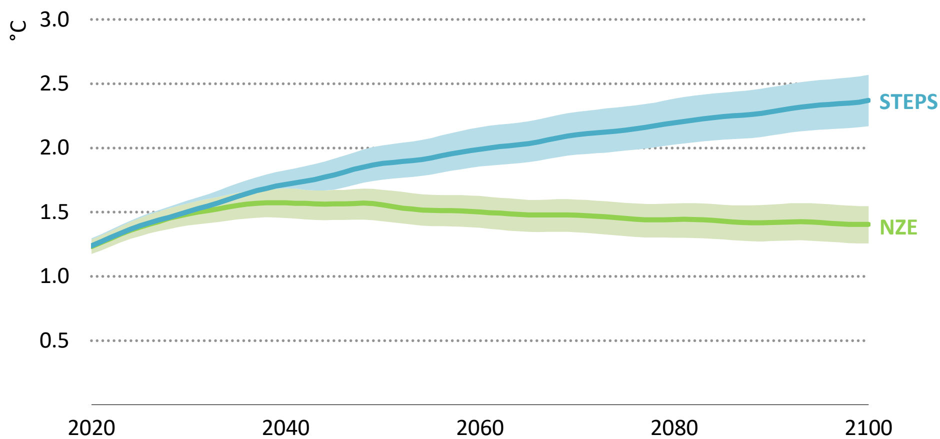
The NZE Scenario therefore meets the criteria of a limited overshoot 1.5 °C pathway as defined by the IPCC. By contrast, the IEA Stated Policies Scenario (STEPS) sees energy sector

[4] Most energy-related greenhouse gases (GHG) in IEA scenarios are modelled using the IEA's GEC Model (https://www.iea.org/reports/global-energy-and-climate-model). Significant sources of other GHG, e.g., black carbon, as well as GHG related to land use consistent with IEA scenarios are modelled by the International Institute of Applied Systems Analysis (IIASA). The MAGICC model supplements all remaining types and sources of GHG using the scenario database published as part of the IPCC Special Report on Global Warming of 1.5 °C (IPCC, 2018).

[5] Unless otherwise stated, temperature rise estimates quoted in this section refer to the median temperature rise, meaning that there is a 50% probability of remaining below a given temperature rise. All changes in temperatures are relative to 1850-1900 and match the IPCC Sixth Assessment Report definition of warming of 0.85 °C between 1995-2014 (IPCC, 2021). Modelled temperature rise estimates reflect anthropogenically induced trends but do not capture natural modes of variability, such as those connected to the El Niño Southern Oscillation (Berkeley Earth , 2023).

CO_2 emissions fall only moderately to 30 Gt by 2050. As a consequence, global warming continues to worsen, with the temperature rise exceeding 1.9 °C around 2050 and heading towards 2.4 °C in 2100. Inherent uncertainties in the Earth's response to future warming mean that there is about a one-third probability of warming exceeding 2.6 °C in the STEPS in 2100; in the NZE Scenario there is just over a one-third probability of exceeding 1.5 °C in 2100.

Figure 2.3 ▷ Median warming in the STEPS and NZE Scenario, 2020-2100



Rapid emission cuts moderate warming below 1.5 °C by 2100 with low overshoot in the NZE Scenario, while temperatures in STEPS reach 2.4 °C by 2100 and continue rising

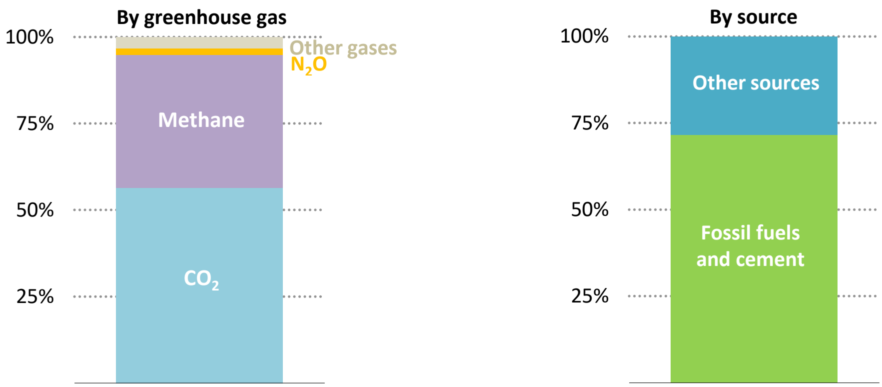
Notes: STEPS = Stated Policies Scenario. Shaded area represents the 33-67% confidence interval. Solid line represents median warming.

Source: IEA analysis based on Climate Resource and MAGICC 7.5.3.

Rapid reductions in greenhouse gases other than CO_2 are also essential to curb the global temperature rise. Less than 60% of the warming avoided to 2050 in the NZE Scenario compared to the STEPS is due to CO_2 emissions cuts. Reduced emissions of methane make up almost 40% and cuts to other GHG such as nitrous dioxide (N_2O) and fluorinated gases account for the remainder. Rapid reductions in these other gases are essential to curb global temperature increases (Figure 2.4).

Sectors other than energy also have an important part to play in cutting emissions. Rapid cuts in GHG emissions from other sectors, such as agriculture, forestry and other land use (AFOLU) and waste treatment, account for just under 30% of the warming avoided in the NZE Scenario compared to the STEPS to 2050, based on IEA modelling with the MAGICC climate model. For example, parallel action to stop deforestation and improve the management of existing forests brings CO_2 emissions from land use to net zero by about 2030 in the NZE Scenario, and improvements in livestock husbandry alongside efficiency gains in crop management and fertiliser use contribute to cuts in AFOLU-related N_2O and methane emissions of around 10% and 35% respectively in 2050 compared to the levels in the STEPS.

Figure 2.4 ▻ Global warming avoided in the NZE Scenario relative to the STEPS by greenhouse gas and source, 2022-2050



Reductions in CO_2 emissions are responsible for less than 60% of the warming avoided to 2050 in the NZE Scenario relative to the STEPS

Source: IEA analysis based on Climate Resource and MAGICC 7.5.3.

Box 2.2 ▻ Effects of global warming at 1.2 °C degrees temperature rise

In summer of this year, Earth had the hottest three-month period ever recorded, and it is now likely that 2023 will be the hottest year on record (Carbon Brief, 2023). To date, the global average temperature has increased to around 1.2 °C above pre-industrial levels (Berkeley Earth, 2023). This is already having an effect in every region around the world. The increasing frequency and intensity of heatwaves, droughts, storms and floods are in line with predictions made in the IPCC Assessment Reports. It has been estimated that hot temperature extremes that would have occurred once in 50 years without human influence are now about five-times more likely to occur (IPCC, 2023). In its most recent assessment report, the IPCC concludes that "the scale of recent changes across the climate system as a whole […] are unprecedented over many centuries to many thousands of years" (IPCC, 2023).

Recent extreme weather events have led to increasingly widespread concern about a "climate crisis". India and Pakistan were hit by disastrous flooding in 2022. Over the summer of 2023, an extreme heat wave hit southern Europe and other parts of the world; in China and the United States, temperatures reached over 52 °C. More than 30 million acres were charred by wildfires in Canada by mid-2023, and the Horn of Africa is experiencing the longest and most severe drought on record.

These extreme weather events take a very high large toll on people, ecosystems and economies. Almost 62 000 heat-related deaths were recorded in Europe in 2022. In Pakistan, flooding in 2022 killed over 1 700 people, and damaged the lives of millions more. In 2023, many months after the flooding, more than 8 million people still live near contaminated flood waters and are consequently exposed to disease. Health risks can also occur indirectly, for example through smog from wildfires travelling large distances. These events also cause serious financial damage and weaken economic prosperity. In the United States, wildfires caused around USD 81.6 billion in damage from 2017 to 2021, a nearly ten-fold increase over the previous five-year period, while the effects of the droughts experienced in South America in 2023 are estimated to have reduced GDP in Argentina in 2023 by three percentage points.

There is a rapidly closing window to secure a liveable and sustainable future for all. Deep, rapid and sustained cuts in CO_2 emissions to net zero can limit future warming, but societies will have to adapt to the effects of the climate change that is already happening.

2.1.3 Key mitigation levers

By mitigation measure

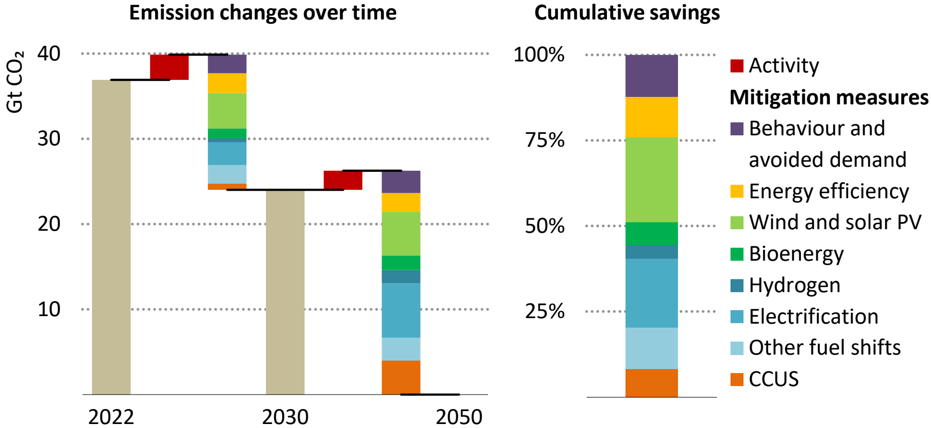
Meeting energy sector net zero emissions by 2050 requires using all available measures to reduce emissions (Figure 2.5). In the near term, almost all emissions reductions are delivered by technologies and measures that are available, scalable and cost effective today.

First among these is the rapid deployment of solar PV and wind, which together account for 4 Gt of CO_2 of emissions reductions by 2030. This is equivalent to the combined emissions of the European Union, Japan and Korea today.

The next largest driver of emissions reductions is electrification. As the electricity sector is increasingly decarbonised, it delivers emissions reductions through the expanding deployment of technologies like EVs and heat pumps in buildings and light industries. In the NZE Scenario, electrification both delivers significant energy demand savings and reduces emissions by around 3 Gt by 2030. Measures such as more efficient end-uses of emissions-intensive materials and reduced material intensity of production also contribute to near-term emissions reductions, as do behavioural changes on the part of consumers such as reducing indoor temperatures and driving speeds on highways. This diverse portfolio of measures cuts emissions by more than 2 Gt in 2030. Without such measures to reduce wasteful material and energy use, the transition would be much more challenging (Box 2.3).

Fuel switching also contributes to emissions reductions through to 2030 in the NZE Scenario. This includes switching from fossil fuels to additional renewable options such as bioenergy, hydropower, solar thermal and geothermal, as well as increasing the use of nuclear power technology and switching from coal to natural gas. These measures together provide more than 3 Gt of emissions reductions by 2030. Energy efficiency improvements of equipment, appliances, trucks, planes and building envelopes reduce emissions further by slightly less than 2 Gt. Hydrogen and CCUS take time to scale up even in the NZE Scenario, but together they deliver a further 1 Gt of reductions by 2030.

Figure 2.5 ⊳ CO_2 emissions reductions by mitigation measure in the NZE Scenario, 2022-2050



Expansion of solar PV, wind and other renewables, energy intensity improvements and direct electrification of end-uses combined contribute 80% of emission reductions by 2030

Notes: Activity = energy services demand changes from economic and population growth. CCUS includes BECCS and DACS.

The outlook changes in the period to 2050. Getting emissions to net zero requires active measures in emission-intensive sectors such as steel, cement and long-distance transport. Together CCUS, hydrogen and hydrogen-based fuels account for one-fifth of emissions reductions in the 2030 to 2050 period. The contribution made by electrification increases, as EVs come to dominate the stock of not just cars and motorbikes but also trucks, and as electrification expands further in the buildings and industry sectors. As a result, electrification accounts for nearly one-quarter of the emissions reductions seen in the 2030-2050 period.

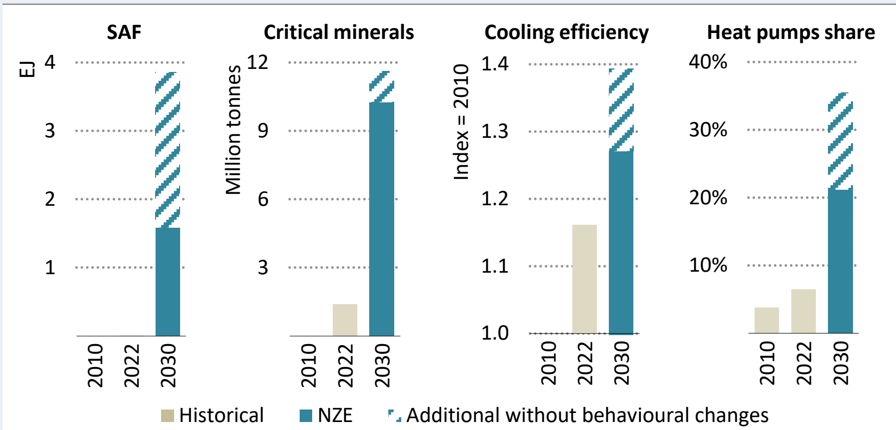
For the period 2022 to 2050, the largest total contribution to emissions reductions in the energy sector is from solar PV and wind, which account for 25% of all cumulative emissions reductions in the NZE Scenario. In addition, measures to reduce demand through increased energy efficiency, more efficient use of materials and behavioural change together account for a further almost 25%. Expanding electrification in the transport, industry and buildings sectors provides 20% of abatement as electricity generation is progressively decarbonised. Increased bioenergy and other fuel shifts account for slightly less than 20%, and hydrogen and CCUS account for slightly less than 15%.

Box 2.3 ▷ Without behavioural changes, clean energy technologies would have to accelerate even more rapidly

Clean energy technologies are deployed at unprecedented speed in the NZE Scenario, but many CO_2-intensive energy assets will still be in use in 2030. Reducing their emissions or replacing them depends on scaling up novel or complex low-emissions solutions and deploying them around the world, and that will take time. In the NZE Scenario, behavioural changes cut around 1 Gt CO_2 from emissions-intensive assets which are still in use in 2030. (Chapter 3 provides more details of what these changes are and how they can be implemented).

In the absence of energy demand reductions from behaviour change, achieving the same emissions reductions in end-uses would require ramping up low-emissions technologies at staggering speed (Figure 2.6). In aviation, the use of sustainable aviation fuel (SAF) would need to increase more than twice as fast as in the NZE Scenario, reaching about 4 exajoules (EJ) by 2030 and accounting for about 25% of the aviation fuel market. In road transport, the use of more EVs would require an additional 1.3 million tonnes (Mt) of critical minerals by 2030 – roughly the amount of critical minerals used in the EV sector today. In buildings, heat pumps would need to provide about 35% of heating demand in 2030, whereas it is 20% in the NZE Scenario, meaning that heat pump sales would need to rise from 10% of all heating equipment sales today to 50% by 2026.

Figure 2.6 ▷ Energy transition levers with and without behavioural change in the NZE Scenario



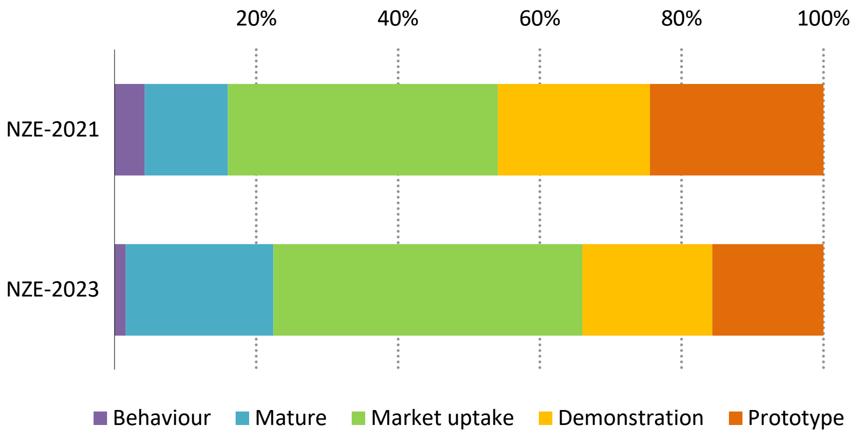
Other mitigation levers offer alternatives to behavioural changes, but the additional pace of uptake required would be very challenging

Notes: SAF = sustainable aviation fuel. Cooling efficiency is measured as the ratio of service demand over final energy consumption, which reflects efficiency of both building envelopes and equipment. Critical minerals in this figure refer to the demand for battery manufacturing for EVs.

By technology readiness level

The share of emissions reductions in the NZE Scenario in 2050 from technologies at either demonstration or prototype stage, i.e. not yet available on the market, has been reduced from around half in the 2021 NZE Scenario to around 35% in the 2023 version (Figure 2.7).

Figure 2.7 ⊳ Comparison of CO_2 emissions reductions in 2050 relative to base year by technology maturity in the 2021 and 2023 NZE Scenarios



Emissions reductions by 2050 from technologies in demonstration or prototype stage have been reduced from almost half in the 2021 NZE to around 35% in the 2023 NZE Scenario

Note: 2020 is the reference base year for the 2021 version of the NZE Scenario and 2022 is the base year for the 2023 NZE Scenario.

This change reflects two factors in particular. First, there has been considerable progress on clean energy innovation in the last few years, with important technology upgrades in several sectors, including the commercialisation of a number of technologies (Figure 2.8).[6] Second, there are differences in the rate of deployment for some clean technologies in the 2023 NZE Scenario relative to the 2021 version to reflect changing technology and market trends.

Key selected examples of changes since 2021 that are reflected in the 2023 NZE Scenario include:

- **Road transport:** Today battery electric passenger cars and lithium-ion batteries are much more widespread than they were in 2021, and markets are maturing even though they still need support in many cases. Cost reductions and standardisation for

[6] For more information on technology development and progress, see: Tracking Clean Energy Progress (https://www.iea.org/reports/tracking-clean-energy-progress-2023) and the Clean Tech Guide, an interactive database of over 550 individual technology designs and components across the whole energy system (https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide).

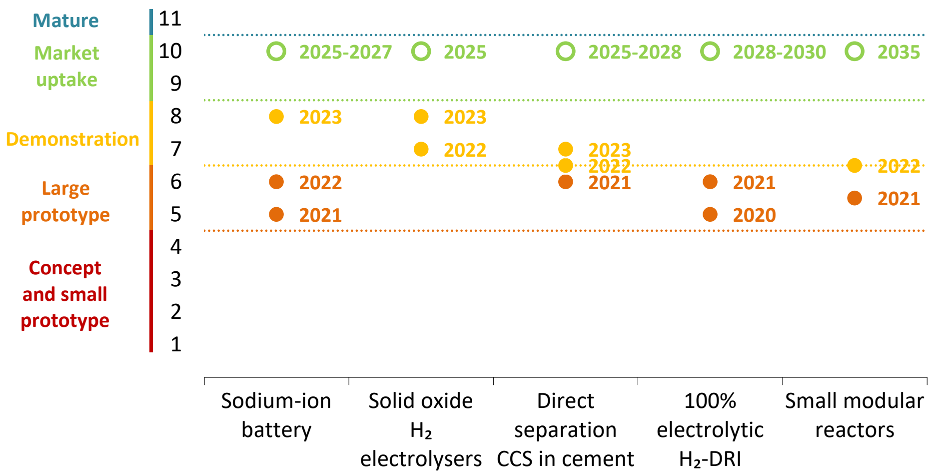
commercial lithium-ion batteries in particular have strengthened the business case for electromobility over other options across all segments of road transport. The first commercialisation of cars powered by sodium-ion batteries was announced in China for 2023; this technology was still at prototype stage in 2021. Other innovative battery chemistries, for example with higher energy density for heavy-duty applications, are emerging, although some, such as solid-state batteries, are still at the prototype stage and are experiencing delays in production. If delays persist, further advances in lithium-ion battery technology might decrease the competitive advantage of these emerging concepts and reduce their future role. Electric vehicle charging infrastructure is expanding rapidly. Developments in ultra-fast electric charging and battery swapping as well as hydrogen refuelling for heavy-duty vehicles are making some progress. Overall, the decarbonisation of road transport in the 2023 NZE Scenario relies around ten percentage points less on technologies under development in 2050 than the 2021 assessment. For example, the share of fuel cell electric heavy-duty vehicles on the road in 2050 is 25-40% lower in the 2023 NZE Scenario than in the 2021 version, with the extent of the reduction varying by segment.

- **Power generation:** Electricity generation from solar PV and wind in 2050 is 13% higher in the 2023 NZE Scenario than in the 2021 version. This reflects the establishment of crystalline solar PV modules and onshore wind technology designs on the market, and increases the scale of advanced designs such as floating offshore wind turbines. Long duration storage is making progress through advances in battery technology and demonstration projects in thermal and mechanical storage for power. On the other hand, fossil fuel-based electricity generation from facilities equipped with CCUS – an area currently with several technologies at demonstration stage – is moving more slowly than projected in 2021. The contribution of CCUS to emissions reductions in power generation by 2050 has been reduced by around 40% in the 2023 NZE Scenario.

- **Heavy industry:** Recently there has been significant progress in 100% electrolytic hydrogen-based direct reduced iron steelmaking, which accounts for nearly half of iron-based steel production by 2050 in the 2023 NZE Scenario. Progress is evident too in cement production, both on carbon capture through indirect calcination, and on alternatives to conventional raw materials and clinker. CCUS applications for a broad range of chemicals are maturing from prototype to demonstration stages. Pilot projects for full electrification of hydrocarbon cracking are making progress. The pipeline of projects for low-emissions ammonia production has expanded rapidly since 2021, mostly electrolytic and some via steam methane reforming with CCUS. Progress is also noted in batteries for heat storage, which could assist variable electricity generation to provide constant high-temperature heat or high-pressure steam.

- **Non-road transport:** Small electric aircraft for regional distance flights are close to being demonstrated for the first time. Production of low-emissions aviation fuels is ramping up. Large prototypes of ammonia-fuelled ships are being built, methanol-powered container ships are being delivered, and small-scale hydrogen fuel cell ferries are starting operations.

Figure 2.8 ▷ Technology readiness level for selected technologies relative to technology maturity targets in the NZE Scenario



Accelerating clean energy innovation has delivered important technology upgrades in the last few years, although much remains to be done to achieve net zero pathways

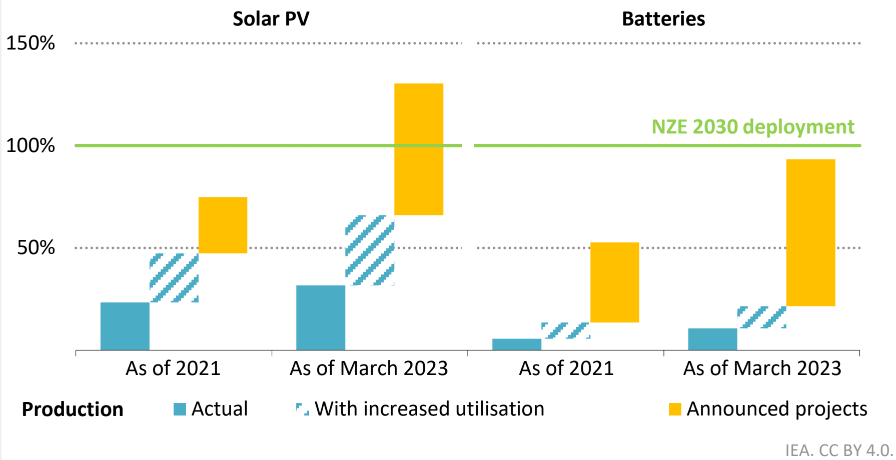
Notes: H_2 = hydrogen; DRI = direct reduced iron. For H_2-based DRI steelmaking, R&D on incorporating hydrogen into steelmaking has been taking place for decades, including at one commercial plant since the 1980s that relies largely on hydrogen. However here we highlight specifically 100% electrolytic-H_2 production. Future years shown in the graph refer to the year when a given technology reaches commercial operation in the NZE Scenario.

Box 2.4 ▷ Announced manufacturing output for solar PV and batteries would deliver around a third of all the emissions reductions required in the NZE Scenario in 2030

Solar PV and batteries are two of the most critical technologies to decarbonise the energy system. Together they deliver around one-third of the emissions reductions needed in the NZE Scenario in 2030. In 2022, solar PV capacity additions and electric car sales – a key driver of battery demand – expanded by rates equivalent to the average compound annual growth needed to meet the requirements for 2030 in the NZE Scenario.

Manufacturers are gearing up to supply rapidly rising demand (Figure 2.9). In 2022 alone, total installed manufacturing capacity jumped by nearly 40% for solar PV and almost 60% for batteries, of which most was for EVs with a small share for grid storage. The pipeline of announced projects is also skyrocketing. As of first-quarter 2023, total manufacturing throughput from existing and announced projects in 2030 for both solar PV and batteries would be about 75% higher than when considering announced projects as of the end of 2021. If all these projects proceed and are completed on time, production from existing and announced manufacturing capacity would exceed demand in 2030 in the NZE Scenario for solar PV, and just about meet demand for batteries.

Figure 2.9 ▷ Solar PV and battery manufacturing throughput, from existing capacity and announced projects compared to deployment in 2030 in the NZE Scenario



Massive growth in the last two years is apparent in both installed and announced capacity for solar PV and battery manufacturing

Notes: Batteries include batteries for EVs and grid storage. 'Increased utilisation' indicates that utilisation of existing manufacturing capacity increases from actual rates to 85%. A utilisation rate of 85% is used for announced projects. For 'As of March 2023', 'Actual' and 'With increased utilisation' are considering production from existing capacity in 2022, and 'Announced projects' are as of the end of March 2023.

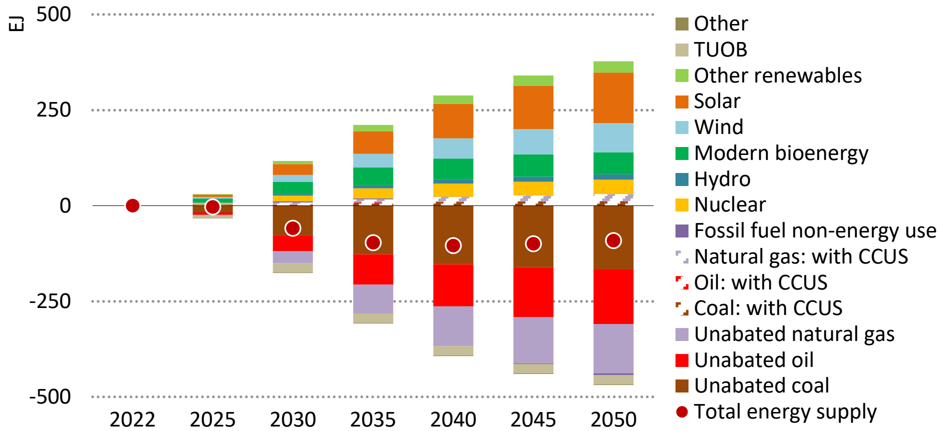
2.2 Energy trends

2.2.1 Total energy supply

The NZE Scenario projects increasing use of low-emissions energy sources in place of unabated fossil fuels (Figure 2.10). Between 2022 and 2030, low-emissions sources increase by over 110 EJ, equivalent to the current total energy supply of the United States and Japan combined. Over the remainder of this decade, the increase in low-emissions energy sources is led by modern bioenergy in its solid, liquid and gaseous forms. Wind and solar PV also increase strongly, although the share in primary energy is not the best indicator to reflect their role in the energy system given that they have lower conversion losses.

Total demand for fossil fuels falls by slightly more than one-quarter, or 140 EJ, by 2030. Coal falls the most at slightly less than 75 EJ reflecting the higher level of maturity of emissions reduction technologies in electricity generation which today accounts for most coal use. This decline in coal demand is much less than in comparable scenarios assessed by the IPCC (see Box 2.1). Oil demand declines by around 39 EJ. Natural gas drops the least, around 26 EJ, partly reflecting its increasing use in combination with CCUS to produce hydrogen.

Figure 2.10 ▷ Changes in total energy supply by source in the NZE Scenario, 2022–2050



NZE Scenario relies on a huge increase in low-emissions sources of energy supply and energy intensity improvements; demand for unabated fossil fuels declines by 2030

Notes: TUOB = traditional use of biomass. Unabated coal, oil and natural gas refer to the use of these fuels for combustion purposes without CCUS.

The rising use of fossil fuels combined with CCUS is far smaller than the decline of unabated fossil fuels. Unabated fossil fuel demand falls by around 150 EJ to 2030, while the use of fossil fuels combined with CCUS increases by around 7.5 EJ to 2030, despite the strong push on CCUS seen in the NZE Scenario (see Chapter 3).

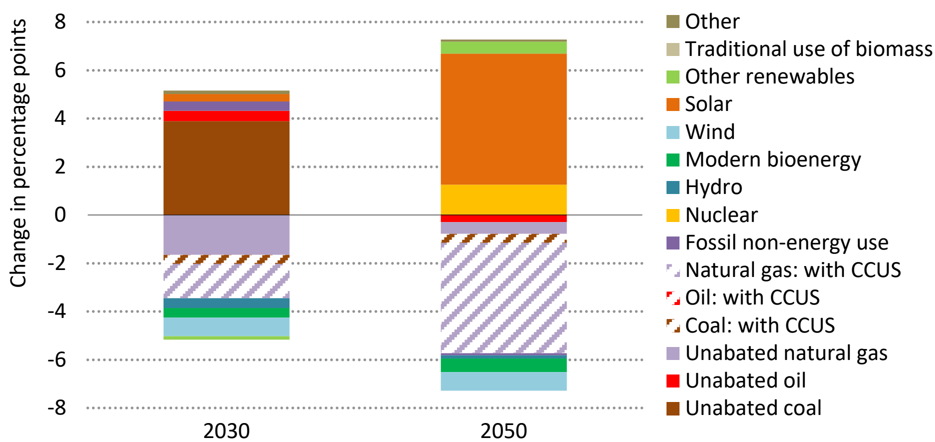
Total energy supply is nearly 10% lower or 60 EJ in 2030 than in 2022, even with global economic growth of over one-quarter. This implies dramatic progress in reducing energy intensity from about 2% per year today to over 4% by 2030. Improving technical efficiency in appliances, motors and building envelopes is key, but a substantial portion of this acceleration in intensity improvement results from a shift to more efficient energy carriers such as electricity. Behavioural changes also contribute to reduced energy demand.

After 2030 the pattern of energy supply continues to evolve rapidly and it is transformed by 2050. Solar, including solar thermal and solar PV, provides nearly 140 EJ in 2050, which is almost equivalent to the total energy supply of unabated natural gas today. Modern bioenergy provides around 100 EJ and wind around 85 EJ. Overall, renewable sources provide more nearly three-quarters of total energy supply by 2050. Abated fossil fuels with CCUS account for a further 5%. Unabated fossil fuels, excluding those used for non-energy purposes, decline from around three-quarters of total energy supply in 2022 to around 5% by 2050. Their emissions are offset through carbon removal technologies. In total, including non-energy uses, fossil fuels account for less than one-fifth of total energy supply in 2050, reversing their share today in which fossil fuels account for about four-fifths of total energy supply, including non-energy uses.

Changes from the 2021 NZE Scenario

The 2023 NZE Scenario represents three broad differences in the composition of total energy supply relative to the 2021 version (Figure 2.11).

Figure 2.11 ▷ Changes in total energy supply by source in the 2021 and 2023 NZE Scenarios in 2030 and 2050



The 2023 NZE Scenario projects slightly higher coal use in the near term and lower use of CCUS, and a higher share of solar PV in total energy supply in the long term

First, unabated fossil fuels account for a somewhat higher share of total energy supply in 2030 than in the 2021 Net Zero Scenario version. For example, although unabated coal drops by around 45% to 2030 compared to levels of use in 2022, its share in total energy supply in 2030 is four percentage points higher in the 2023 NZE Scenario than it was in the 2021 version. This reflects developments since the 2021 version, notably the unexpectedly strong rebound in total energy demand post Covid-19 pandemic. It also reflects adjustments to the design of the scenario, which aims to give more time to emerging market and developing economies to transition to clean energy (see Box 2.1). While coal and oil use in 2030 is higher in the 2023 NZE Scenario than in 2021, natural gas use is somewhat lower because of energy security concerns arising from the global energy crisis.

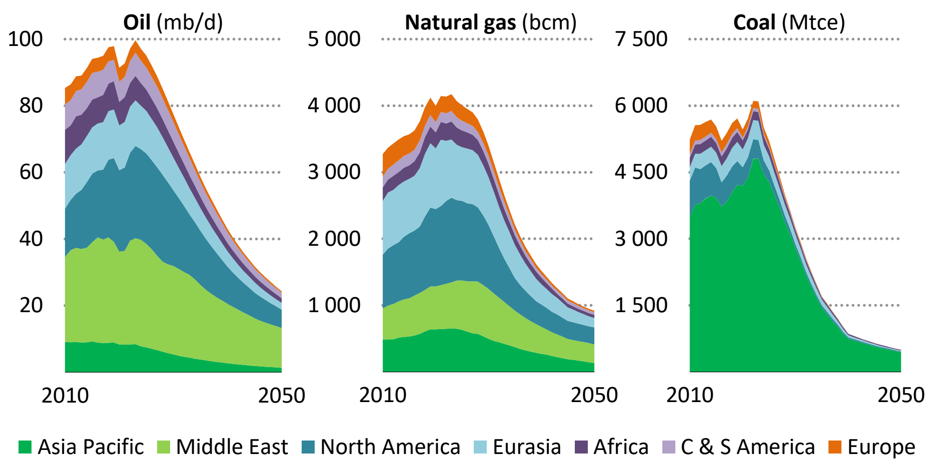
Second, the long-term share of solar in total energy supply is higher than in the 2021 version (section 2.2.3). Third, the share of fossil fuels with CCUS, notably natural gas, is lower than in the 2021 NZE Scenario. This reflects a downward revision to hydrogen demand, caused in part by boosted confidence in the possibility that direct electrification can play a larger role in uses such as trucking. It also reflects a rebalancing towards electrolytic hydrogen production and away from production using natural gas with CCUS; this takes account of the slow pace of current progress on the development of CCUS. In the 2023 NZE Scenario, reduced CCUS deployment is compensated by more renewables and electrification.

2.2.2 Fuel supply

Fossil fuels

Oil, natural gas and coal accounted for around four-fifths of total energy supply worldwide in 2022.[7] The surge in clean energy investment in the NZE Scenario – from USD 1.8 trillion in 2023 to USD 4.5 trillion in the early 2030s – drives sharp declines in fossil fuel demand. The share of fossil fuels in total energy supply drops below two-thirds by 2030 and to less than one-fifth in 2050. Coal demand declines by 45%, and oil and natural gas by around 20% to 2030 (Figure 2.12).

Figure 2.12 ▷ Oil, natural gas and coal supply by region in the NZE Scenario, 2010-2050



Declines in demand can be met without approving new, long lead time upstream conventional oil and gas projects, new coal mines or mine lifetime extensions

Note: mb/d = million barrels per day; bcm = billion cubic metres; Mtce = million tonnes of coal equivalent; C & S America = Central and South America.

[7] Further information on oil and natural gas is forthcoming this year with the World Energy Outlook Special Report: The Role of the Oil and Gas Industry in Net Zero Transitions.

Coal demand falls quickly in the 2020s, declining by 7% on average each year to 2030 from 5 800 million tonnes of coal equivalent (Mtce) in 2022 to 3 300 Mtce in 2030 and less than 500 Mtce in 2050. Oil demand drops from 97 million barrels per day (mb/d) in 2022 to 77 mb/d in 2030 and 24 mb/d in 2050. Demand for natural gas falls from 4 160 billion cubic metres (bcm) in 2022 to 3 400 bcm in 2030, and 920 bcm in 2050.

Just under 90 EJ of fossil fuels are consumed in 2050 in the NZE Scenario. One-third of this, including 60% of natural gas and 80% of coal, is used in facilities equipped with CCUS. A further 40%, including 70% of oil, is consumed in applications where the carbon is embodied in the product and there are no direct CO_2 emissions, e.g. chemical feedstocks, lubricants, paraffin waxes and asphalt. The remaining 25% is used in sectors where clean energy technologies are least feasible and cost effective, for example, oil accounts for around 20% of fuel use in aviation in 2050 in the NZE Scenario. The unabated combustion of fossil fuels results in 1.4 Gt CO_2 emissions in 2050 which are fully balanced by removal of CO_2 from the atmosphere through BECCS and DACS.

The sharp decline in fossil fuel demand in the NZE Scenario means that no new conventional long lead time oil and gas projects are approved for development after 2023, and that there are no new coal mines or coal mine lifetime extensions. The pace of decline in oil and gas demand in the 2030s may also mean that a number of high cost projects come to an end before they reach the end of their technical lifetimes.

Investment in existing fossil fuel supply projects, however, is still needed in the NZE Scenario to ensure that supply does not fall faster than the decline in demand. This includes the use of in-fill drilling and improved management of reservoirs as well as some enhanced oil recovery and tight oil drilling to avoid a sudden near-term drop in supply. Investment is also undertaken to reduce the emissions intensity of remaining fossil fuel operations, especially to tackle methane emissions and flaring. In the NZE Scenario, this leads to a 50% reduction in the global average GHG emissions intensity of oil and gas production between 2021 and 2030, and to almost zero emissions from oil and gas operations soon after 2040.

A large and sustained surge in clean energy investment is what removes the need for new fossil fuel projects in the NZE Scenario: reducing fossil fuel supply investment in advance of, or instead of, policy action and investment to reduce demand would not lead to the same outcomes. Prolonged high prices would result if the decline in fossil fuel investment in this scenario were to precede the expansion of clean energy and the action to cut overall energy demand that are also set out in this scenario. This would reduce the chances of an orderly transition to net zero emissions by 2050 and underlines the importance of action to secure the kind of surge in investment in clean energy and the demand reductions that are seen in the NZE Scenario.

What has changed since the 2021 NZE Scenario?

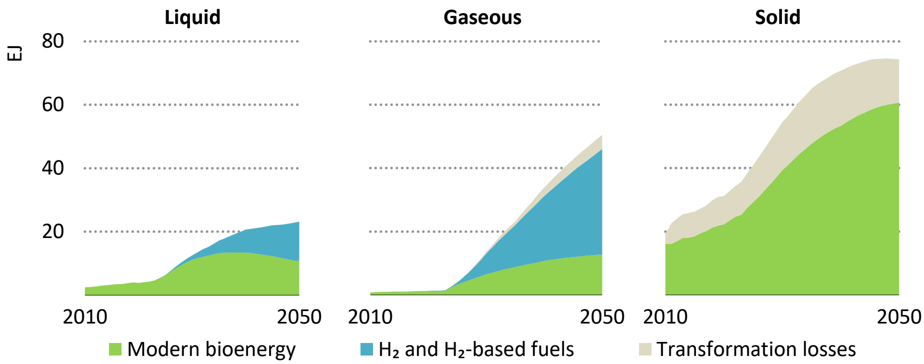
Natural gas plays less of a role in the 2023 NZE Scenario than in the 2021 version. Natural gas use is 10% lower in 2030 and 45% lower in 2050 than in the 2021 version. Price spikes in 2022 have shaken confidence in natural gas as an affordable alternative to coal or oil, especially among some import-dependent emerging market and developing economies. Much less natural gas is also used to produce low-emissions hydrogen than was the case in the 2021 NZE Scenario.

On the supply side, additional oil and gas projects approved since the 2021 NZE Scenario are likely to add around 4 mb/d and 170 bcm of production in 2030 (mainly in the Middle East and South America). This additional supply and the increased pace of reduction in natural gas demand in the NZE Scenario in the 2030s and 2040s now means that some production is closed before fields have reached the end of their technical lifetimes. Russia's invasion of Ukraine is also relevant here. The drop in Russian production to date (Russian natural gas production in 2022 was 100 bcm lower than in 2021) is smaller than the additional production from new projects that have recently been approved for development. Governments are rightly concerned about energy security, but new conventional field approvals cannot provide immediate relief for tight markets and may well make the later stages of the transition even more challenging.

Low-emissions fuels

The supply of low-emissions fuels, including modern bioenergy, hydrogen and hydrogen-based fuels, increases rapidly in the NZE Scenario (Figure 2.13). They play an important role in reducing emissions, notably those from long-distance transport and heavy industry. In the NZE Scenario, demand for low-emissions hydrogen and hydrogen-based fuels rises fastest, albeit from a low starting point, with an average annual growth rate of 80% to 2030 and 9% between 2030 and 2050. However, in absolute terms, solid bioenergy also increases its contribution to clean energy supply substantially. Demand for solid bioenergy increases by 15 EJ by 2030, equivalent to 500 Mtce.

Figure 2.13 ⊳ Low-emissions fuel demand in the NZE Scenario, 2010-2050



Gaseous low-emissions fuels – including hydrogen – increase at the fastest rate in the NZE Scenario, but solid fuels increase nearly as much in absolute terms

Notes: H_2 = hydrogen. Liquid, gaseous and solid refer to the phase of the fuel at the point of use or conversion. Transformation losses are those incurred during conversion from one low-emissions fuel to another and exclude upstream energy losses associated with producing the converted fuel. Demand for hydrogen is inclusive of what is met by captive production onsite at industrial and refining facilities.

Modern solid bioenergy is mostly used today for industrial purposes. By 2050, however, power generation accounts for 40% of the total, ahead of industry at 30% and inputs to liquid and solid biofuels at 20%. Around 24 EJ or 40% of current bioenergy consumption comes from the traditional use of biomass, but this is phased out by 2030 in the NZE Scenario as full access to modern cooking technologies is achieved (see Chapter 3).

Modern liquid biofuel demand, including gasoline, diesel, marine and aviation fuels that derive their energy content primarily from biogenic non-electricity sources, increases by 200% before peaking around 2040. Afterwards the continued phase-out of internal combustion engine cars means that it is less in demand as a blending fuel for road vehicles, and this reduction in demand outweighs steady increases in demand for maritime and aviation uses.

Gaseous bioenergy, including biogas and biomethane, becomes a highly valuable component of the energy system in the NZE Scenario by 2030, notably in the power sector. This is in part because it is the most cost-effective direct substitute for natural gas, an attribute that has taken on a significant energy security dimension since the Russian invasion of Ukraine in early 2022. By 2050, biogas from anaerobic digestors and other production techniques take on a wide variety of roles because it offers one of the cheapest ways to meet rising demand for clean, gaseous fuels for flexible power generation, industrial heat, hydrogen production and, potentially, maritime fuel. In addition, they are able to provide sustainable carbon inputs to hydrogen-based fuels. However, the accessible resource base for biogas production is limited, which in effect rations its use.

Low-emissions hydrogen production increases from 0.6 Mt (75 petajoules) today to 70 Mt in 2030 and 420 Mt in 2050. Of the low-emissions hydrogen produced in 2050, 80% is produced via water electrolysis, and nearly all the remainder from fossil fuels equipped with CCUS. From around 1 GW today, the installed capacity of electrolysers reaches 590 GW in 2030, a rate of growth that could be within reach if all the projects currently planned are taken forward, including early stage projects. By 2050, 3 300 GW of electrolysis capacity and 15 000 terawatt-hours (TWh) of electricity are used to produce low-emissions hydrogen; the electricity required is more than half of today's total global electricity demand. Around 80% of total hydrogen and hydrogen-based fuel use in 2050 is for industry and transport, with roughly one third of total low-emissions hydrogen in 2050 being converted to low-emissions hydrogen-based transport fuels. Synthetic kerosene produced from hydrogen (and combined with a non-fossil fuel source of CO_2) provides around 40% of energy use in the aviation sector, and ammonia and hydrogen provide more than 60% of energy use in shipping.

What has changed since the 2021 NZE Scenario?

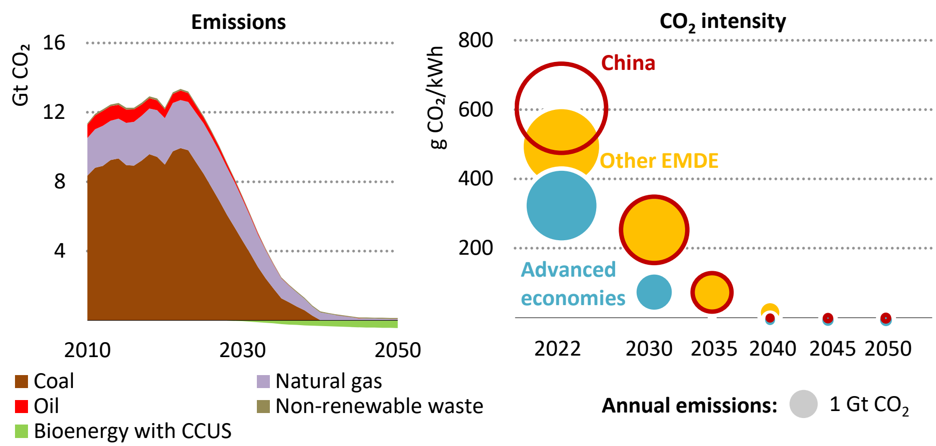
Overall, the level of low-emissions hydrogen in 2050 is broadly similar in the 2023 NZE Scenario compared with the 2021 version, indicating that it retains its competitive position as a leading option to reduce fossil fuel use in certain sectors. However, as support from governments and potential low-emissions hydrogen users has not ramped up at the pace envisaged by the 2021 NZE Scenario, the corresponding 2030 level has been adjusted downwards to reflect what can still be achieved this decade. In addition, the sources of low-emissions hydrogen have been somewhat rebalanced: the sluggishness of progress on CCUS outside North America, coupled with a higher emphasis on reducing natural gas demand in some regions, has led to a reduction in the amount of hydrogen produced with fossil fuels and CCUS in the NZE Scenario.

2.2.3 Electricity generation

Overview

Global electricity generation increases over two-and-a-half-times in the NZE Scenario from 2022 to 2050, growing significantly faster over this period (3.5% per year) than over the past decade (2.5%). The electrification of end-uses ranging from EVs to space heating to industrial production, combined with economic development and population growth, drives this growth and raises the share of electricity in final consumption from 20% in 2022 to almost 30% in 2030 and more than 50% in 2050. In addition, hydrogen production via electrolysis increases rapidly in the NZE Scenario and accounts for almost 20% of global electricity demand in 2050.

Figure 2.14 ▷ Global electricity sector emissions and CO_2 intensity of electricity generation in the NZE Scenario, 2010-2050



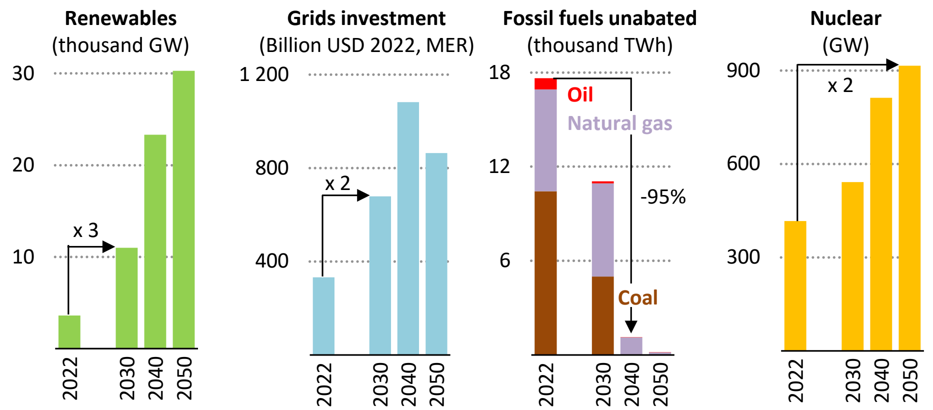
Electricity sector reaches net zero emissions in advanced economies in aggregate in 2035, in China around 2040 and globally before 2045

Note: g CO_2 /kWh = grammes of carbon dioxide per kilowatt-hour; other EMDE = emerging market and developing economies excluding China.

Low-emission sources of electricity – renewables, nuclear, fossil fuels with CCUS, hydrogen and ammonia – expand rapidly in the NZE Scenario, overtaking unabated fossil fuels just after 2025 and reaching 71% of total generation by 2030, almost twice the share in 2022. Electricity sectors in advanced economies, in aggregate, reach net zero emissions by 2035 in the NZE Scenario, around 2040 in China and by 2045 in other emerging market and developing economies (Figure 2.14). In each case, electricity is the first energy sector to reach net zero emissions, creating opportunities for electrification in other sectors to further drive down emissions.

The first of four key milestones for the electricity sector in the NZE Scenario is the tripling of global renewables capacity by 2030 from the level of 3 630 GW in 2022 (Figure 2.15). This leads to the share of renewables in electricity generation rising from 30% in 2022 to about 60% in 2030. By 2050 in the NZE Scenario, the total installed capacity of renewables is eight-times the level in 2022, and it generates nearly 90% of global electricity supply.

Figure 2.15 ▷ Key milestones for the electricity sector in the NZE Scenario, 2022-2050



Renewables capacity triples and grid investment doubles by 2030, unabated coal is phased out by 2040 in the NZE Scenario and nuclear capacity more than doubles by 2050

The second key milestone for the electricity sector is the doubling of grid investments by 2030. In the NZE Scenario, electricity transmission and distribution grids expand to meet the growing demands of electrification, connect thousands of new renewable energy projects, and reinforce systems that need to adapt to changing system dynamics. Global annual investment in grids to 2030 reaches USD 680 billion, and it remains at a high level through to 2050. Close to 70% of this investment is for distribution grids with the aim of expanding, strengthening and digitalising networks. In addition to the scaling up of investment, regulatory and policy reforms facilitate timely and efficient development and modernisation of grids to support clean energy transitions.[8]

The third key milestone for the electricity sector is a 95% reduction by 2040 in the unabated use of fossil fuels to generate electricity which includes the complete phase out of unabated

[8] *Electricity Grids and Secure Energy Transitions*, a forthcoming IEA report, will be published in late 2023.

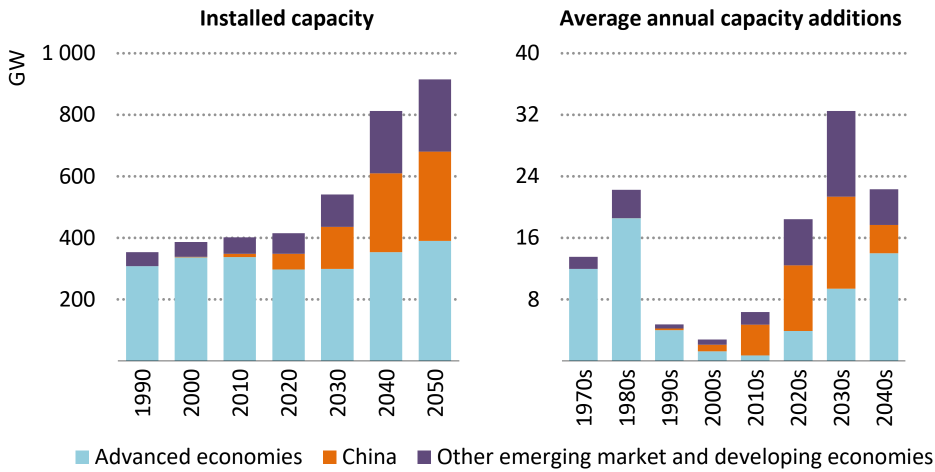
coal. Emissions from unabated coal were nearly 10 Gt CO_2 in 2022, making up almost 75% of the electricity sector total and 27% of total energy sector emissions. Despite a temporary boost from the energy crisis, the share of unabated coal in global electricity generation falls rapidly in the NZE Scenario from 36% in 2022 to 13% in 2030, and to zero by 2040 and beyond. Coal phase-outs are already underway, and over 90 countries representing nearly all coal-fired power in the world have either committed to phase out unabated coal specifically or set net zero emissions targets (IEA, 2022a). Low-emissions sources of generation rise so rapidly that no new unabated coal plants beyond the 150 GW under construction at the start of 2023 are built in the NZE Scenario. Emissions from unabated natural gas use for electricity generation were 2.8 Gt CO_2 in 2022, contributing just over 20% of electricity sector emissions, while oil use led to a further 0.5 Gt of emissions. Unabated natural gas declines by over 80% by 2040 in the NZE Scenario, and large-scale oil-fired power plants are fully phased out by then.

The fourth key milestone for the electricity sector is for nuclear power to more than double from 417 GW in 2022 to 916 GW in 2050. Despite this growth, the share of nuclear power in generation declines slightly in the NZE Scenario from 9% in 2022 to 8% in 2050. After three decades of modest growth, a changing policy landscape is opening opportunities for a nuclear comeback. As a means of pursuing emissions reductions targets and addressing energy security concerns, several countries have announced strategies that include a significant role for nuclear power, including Canada, China, France, India, Japan, Korea, Poland, United Kingdom and United States. At the start of 2023, nuclear reactors totalling 64 GW were under construction in 18 countries around the world. In the longer term, more than 30 countries which accept nuclear power today increase their use of nuclear power in the NZE Scenario.

To achieve the overall doubling of nuclear capacity by 2050, an average of 26 GW of new capacity comes online every year from 2023 to 2050 in the NZE Scenario, some of which is needed to offset retirements (Figure 2.16). This calls for average annual investment of over USD 100 billion, which is triple the level in recent years. Following the completion of projects already underway, the peak of expansion comes in the 2030s, when an annual average of 33 GW of new nuclear capacity comes online, marking a new high for the nuclear industry.

China leads the way in nuclear power expansion, accounting for one-third of all new nuclear capacity to 2050 in the NZE Scenario, with other emerging market and developing economies accounting for almost another one-third. In advanced economies, where reactors have been in operation on average for over 35 years, nuclear capacity additions rise over time largely to offset the retirement of existing reactors, though lifetime extensions continue to play an indispensable role as part of a cost-effective approach to achieving net zero emissions by 2050 (IEA, 2022b). All regions increasingly draw on advanced nuclear technologies, including new large reactor designs (generation III+ and IV) and small modular reactors. While the biggest opportunity for nuclear power is in the electricity sector, new nuclear power in this scenario helps to decarbonise heat and to supply low-emissions hydrogen.

Figure 2.16 ▷ Nuclear power capacity and average annual capacity additions in the NZE Scenario, 1990-2050



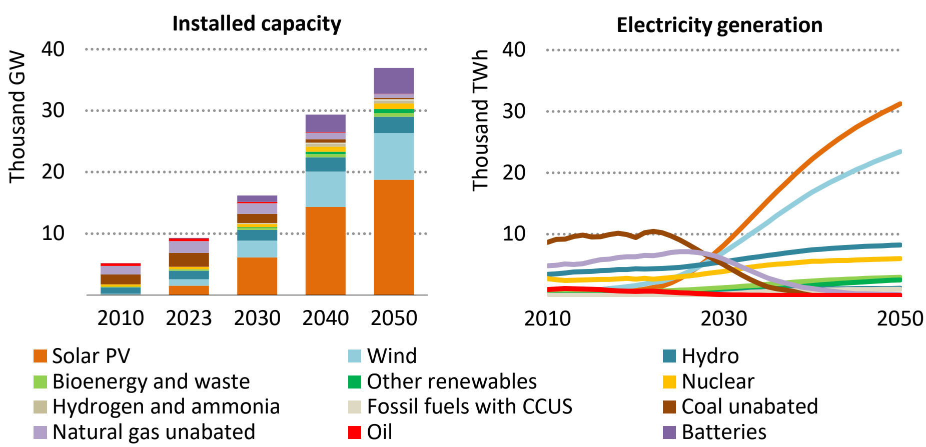
Nuclear power capacity more than doubles to over 900 GW by 2050, with recent policy decisions opening opportunities for a nuclear comeback

Solar PV and wind are the leading means of cutting electricity sector emissions: their combined global share of electricity generation increases from 12% in 2022 to 40% by 2030 and 70% by 2050. Solar PV additions expand almost fourfold to 820 GW by 2030, one-quarter of which is dedicated to the production of hydrogen. Wind additions reach 320 GW by 2030, more than 30% of which is offshore, and with just over 10% of all wind dedicated to hydrogen production. Solar PV becomes the largest source of electricity by 2030 and holds that position through to 2050; wind becomes the second-largest source (Figure 2.17).

Rising shares of solar PV and wind put a premium on power system flexibility and stability in the NZE Scenario. Hourly flexibility needs quadruple between today and 2050 due to new demand patterns and to the variable output of solar PV and wind. Seasonal variability also increases in many regions in the NZE Scenario, calling on hydropower, low-emissions thermal plants and new forms of long duration storage, including hydrogen. In addition, the high shares of inverter-based resources, such as wind, solar PV and batteries, increase system stability challenges.

In the NZE Scenario, natural gas-fired generation peaks in the mid-2020s before starting a long-term decline. Even as output falls, however, natural gas-fired capacity remains a critical source of power system flexibility in many markets, particularly to address seasonal flexibility needs. Capacity additions of hydropower and other dispatchable renewables triple by 2030 to over 125 GW, expanding the supply of both low-emissions electricity and flexibility. Stationary utility-scale battery storage is a relatively new source of flexibility, and it expands 36-fold in the NZE Scenario by 2030. Batteries are well suited to provide power system flexibility on the scale of seconds, minutes or hours, and can bolster the stability and reliability of electricity networks by providing fast frequency response. By 2030, global utility-scale battery capacity reaches 1 000 GW in the NZE Scenario and accounts for about 15% of all dispatchable power capacity. Pumped hydro is already well established as an important form of storage; other forms of storage, including thermal and gravity-based systems, are now under development. Expanding fleets of EVs and the increased electrification of end-uses also provide increasing scope for demand response measures to provide flexibility. Alongside this, the NZE Scenario sees the deployment of existing and new technologies to support system stability: these include synchronous condensers, flexible alternating current (AC) transmission systems, grid-forming inverters and fast frequency response capabilities.

Figure 2.17 ▷ Total installed capacity and electricity generation by source in the NZE Scenario, 2010-2050

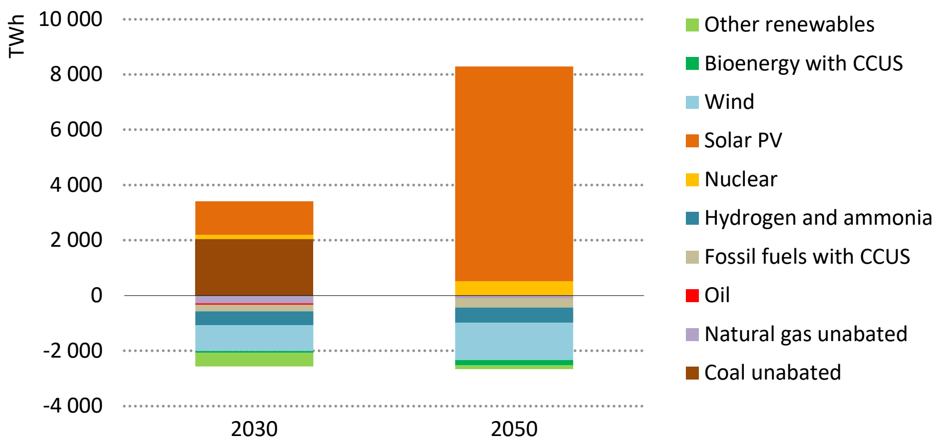


Solar PV and wind lead decarbonisation of the electricity sector, becoming the largest sources of electricity by 2030, complemented by nuclear and other low-emissions sources

What changed compared to 2021 NZE Scenario?

The 2023 NZE Scenario includes a faster and larger increase in solar PV than the 2021 version (Figure 2.18). Solar PV capacity additions in 2030 are 30% higher than in the 2021 version, reflecting recent market acceleration and the rapid scaling up of manufacturing capabilities (see Chapter 1). Nuclear power expansion also proceeds more vigorously, with almost 15% more capacity in 2050 in the updated NZE Scenario than in the 2021 version, reflecting strengthened policy support in leading markets and brighter prospects for small modular reactors. On the other hand, wind power increases less strongly in the 2023 NZE Scenario, and 2030 capacity additions in 2030 are 20% lower than in the 2021 version due to limited plans globally to expand manufacturing and challenging financial conditions across the supply chain. Hydrogen and ammonia also play a smaller role than in the 2021 version as a result of continuing high costs and competition for potential end-uses. The role of carbon capture in reducing emissions from fossil fuel power plants has also diminished mainly due to a lack of new projects.

Figure 2.18 ▷ Global changes in electricity generation in the 2023 NZE Scenario relative to the 2021 version, 2030 and 2050



Recent developments in generation are included in the 2023 NZE Scenario with increases in solar PV and nuclear, and less wind, hydrogen, CCUS and BECCS than the 2021 version

2.2.4 Final energy consumption

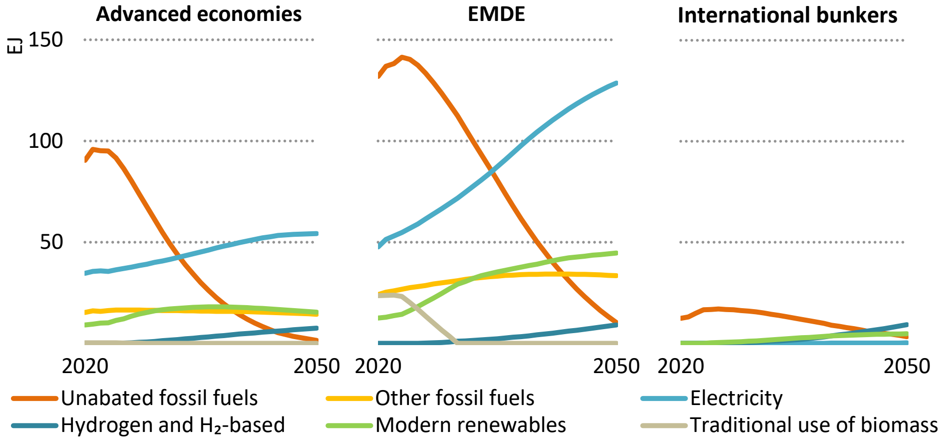
Overview

Today, global total final energy consumption is 442 EJ. Emerging market and developing economies account for 60% and advanced economies for 36%, with the remainder used in aircraft and ships for international travel and seaborne trade. Fossil fuels, led by oil, account for two-thirds of global total final consumption, electricity for a fifth and bioenergy[9] for a tenth. The remainder is district heat, solar thermal, geothermal and non-renewable wastes combusted in industrial processes.

By 2030, the share of fossil fuels in final consumption falls 9 percentage points in the NZE Scenario, although they still account for more than half of the total (Figure 2.19). The decline of fossil fuels is fastest in advanced economies, where their share in final consumption falls by more than 15 percentage points to 2030 in the light of action to boost EVs, heat pumps and modern bioenergy, and to moderate energy demand through energy efficiency and behaviour change.

[9] Including renewable wastes.

Figure 2.19 ▷ Total final energy consumption by fuel and region in the NZE Scenario, 2020-2050



Use of unabated fossil fuels and traditional use of biomass plummets as more end-uses switch to progressively decarbonised electricity and other low-emissions fuels

Notes: EMDE = emerging market and developing economies. Other fossil fuels include fossil fuels equipped with CCUS and those used for non-combustion purposes, such as feedstock for chemicals production.

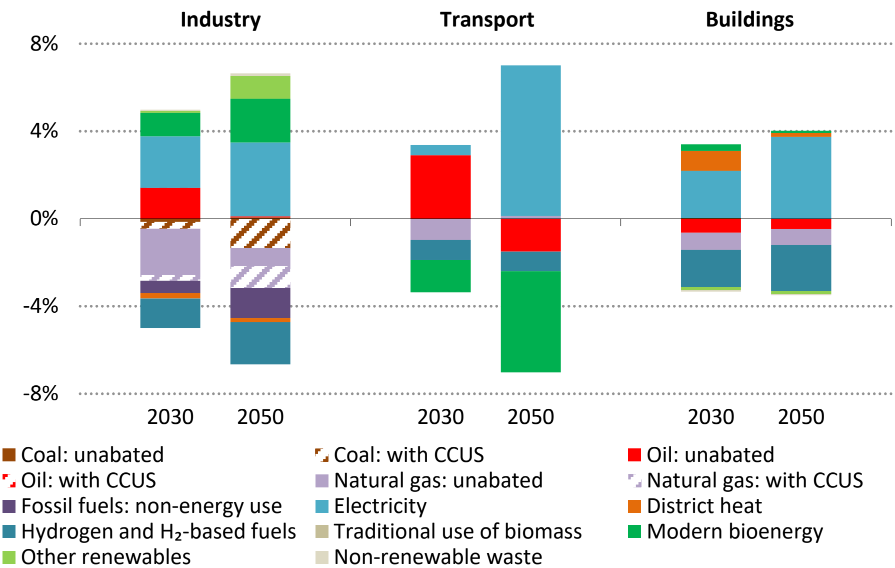
Floorspace in the buildings sector and the total road vehicle fleet both increase more than 15% globally by 2030, driven by emerging market and developing economies. The transitions that take place in end-use sectors are somewhat slower in emerging market and developing economies, with the share of unabated fossil fuels falling by 6 percentage points by 2030, compared with a more than 15 percentage point drop in advanced economies. Universal access to clean cooking and electricity is achieved by 2030, and 24 EJ of inefficient and polluting traditional biomass is replaced by electricity, liquefied petroleum gases and efficient cookstoves.

After 2030, unabated fossil fuels are rapidly replaced in all countries by electricity, the direct use of renewables – e.g. modern bioenergy, solar thermal and geothermal – and low-emissions hydrogen and hydrogen-based fuels. By 2050, global total final consumption reaches around 340 EJ, of which electricity provides 53%. Electrification occurs in every sector to provide, heating, cooling and mobility, to power motors and appliances, and to produce onsite electrolytic hydrogen for heavy industries. Most of the small remaining quantities of unabated fossil fuels used for combustion applications, around 15 EJ globally in 2050, are consumed in long-distance transport, especially aviation and shipping, and in heavy industries.

What changed compared to 2021 NZE Scenario?

In the industry sector, the 2023 NZE Scenario envisages a smaller role for CCUS than the 2021 version (Figure 2.20). Despite multiple CCUS project announcements for specific industrial applications like cement, the plants involved collectively only account for a small share of total production (see Chapter 3). Moreover, there has been little progress in CCUS in the iron and steel industries. In contrast, the number of project announcements for hydrogen-based direct reduced iron (DRI) steel production increased significantly since 2021, which is reflected in the four percentage point increase in the share of iron production in 2035 between the two versions of the NZE Scenario.

Figure 2.20 ▷ Fuel mix changes in final energy consumption by sector in the 2023 NZE Scenario relative to the 2021version, 2030 and 2050



Better prospects for heat pumps, EVs and hydrogen-based steel production drive stronger electricity demand, while synthetic fuels, liquid biofuels and CCUS are reduced

Note: Where low-emissions hydrogen is produced and consumed onsite at an industrial facility, the fuel input, such as electricity or natural gas, is reported as final energy consumption, rather than the hydrogen output.

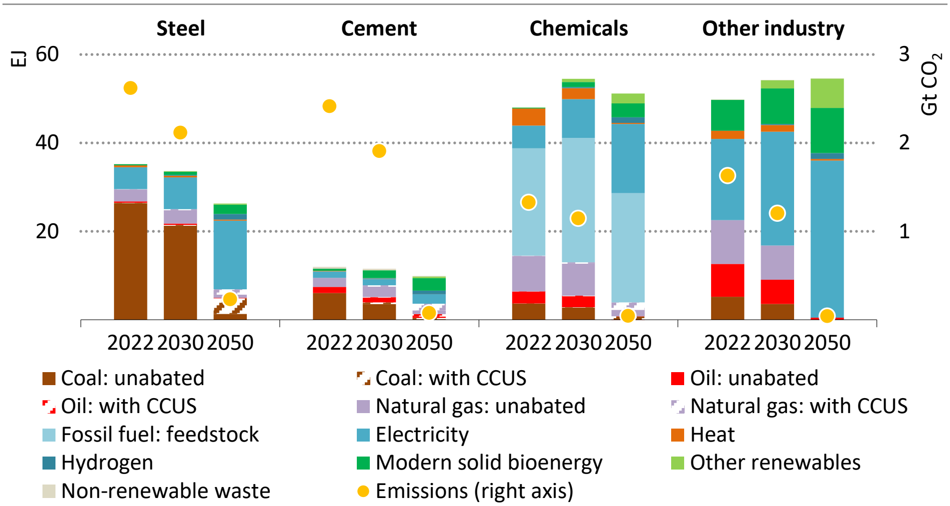
In the transport sector, the key change compared to the 2021 NZE Scenario version is faster growth in EV sales. It reflects the very strong advances in terms of annual sales, announced manufacturing capacity for batteries, strategy announcements from car and truck makers, and technology improvements. Biofuel use in transport, however, has not advanced in a similar way, reflecting that food and fertiliser prices remain a concern. EV technologies and manufacturer strategies have advanced in trucks, a segment of the market that is particularly conducive to the use of biofuels, particularly in the short term. As a result, the 2023 NZE Scenario sees a diminished role for biofuels in transport in both the near and longer term. A similar downward revision also applies for hydrogen and hydrogen-based fuels. In the near term this results in a slightly higher share of oil in transport energy demand, in the longer term it leads to even higher levels of EV sales share and to a substantially higher share of electricity in transport energy demand by 2050.

In the buildings sector, the main change is a faster switch from natural gas to electricity which primarily reflects advances in heat pump technology and concerns about natural gas supply in the wake of Russia's invasion of Ukraine.

Industry

Energy and materials efficiency measures are important levers to reduce industrial CO_2 emissions in the short term. Examples include the deployment of best available technologies to reduce energy consumption, waste heat recovery and process integration, building and product lifetime extensions, recycling, and product designs that are less material-intensive and that facilitate component repair and reuse. These measures are generally incremental in impact, and there are practical limits to what they can do to mitigate emissions. Step changes in the emissions intensity of production – particularly of emissions-intensive bulk materials like steel, cement and primary chemicals – are still required, and these are achieved in large part by the use of hydrogen, CCUS and direct electrification technologies.

Figure 2.21 ▷ Final energy consumption by fuel in selected industry sub-sectors, 2022-2050



Net zero emissions in industry relies heavily on electricity, hydrogen and CCUS. Unabated fossil fuel use plummets while petrochemical feedstock demand decreases more slowly.

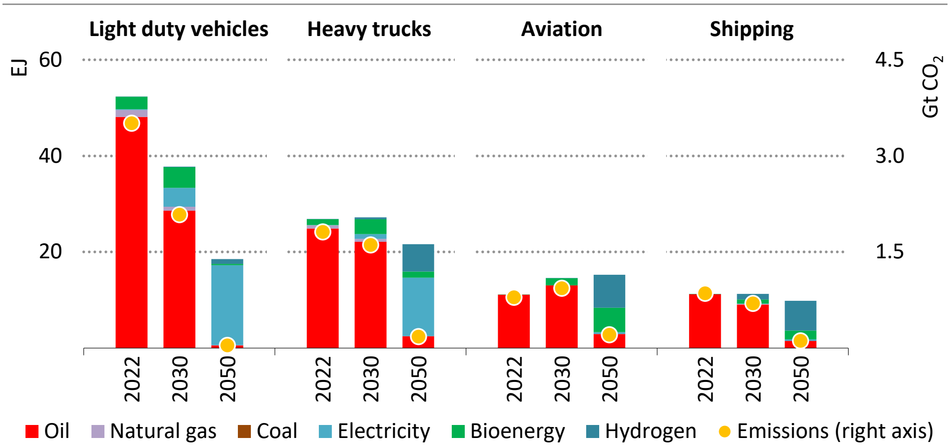
Notes: Where low-emissions hydrogen is produced and consumed onsite at an industrial facility, the fuel input, such as electricity or natural gas, is reported as final energy consumption, not the hydrogen output. Other industry category includes light industries and non-specified industry. CO_2 emissions from chemicals do not include CO_2 removal from onsite direct air capture.

Most of the remaining industry sector energy-related emissions are addressed by using alternatives to fossil fuels to provide heat. Chief among these alternatives is electricity, which is used primarily to provide low-temperature heat, which increases its share of industrial energy consumption from 23% in 2022 to 49% in 2050 (Figure 2.21). Hydrogen and bioenergy are used in the NZE Scenario to provide high-temperature heat.

Transport

Electrification is the main lever for emissions reductions in road transport in the NZE Scenario (Figure 2.22). EV sales account for around 65% of the new car market by 2030, and no new internal combustion engine (ICE) cars are sold after 2035. Electric and hydrogen-fuelled trucks displace ICE medium and heavy trucks: new fossil-fuelled ICE truck sales end in 2040 in advanced economies and China, and in 2045 in the rest of the world. Battery electric trucks make significant advances, particularly in medium-duty trucks and other trucks with relatively short and regular routes; fuel cell electric powertrains are most successful in long-haul, heavy-duty trucks where fast charging of battery electric versions may prove difficult. These changes mean that oil demand for road transport – the single largest oil consuming sector today – falls at an average 1.4 mb/d per year to 2050.

Figure 2.22 ▷ Final energy consumption in transport by fuel for selected modes, 2022-2050



Road transport relies strongly on electrification to substitute its oil thirst, whereas aviation and shipping oil substitutes are mainly liquid biofuels, hydrogen and synthetic fuels

Notes: Only direct CO_2 emissions are included. Hydrogen includes hydrogen-based fuels.

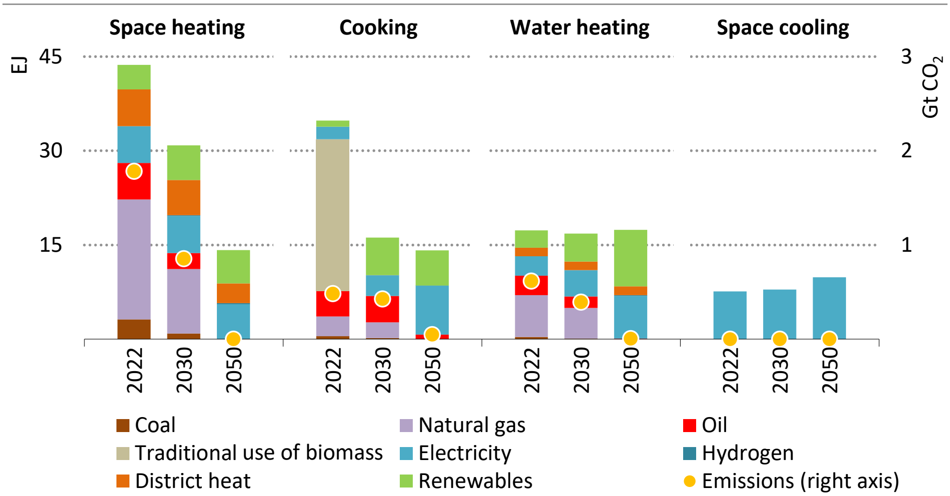
Aviation sees strong growth in emerging market and developing economies, but traffic optimisation measures, energy efficiency gains, behavioural changes and rapid development of bio-based SAF mean that aviation oil demand peaks in the mid-2020s in the NZE Scenario.

After 2030, oil use decreases rapidly – by more than 0.2 mb/d per year on average – with the development of synthetic SAF and the deployment of the first hydrogen aircraft in the second-half of the 2030s. In shipping, efficiency improvements including the use of wind assistance and fuel switching cut oil use. Ammonia is the primary low-emissions fuel used to decarbonise shipping, with the contributions from biofuels and hydrogen limited in large part by their relatively high costs.

Buildings

Making buildings zero-carbon-ready[10] means that existing buildings need to undergo deep retrofits and that new buildings need to meet very stringent standards and be equipped with technologies that will be fully decarbonised by 2050. In the NZE Scenario, the global average retrofit rate reaches 2.5% per year by 2030 and remains at around that level through to 2050. This leads to around half of existing buildings being retrofitted and becoming zero-carbon-ready by 2040. This in turn more than halves demand for space heating and cooling between today and 2050, despite a 55% increase in the amount of floorspace in the buildings sector.

Figure 2.23 ⊳ Final energy consumption in the buildings sector by selected end-use, 2022-2050



Deep retrofits and efficient devices lower energy intensity in buildings by 60% compared to today; electricity, district heat and direct renewables displace fossil fuels by 2050

Note: Only direct CO_2 emissions are included.

The use of fossil fuels for heating and cooking is rapidly reduced in the NZE Scenario in favour of electricity and clean energy alternatives (Figure 2.23). In emerging market and developing

[10] Zero-carbon-ready buildings become zero-carbon without any further renovation once the power and natural gas grids that they rely on are fully decarbonised.

economies, traditional use of biomass is replaced by modern energy use as universal access to clean cooking is achieved by 2030. From 2025 onwards, sales of new coal and oil boilers come to an end (gas boilers continue to be used in a minority of cases, fuelled by biomethane and hydrogen). They are largely replaced by heat pumps with 290 million dwellings equipped with heat pumps by 2030 and 875 million by 2050. Solar water heaters are also deployed extensively with 350 million dwellings equipped with solar thermal for water heating by 2030 and around a billion by 2050. The use of biomethane in buildings reaches 75 bcm of natural gas equivalent by 2050, and district heating is virtually fully decarbonised by 2050.

2.3 Net zero emissions guide

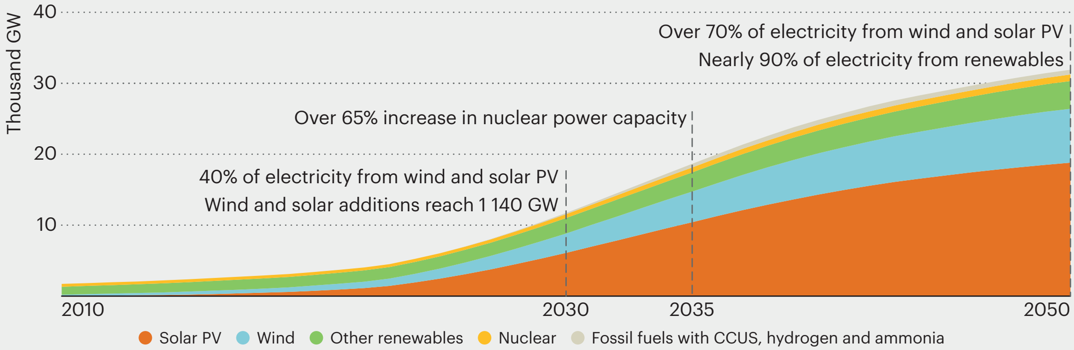
Our 2021 *Net Zero by 2050* report included numerous tables presenting more than 400 key milestones for different sectors and technologies on the pathway to reach net zero emissions from the global energy sector by 2050. These proved to be highly useful for numerous stakeholders, including actors from industry, finance, and policymaking. In this year's edition, we have brought together these milestones in one place as a set of fifteen technology and sector-specific dashboards. These are presented in the pages that follow. Clarificatory notes to the dashboards are given on page 106.

Low-emissions sources of electricity

34% OF CUMULATIVE EMISSIONS REDUCTIONS

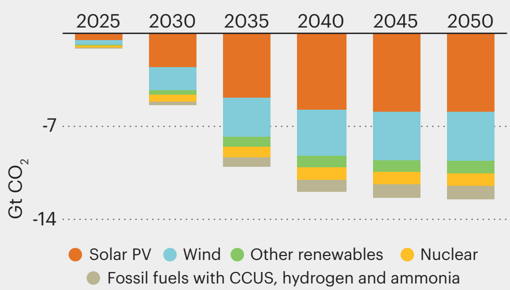
Renewables capacity triples by 2030 led by solar PV and wind, complemented by growth in nuclear and other sources, raising the share of low-emissions sources in electricity generation from 39% in 2022 to 71% in 2030 and nearly 100% in 2050.

Low-emissions electricity generation capacity by source

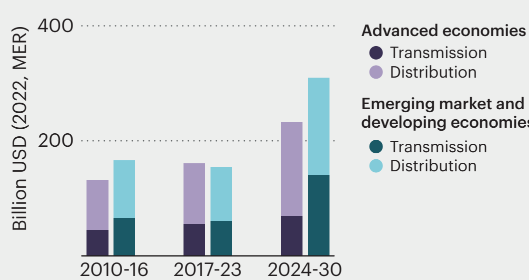


Milestones	**2022**	**2030**	**2035**	**2050**
Total electricity generation from low-emissions sources (TWh)	**11 281**	**27 061**	**43 117**	**76 603**
Solar PV and wind	3 416	15 247	27 362	54 679
Other renewables	5 183	7 284	9 377	13 752
Nuclear	2 682	3 936	4 952	6 015
Share of low-emissions sources in total generation	**39%**	**71%**	**91%**	**99.7%**
Share of solar PV and wind in total generation	12%	40%	58%	71%
Share of renewables in total generation	30%	59%	77%	89%
Annual capacity additions of low-emissions sources (GW)	**344**	**1 301**	**1 382**	**1 268**
Solar PV	220	823	878	815
Wind	75	318	350	352
Nuclear	8	35	37	21
Average annual investment (USD billion 2022, MER)	**2017-22**	**2023-30**	**2031-35**	**2036-50**
Low-emissions	**507**	**1 202**	**1 321**	**973**
Renewables	466	1 080	1 185	875
Nuclear	41	114	121	93

Solar PV and wind account for 65% of the global power sector CO_2 emissions reductions by 2050



Scaling up investment in electricity infrastructure is critical to unlock clean energy transitions

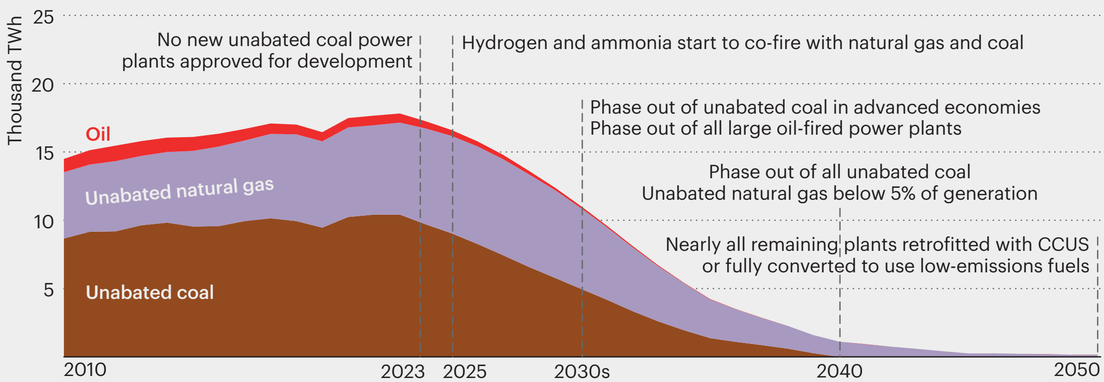


Unabated fossil fuels in electricity generation

95% REDUCTION BY 2040

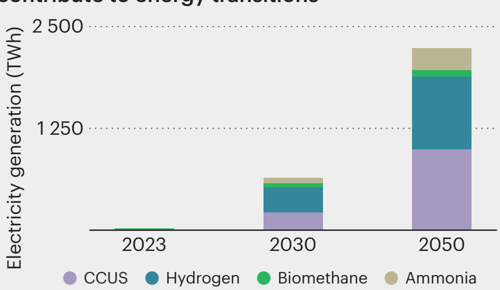
Electricity output from unabated fossil fuels falls by 40% to 2030 and virtually disappears by 2050, as plants are run less, retired, retrofitted with CCUS or repurposed to use low-emissions fuels.

Unabated fossil fuels electricity generation

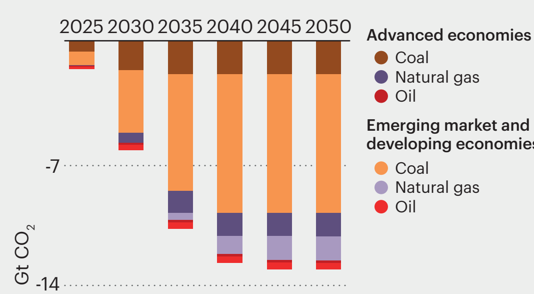


Milestones	2022	2030	2035	2050
Total electricity generation from unabated fossil fuels (TWh)	**17 636**	**11 066**	**4 241**	**158**
Coal	10 427	4 988	1 379	0
Natural gas	6 500	5 943	2 834	158
Share of unabated fossil fuels in total generation	**61%**	**29%**	**9%**	**0.2%**
Coal	36%	13%	3%	0%
Natural gas	22%	16%	6%	0.2%
Retrofits and blending				
Coal and gas plants equipped with CCUS (GW)	0.12	50	141	241
Average ammonia blending in global coal-fired generation (without CCUS)	0%	1%	11%	100%
Average hydrogen blending in global gas-fired generation (without CCUS)	0%	5%	16%	79%
Average biomethane blending in global gas-fired generation (without CCUS)	0.1%	1%	1%	7%
Average annual capacity retirements (GW)	**2017-22**	**2023-30**	**2031-35**	**2036-50**
Coal	27	110	81	43
Natural gas	8	39	43	46

CCUS retrofits and blending low-emissions fuels enable coal- and gas-fired power plants to contribute to energy transitions



Reducing coal-fired power in EMDE accounts for 60% of global power sector emissions reductions

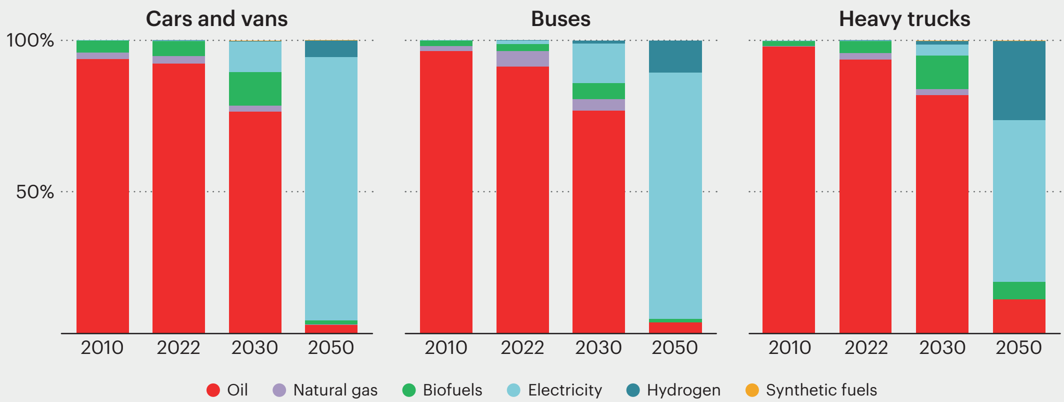


Road transport

16% OF CUMULATIVE EMISSIONS REDUCTIONS

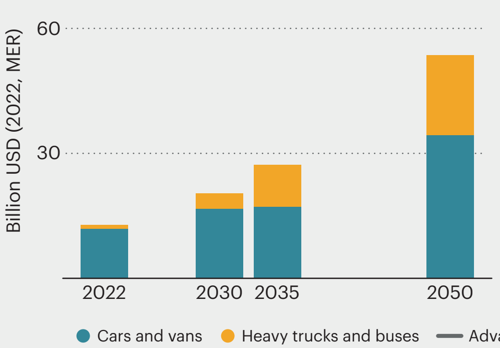
Ramping up electrification and biofuels plays a major role to decarbonise road transport to 2030. Thereafter, electrification is the prominent lever, with electricity representing three-quarters of energy consumption in road transport in 2050.

Fuel shares of road energy consumption

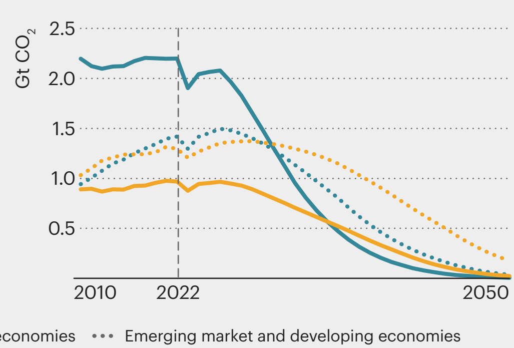


Milestones	2022	2030	2035	2050
Sales share of plug-in hybrid, battery and fuel cell electric vehicles	**13%**	**70%**	**98%**	**100%**
Two/three-wheelers	16%	78%	100%	100%
Cars and vans	13%	67%	100%	100%
Buses	4%	56%	90%	100%
Heavy trucks	1%	37%	65%	100%
Alternative fuel shares	**5%**	**20%**	**36%**	**93%**
Biofuels	5%	11%	12%	3%
Electricity	0%	8%	22%	74%
Hydrogen	0%	1%	2%	16%
Fuelling infrastructure				
Electric vehicle public charging points (million)	3	17	18	31
Hydrogen refuelling stations (thousand)	1	12	15	46

Investments in public chargers scales up, first for cars and vans, then for heavy trucks and buses



Road transport emissions drop dramatically to 2030, particularly in advanced economies

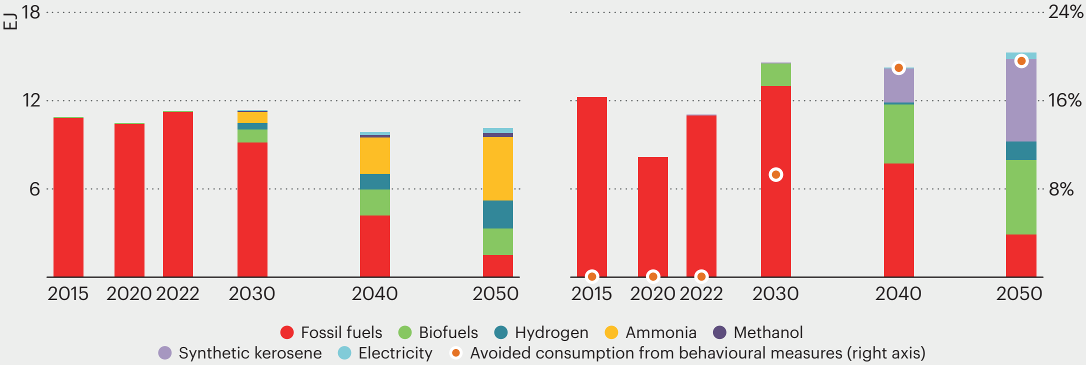


Shipping and aviation

5% OF CUMULATIVE EMISSIONS REDUCTIONS

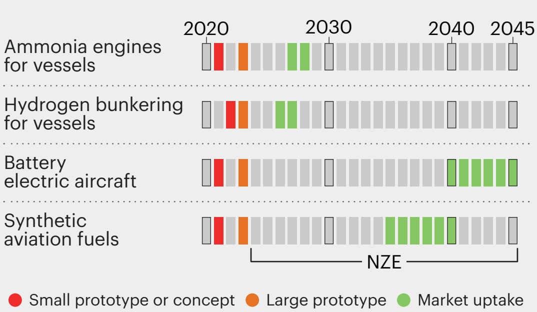
Bioenergy, hydrogen and hydrogen-based fuels ramp up from less than 1% of energy consumed today in shipping and aviation to almost 15% in 2030 and 80% by 2050. Also important to decarbonise these transport modes are energy efficiency improvements in shipping to 2030 and behaviour-driven demand reduction in aviation to 2050.

Shipping energy consumption / Aviation energy consumption

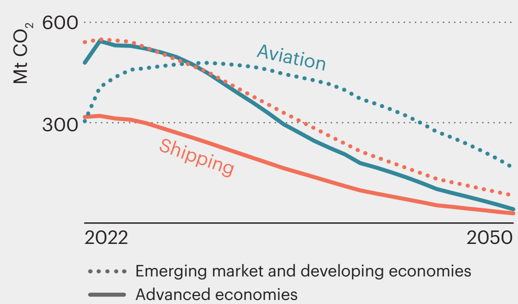


Milestones	2022	2030	2035	2050
Shipping				
International shipping activity (trillion tonne-kilometres)	125	145	165	265
Share in final energy consumption				
Biofuels	0%	8%	13%	19%
Hydrogen	0%	4%	7%	19%
Ammonia	0%	6%	15%	44%
Methanol	0%	1%	1%	3%
Aviation				
International and domestic aviation activity (trillion passenger-kilometres)	6.0	10.9	11.4	16.5
Avoided demand from behavioural measures	0%	9%	14%	20%
Share in final energy consumption				
Biofuels	0%	10%	22%	33%
Synthetic hydrogen-based fuels	0%	1%	4%	37%

Technologies are being developed to enable the use of low-emissions fuels in shipping and aviation



CO_2 emissions from shipping and aviation decrease more rapidly in advanced economies

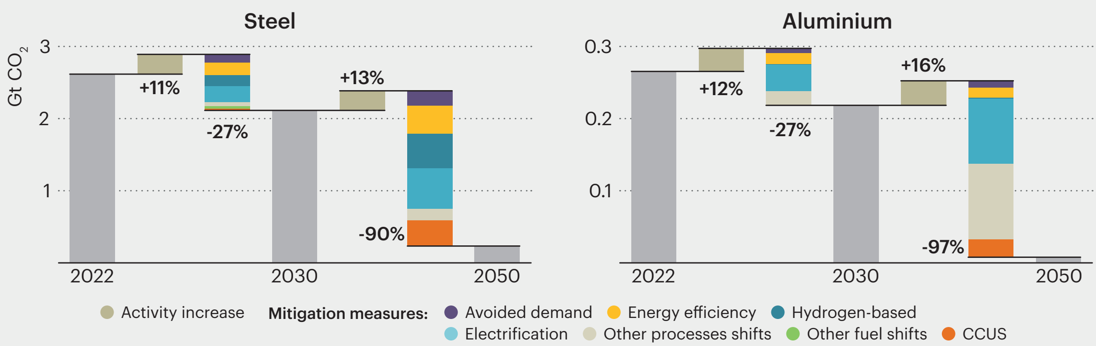


Steel and aluminium

6% Steel
1% Aluminium
OF CUMULATIVE EMISSIONS REDUCTIONS

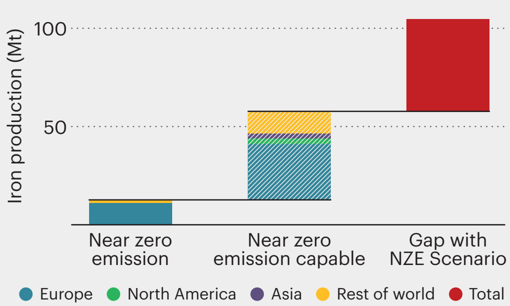
Emissions reductions from steel and aluminium production are challenging due to a heavy reliance on fossil fuels today, process emissions from incumbent routes and high trade exposure. Increased scrap recycling and mass deployment of innovative technologies are key levers for reducing emissions.

Emissions reductions by mitigation measure

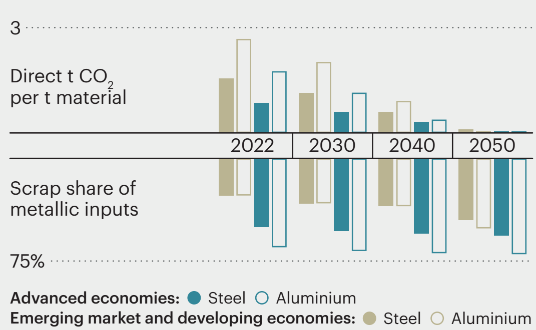


Milestones	2022	2030	2035	2050
Steel				
Crude steel production (Mt)	**1 880**	**1 970**	**1 970**	**1 960**
Share of scrap in metallic inputs	**33%**	**38%**	**40%**	**48%**
Share of near zero emission iron production	**0%**	**8%**	**27%**	**95%**
CCUS-equipped	0%	3%	10%	37%
Electrolytic hydrogen-based	0%	5%	15%	44%
Iron ore electrolysis	0%	0%	2%	14%
CO_2 captured (Mt CO_2)	**1**	**27**	**131**	**399**
Low-emissions hydrogen demand (Mt)	**0**	**6**	**17**	**41**
Aluminium				
Aluminium production (Mt)	**108**	**120**	**128**	**146**
Share of secondary production	**36%**	**42%**	**44%**	**56%**
Share of near zero emission primary aluminium production	**0%**	**7%**	**19%**	**96%**
Share of low-emissions thermal energy in alumina production	**0%**	**16%**	**39%**	**99%**

Announced projects meet 12% of 2030 near zero emission iron production needs; 'capable' capacity needs clear decarbonisation plans



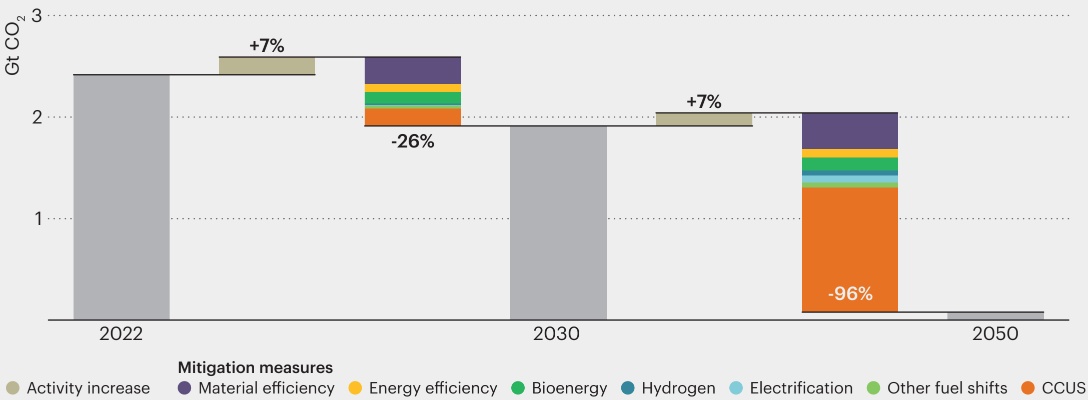
Emissions intensities drastically improve and scrap metal use increases



Cement

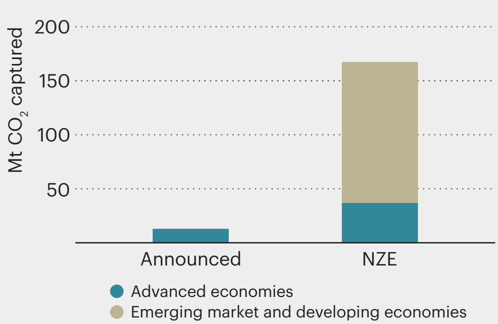
Cutting emissions from cement production is difficult due to the present reliance on carbon-containing raw materials and high-temperature heating requirements. Energy and material efficiency, and low-emissions fuels are key measures in the near term. Deep reductions require a massive roll out of innovative technologies such as cements made with alternative raw materials and CCUS.

Emissions reductions by mitigation measure

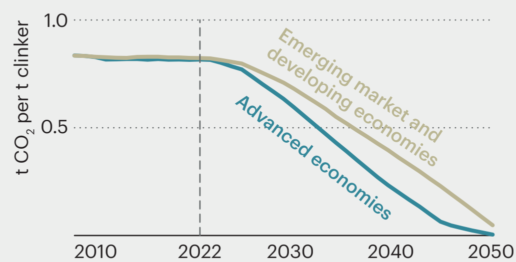


Milestones	**2022**	**2030**	**2035**	**2050**
Cement production (Mt)	4 160	4 260	4 140	3 930
Clinker-to-cement ratio (tonne per tonne)	0.71	0.65	0.61	0.57
Kiln thermal energy intensity (GJ per tonne of clinker)	3.6	3.4	3.3	2.9
Share of near zero emission clinker production	0%	8%	27%	93%
CO_2 captured (Mt CO_2)	0	170	480	1 310
Share of low-emissions fuel in thermal energy use	5%	30%	49%	86%
Bioenergy without CCUS	5%	15%	17%	19%
Bioenergy with CCUS	0%	2%	8%	19%
Fossil fuels and non-renewable waste with CCUS	0%	10%	22%	31%
Hydrogen	0%	1%	3%	9%
Electricity	0%	0%	0%	8%

Announced CCUS projects fall short of 2030 target



Advanced economies move first, but most of the challenge lies in emerging market and developing economies

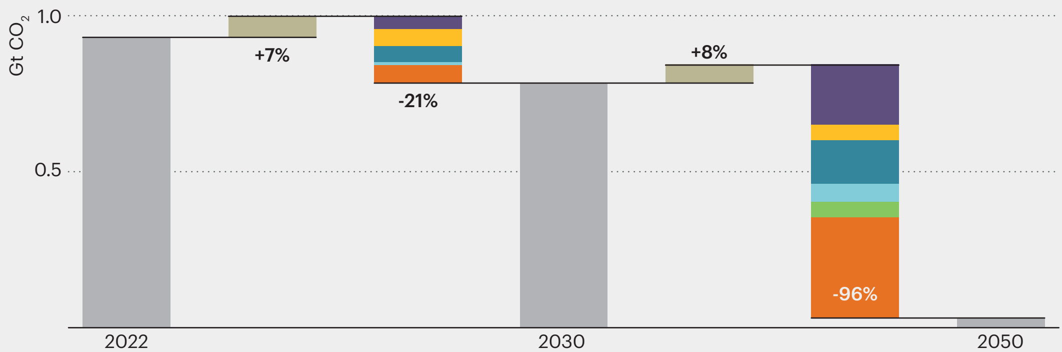


Primary chemicals

3% OF CUMULATIVE EMISSIONS REDUCTIONS

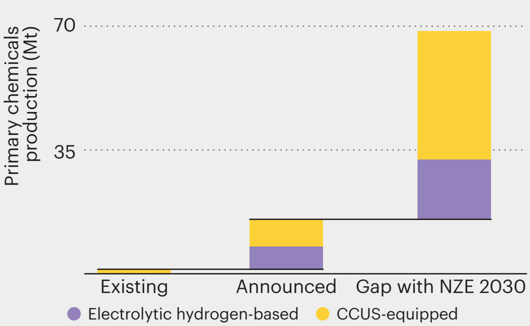
Increases in plastics recycling and more efficient fertiliser use dampen rising demand for primary chemicals and energy consumption for their production. Electrolytic hydrogen, CCUS and direct electrification technologies are key to deliver the step changes in emissions intensities needed for primary chemical production.

Emissions reductions by mitigation measure

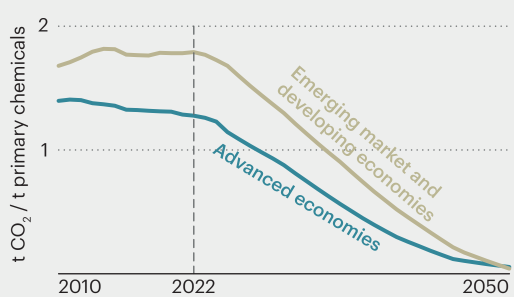


Milestones	2022	2030	2035	2050
Primary chemicals production (Mt)	**719**	**861**	**905**	**878**
Share of near zero emission primary chemicals production	**2%**	**17%**	**39%**	**93%**
CCUS-equipped	0.5%	8%	22%	56%
Electrolytic hydrogen-based	0%	7%	13%	28%
Other	1%	2%	4%	9%
CO_2 captured (Mt)	**4**	**52**	**143**	**344**
Hydrogen demand (Mt)	**48**	**53**	**55**	**60**
Plastics recycling				
Share of plastics waste collected	16%	24%	31%	51%
Share of secondary production	8%	13%	18%	35%
Primary chemicals savings (Mt)	9	25	42	116

Announced projects for net zero emission production are increasing, but more efforts are needed to close the gap with the NZE in 2030



Higher use of coal in emerging market and developing economies makes the path to net zero more challenging

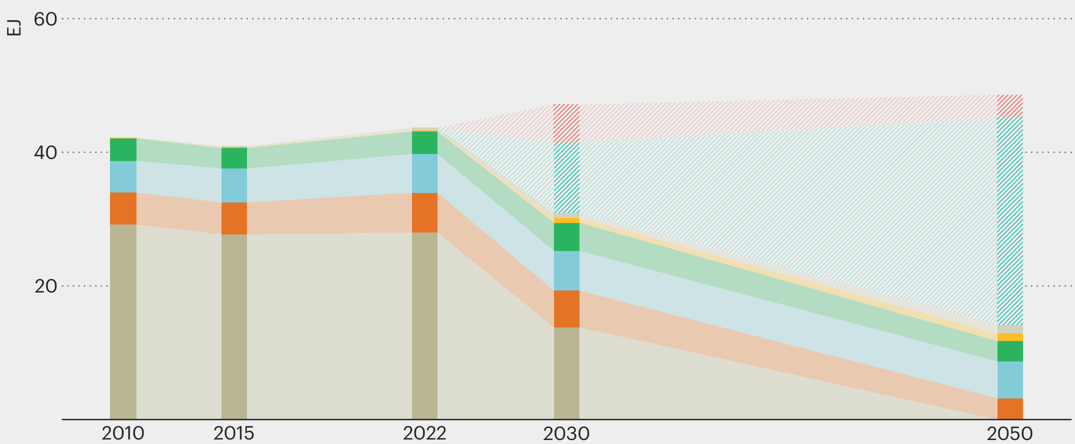


Space heating

Space heating energy consumption in buildings decreases by almost 70% by 2050 even with a 30% increase in heated floor area thanks to zero-carbon-ready buildings energy codes and increasingly efficient equipment.

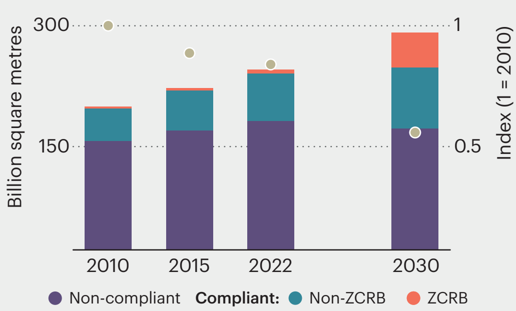
4% OF CUMULATIVE EMISSIONS REDUCTIONS

Space heating energy consumption

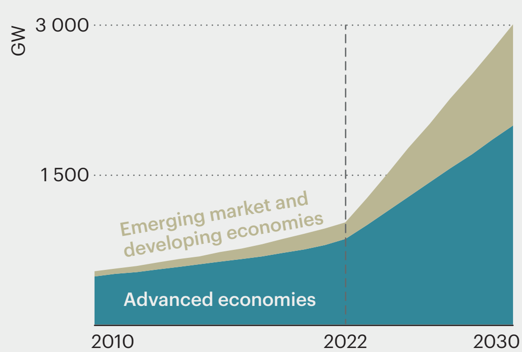


Milestones	2022	2030	2035	2050
Heat pumps installed in buildings (GW)	**1 000**	**3 000**	**4 400**	**6 500**
Share of space heating service demand met by heat pumps	**12%**	**25%**	**40%**	**55%**
Share of buildings that are zero-carbon-ready				
In new buildings and deep renovations	<1%	100%	100%	100%
In existing building stock	<5%	20%	35%	80%
Retrofit rate in advanced economies	**<2%**	**2.5%**	**2.5%**	**2.5%**
Heated floor area (billion square metres)	**157**	**170**	**180**	**200**

Share of zero-carbon-ready buildings expands rapidly and by 2030 those standards are met in all new buildings



Global heat pump stock nears 3 000 GW in 2030, almost tripling today's capacity

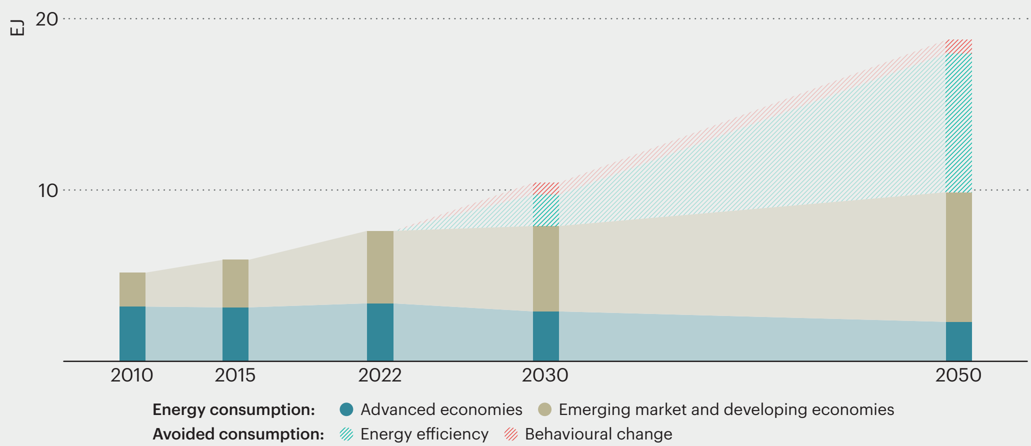


Space cooling

4%
OF CUMULATIVE ENERGY SAVINGS

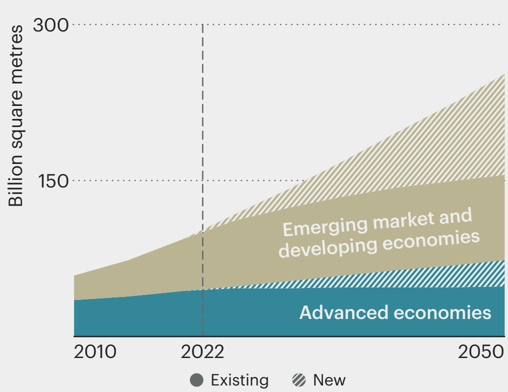
Space cooling energy consumption is set to more than double by 2050 with no action taken. Passive designs, behavioural change and more efficient equipment are vital to temper demand growth and reduce the strain on electricity systems.

Space cooling energy consumption

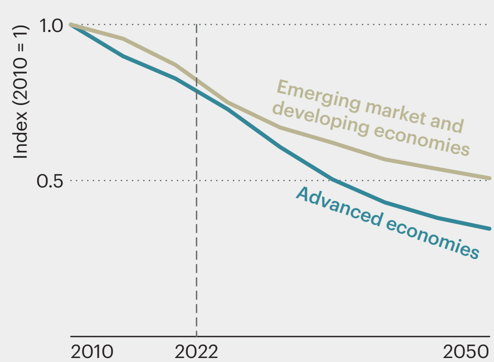


Milestones	**2022**	**2030**	**2035**	**2050**
Cooled floor area in buildings (billion square metres)	105	140	170	250
Share of households with air conditioners	36%	45%	50%	60%
Installed capacity of space cooling equipment (GW)	850	1 400	1 750	2 700
Share of space cooling in final electricity consumption	9%	7%	6%	5%
Share of buildings that are zero-carbon-ready				
In new buildings and deep renovations	<1%	100%	100%	100%
In existing building stock	<5%	20%	35%	80%
Average efficiency of new space cooling equipment (Watt-hour/Watt-hour)	3.5-4.5	5.0-6.5	6.5-8.0	7.5-9.0

Cooled floor area more than doubles by 2050, with additions principally occurring in EMDE



Space cooling energy intensity from 2022 to 2050 decreases twice as fast as the last decade

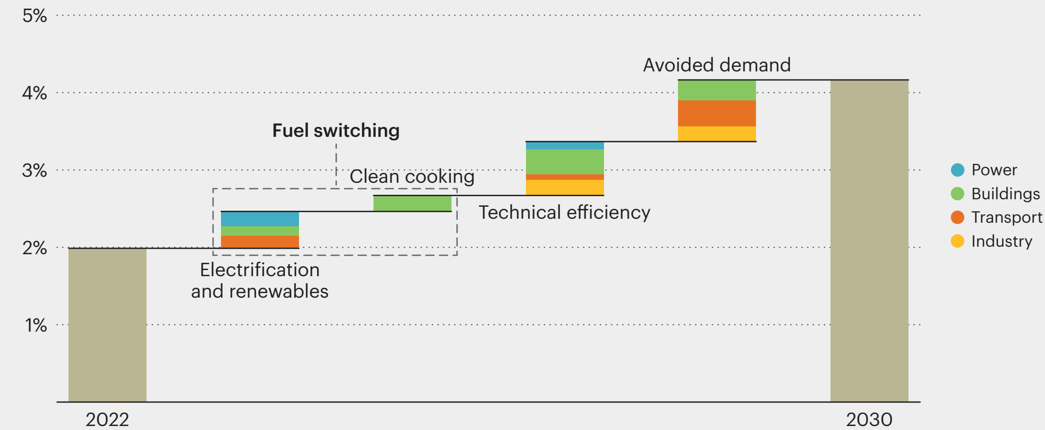


Energy efficiency and behavioural change

11% OF CUMULATIVE EMISSIONS REDUCTIONS

Scaling up energy efficiency, behavioural change and fuel switching are key to double the rate of energy intensity improvements by 2030, as current measures lead to only marginal progress.

Average annual rate of total energy intensity reduction by contributor

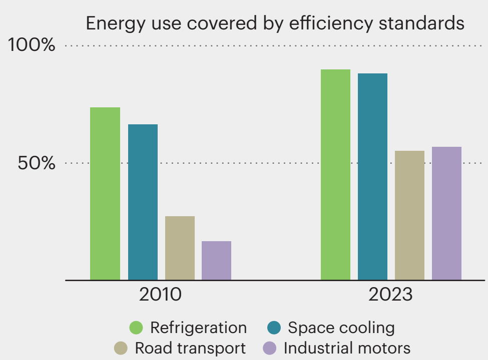


Milestones	**2022**	**2030**	**2035**	**2050**
Annual energy intensity improvement	2.0%	4.9%	3.6%	1.8%
Unit electricity consumption of new air conditioners (index 2022 = 100)	100	70	59	52
Unit electricity consumption of refrigerators (index 2022 = 100)	100	60	53	41
Fuel consumption of new internal combustion engine trucks (index 2022 = 100)	100	84	79	
Energy intensity of clinker production (GJ/t)	3.6	3.4	3.3	2.9

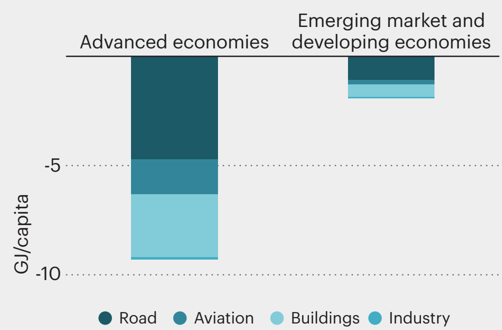
Key behavioural changes in buildings and transport

- Eco-driving and motorway speed limits of 100 km/h introduced by 2030
- Use of internal combustion engine cars phased out in large cities by 2030
- Space heating temperatures moderated to 19-20 °C and space cooling temperatures to 24-25 °C on average by 2030
- One-out-of-two long-haul business flights are avoided by 2040

Efficiency standards cover 90% of energy use for key appliances but other uses lag



Reductions of energy demand from behavioural changes are nearly five times higher per capita in 2030 in advanced economies

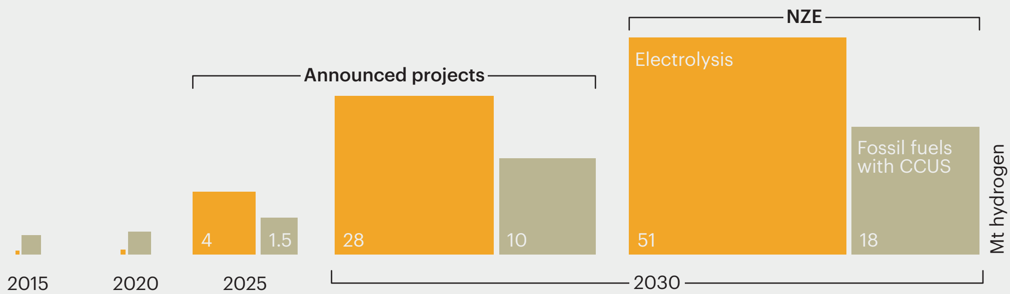


Hydrogen

4%
OF CUMULATIVE EMISSIONS REDUCTIONS

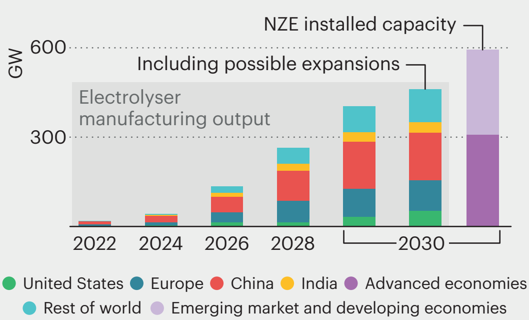
Announced low-emissions hydrogen production projects, if realised, represent 55% of the level in the NZE Scenario in 2030. Bold policy action is needed to create demand for low-emissions hydrogen in order to stimulate investment in production projects.

Low-emissions hydrogen production

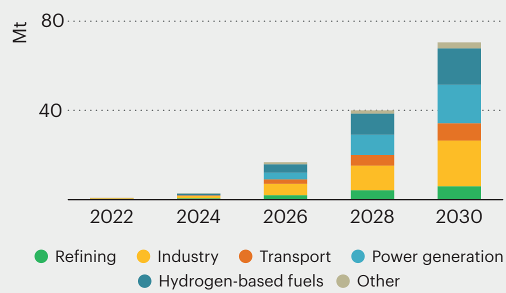


Milestones	2022	2030	2035	2050
Total hydrogen demand	95	150	215	430
Refining (Mt H_2)	42	35	26	10
Industry (Mt H_2)	53	71	92	139
Transport (Mt H_2-eq, including hydrogen-based fuels)	0	16	40	193
Power generation (Mt H_2-eq, inlcluding hydrogen-based fuels)	0	22	48	74
Other (Mt H_2)	0	6	10	14
Share of total electricity generation	**0%**	**1%**	**1%**	**1%**
Low-emissions hydrogen production (Mt H_2)	**1**	**70**	**150**	**420**
From low-emissions electricity	0	51	116	327
From fossil fuels with CCUS	1	18	34	89
Cumulative installed electrolysis capacity (GW electric input)	**1**	**590**	**1 340**	**3 300**
Cumulative CO_2 storage for hydrogen production (Mt CO_2)	**11**	**215**	**410**	**1 050**
Hydrogen pipelines (km)	**5 000**	**19 000**	**44 000**	**209 000**
Underground hydrogen storage capacity (TWh)	**0.5**	**70**	**240**	**1 200**

Announced cumulative electrolyser manufacturing capacity output, if fully realised, would be 80% of the NZE level in 2030



Demand for low-emissions hydrogen grows quickly in the NZE, particularly in heavy industry, transport and the production of hydrogen-based fuels

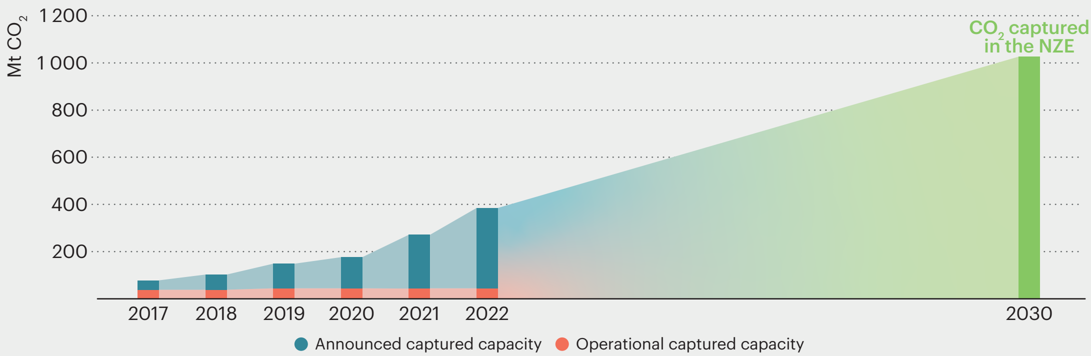


Carbon capture, utilisation and storage

8% OF CUMULATIVE EMISSIONS REDUCTIONS

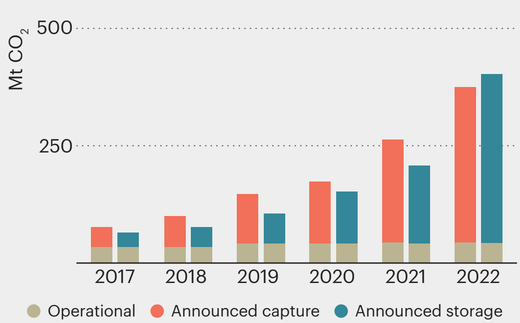
If all announced CO_2 capture capacity is realised and the current growth trend continues, global capacity could reach NZE levels by 2030. Reducing project lead times, particularly related to the development of CO_2 storage, will be critical to achieve those levels.

Capture capacity

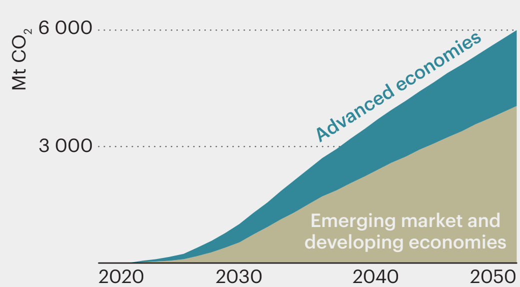


Milestones	**2022**	**2030**	**2035**	**2050**
Total CO_2 captured (Mt CO_2)	**45**	**1 024**	**2 421**	**6 040**
CO_2 capture from fossil fuels and industrial processes	**44**	**759**	**1 712**	**3 736**
Power	1	188	568	811
Industry	4	247	769	2 152
Merchant hydrogen	0	161	285	756
Other fuel transformation	38	163	90	17
CO_2 capture from bioenergy	**1**	**185**	**506**	**1 263**
Power	0	44	204	438
Industry	0	23	77	232
Biofuels production	1	114	213	474
Other fuel transformation	0	5	13	121
Direct air capture	**0**	**80**	**203**	**1 041**
Total CO_2 removed (Mt CO_2)	**1**	**234**	**632**	**1 710**

Planned storage capacity is catching up with planned capture



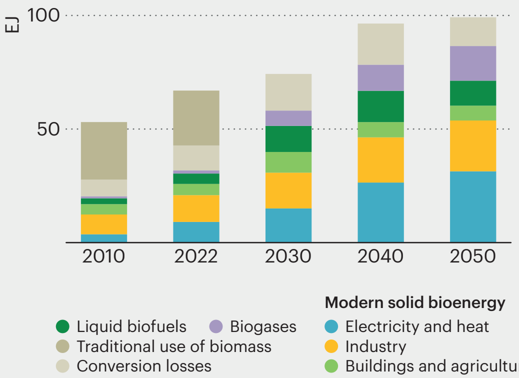
Two-thirds of total CO_2 capture is in the emerging market and developing economies

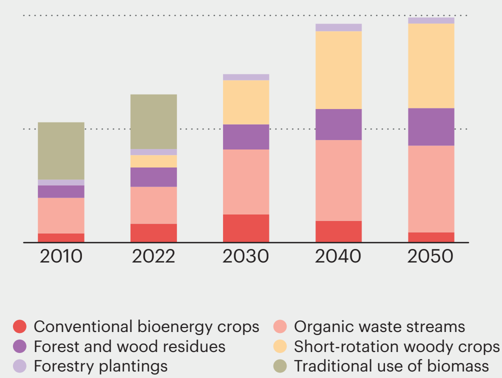


Bioenergy

7%
OF CUMULATIVE EMISSIONS REDUCTIONS

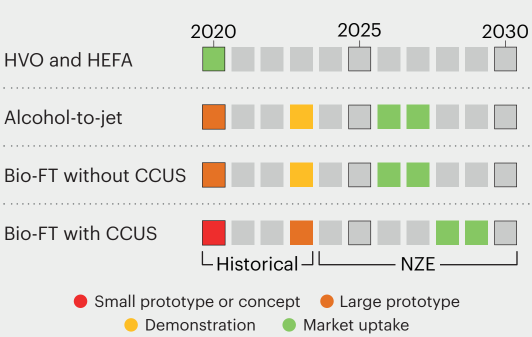
While traditional use of biomass is phased out in the NZE Scenario, modern bioenergy use more than doubles to 2050, due to its ability to be used as a direct drop-in substitute for fossil fuels. Advanced feedstock supply grows considerably, supported by investments and commercialisation of advanced conversion technologies.



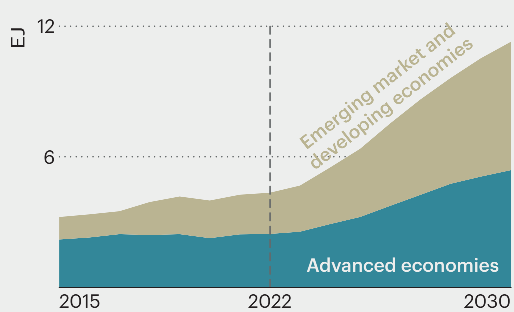


Milestones	2022	2030	2035	2050
Total bioenergy supply (EJ)	**67**	**74**	**89**	**99**
Share of advanced feedstock	45%	80%	85%	90%
Modern gaseous bioenergy (EJ)	**1**	**7**	**9**	**15**
Biomethane	0	5	6	10
Modern liquid bioenergy (EJ)	**4**	**11**	**13**	**11**
Share of advanced biofuels	12%	40%	55%	75%
Modern solid bioenergy (EJ)	**35**	**55**	**65**	**73**
Electricity and heat	9	15	21	30
Industry	11	15	18	22
Buildings and agriculture	5	9	8	6
Traditional use of solid biomass (EJ)	**24**	**0**	**0**	**0**
Million people using traditional biomass for cooking	2 049	0	0	0

Advanced biofuels are being developed to enable net zero



Liquid biofuel production must expand 150% to reach levels required by 2030 in the NZE

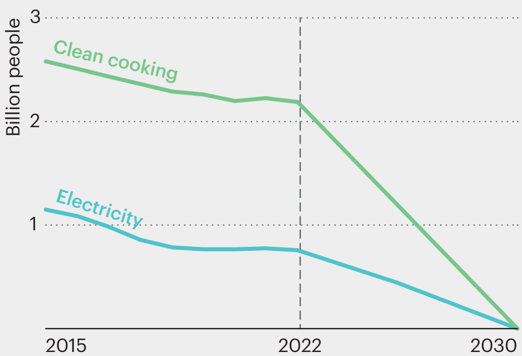


Energy access and air pollution

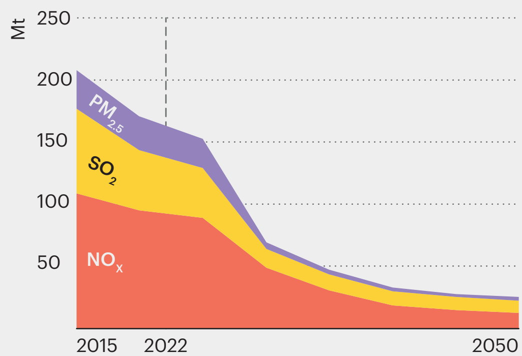
1.5 Gt CO_2-eq
SAVED VIA ENERGY ACCESS IN 2030

Achieving universal modern energy access by 2030, in line with SDG 7, delivers socioeconomic benefits and reduces greenhouse gas emissions. In addition, major air pollutant emissions are halved by 2030 which reduces premature deaths by 3.6 million, predominately in emerging market and developing economies.

Population without modern energy access

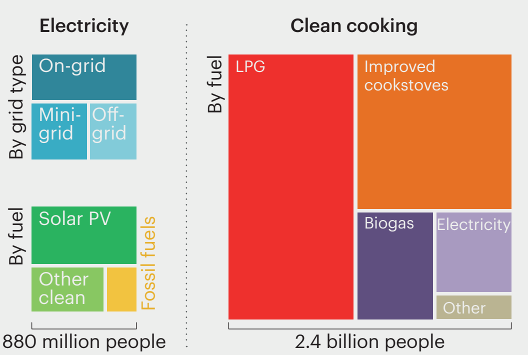


Air pollution emissions

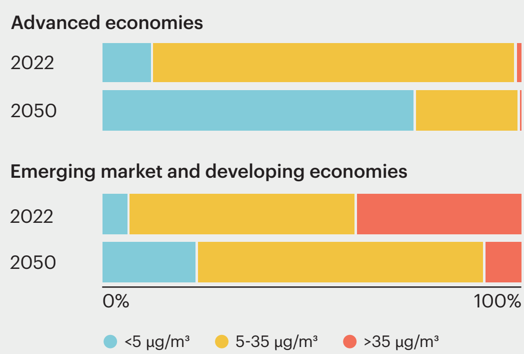


Milestones	2022	2025	2030	2050
Share of population with modern energy access				
Electricity	90%	93%	100%	100%
Clean cooking	72%	80%	100%	100%
Net change in greenhouse gas emissions from universal access (Mt CO_2-eq)		**-450**	**-1 500**	
Investment needed to achieve universal energy access (billion USD)		**30**	**58**	
Share of total global energy investment		0.9%	1.3%	
Premature deaths related to air pollution (million)				
Ambient air pollution	4.4	4.3	2.7	2.9
Household air pollution	3.2	2.5	0.7	0.8
Share of population exposed to high levels of air pollution (>35 μg/m³)	**33%**	**29%**	**7%**	**7%**

A mix of technologies is needed to provide modern energy access to all by 2030



People in developing economies are more likely to be exposed to higher concentrations of $PM_{2.5}$

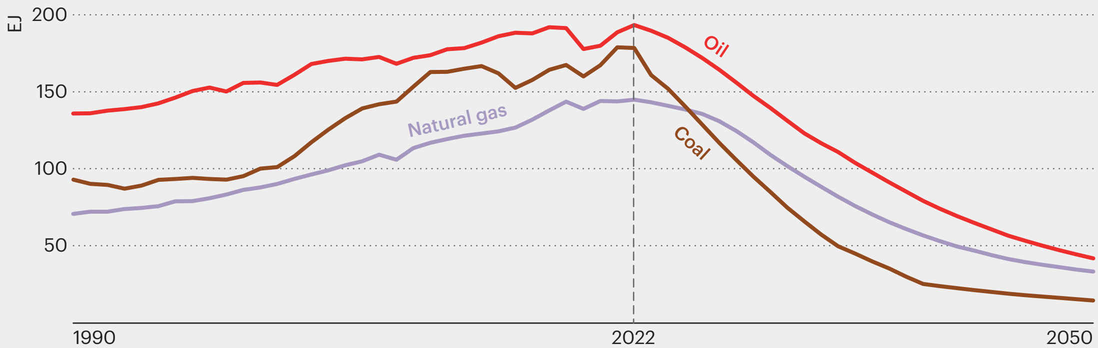


Fossil fuel supply

97% REDUCTION IN FOSSIL FUEL GHG EMISSIONS

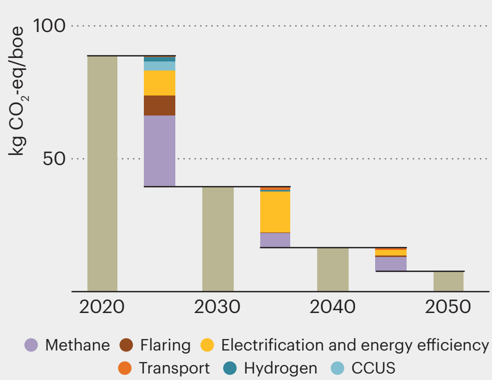
Declines in fossil fuel demand are sufficiently steep that there is no need for new long lead time upstream oil and gas conventional projects, nor from new coal mines or mine extensions.

Total fossil fuel supply

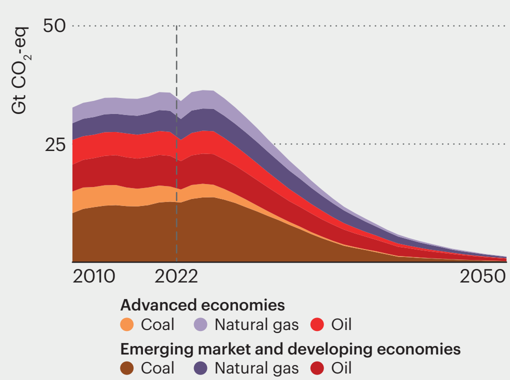


Milestones	2022	2030	2035	2050
Fossil fuel supply (EJ)	**511**	**362**	**237**	**88**
Oil	189	148	110	42
Natural gas	144	118	77	32
Coal	179	95	50	15
Scope 1 and 2 emissions (Gt CO_2-eq)				
Oil	3.4	1.3	0.7	0.1
Natural gas	1.7	0.6	0.3	0.03
Scope 3 emissions (Gt CO_2-eq)				
Oil	8.9	6.9	4.7	0.8
Natural gas	6.9	5.5	3.2	0.3
Coal	15.3	8.2	3.5	0.2

The emissions intensity of global oil and gas operations falls by more than 50% to 2030



Fossil fuel GHG emissions fall by 97% to 2050; nearly 80% of fossil fuel demand in 2050 is for non-combustion applications or used with CCUS



Dashboard notes

Steel and aluminium

Other processes shifts include process emissions reductions from increased scrap-based and inert anode production.

Aluminium production and share of secondary production excludes production based on internally generated scrap.

Near zero emission = projects that, once operational, are near zero emission from the start, according to the definitions in IEA (2022c) *Achieving Net Zero Heavy Industry Sectors in G7 Members*. Near zero emission capable = projects that achieve substantial emissions reductions from the start – but fall short of near zero emissions initially – with plans to continue reducing emissions over time such that they could later achieve near zero emission production without additional capital investment. Production from announced projects shown in the dashboard excludes near zero emission steel from scrap.

Cement

Announced CCUS projects include all facilities with a capacity larger than 0.1 Mt CO_2 per year as of June 2023, and projects with an announced operation date by 2030.

Primary chemicals

Near zero emission primary chemicals production is calculated excluding CCU for urea in ammonia production and high value chemicals produced in refineries.

CCUS-equipped near zero emission production excludes CCU for urea in ammonia production.

Energy efficiency and behavioural change

Avoided demand includes behavioural change. The 2030 value shown in the top graph of the dashboard refers to the average annual rate of energy intensity improvement between 2022 and 2030 in the NZE Scenario.

No new internal combustion engine trucks are sold after 2040 in advanced economies and after 2045 in the emerging market and developing economies.

Carbon capture, utilisation and storage

Announced capture and storage capacity include all facilities with a capacity larger than 0.1 Mt CO_2 per year as of June 2023, and projects with an announced operation date by 2030.

Planned capture capacity shown in the bottom graph excludes capacity for utilisation.

Bioenergy

HVO = hydrotreated vegetable oil. HEFA = hydrotreated esters and fatty acids. Bio-FT = biomass-based Fischer-Tropsch synthesis. Modern gaseous bioenergy refers to biogases, which comprise biogas and biomethane.

Making the NZE Scenario a reality

What will it take?

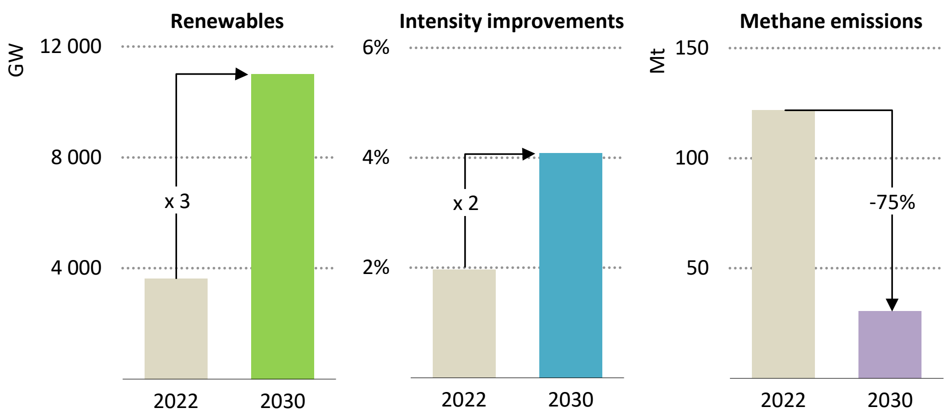
SUMMARY

- Increasing renewables capacity threefold is the single largest driver of emissions reductions to 2030 in the Net Zero Emissions by 2050 Scenario (NZE Scenario). Advanced economies and China are projected to reach around 85% of the required renewables capacity by 2030 with current policies; more robust policies and international support are needed in other developing countries.
- Doubling the rate of energy intensity improvements makes a critical contribution to emissions reductions to 2030 and also bolsters energy affordability and security. This is achieved in the NZE Scenario by efficiency gains from fuel switching to electricity, improvements in technical efficiency, and the more efficient use of materials and energy including through behavioural change.
- Further electrification of end-uses makes the third largest contribution to emissions reductions by 2030. The current growth rate of electric cars sales would be sufficient to meet the 2030 level of deployment envisaged in the NZE Scenario, although faster uptake is needed in trucks. Installations of heat pumps need to expand by almost 20% per year to 2030, compared with 11% in 2022.
- Cutting energy sector methane emissions also brings huge climate benefits. In the NZE Scenario, around USD 75 billion in cumulative spending is required to 2030 to deploy all methane abatement measures in the oil and gas sector. This is equivalent to just 2% of the net income received by the oil and gas industry in 2022.
- Emerging technologies such as hydrogen and carbon capture, utilisation and storage (CCUS) cut emissions mainly after 2030. If all announced projects for hydrogen electrolysis capacity are realised, they would provide around 70% of what is required in the NZE Scenario by 2030. Announced CCUS projects, currently mostly in advanced economies, would provide nearly 40% of what is needed by 2030 globally. A stronger policy focus on creating demand for low-emissions products and fuels is needed.
- A net zero emissions energy system requires more and varied infrastructure. Transmission and distribution grids expand by around 2 million km each year to 2030, and around 30 000 to 50 000 km of CO_2 pipelines need to be installed in the NZE Scenario. New hydrogen infrastructure is also necessary. Delivering the needed infrastructure depends in part on expediting planning and permitting processes.
- If policy ambition is not increased before 2030, limiting the increase in global average temperature to 1.5 °C by 2100 will become much harder. Much more CO_2 would need to be removed from the atmosphere after 2050. The Delayed Action Case indicates that postponing stronger action would cost the world an additional USD 1.3 trillion per year, 50% more than was invested in fossil fuel supply in 2022.

3.1 Achieving deep emissions reductions by 2030

Getting to net zero emissions by 2050 requires rapid and deep cuts in emissions of both carbon dioxide (CO_2) and other greenhouse gases (GHG), particularly methane, by 2030. Delaying these cuts will make it all but impossible to achieve the net zero emissions goal. Emissions reductions can be delivered using technologies and mitigation options that are readily available. In the NZE Scenario, they are achieved in particular with a threefold increase in the capacity of renewables-based electricity generation, doubling the rate of energy intensity improvements, sharp increases in electrification, and a drop of three-quarters in energy sector methane emissions (Figure 3.1). This section analyses how these milestones can be achieved.

Figure 3.1 ▷ Global renewables power capacity, primary energy intensity improvements, and energy sector methane emissions in the NZE Scenario, 2022 and 2030



Renewables, energy efficiency and methane emissions reduction options are available today and crucial to reducing near-term emissions

Notes: GW = gigawatts; Mt = million tonnes. For energy intensity improvements, the 2030 value reflects the annual improvement between 2022 and 2030 in the NZE Scenario.

3.1.1 Triple renewables capacity

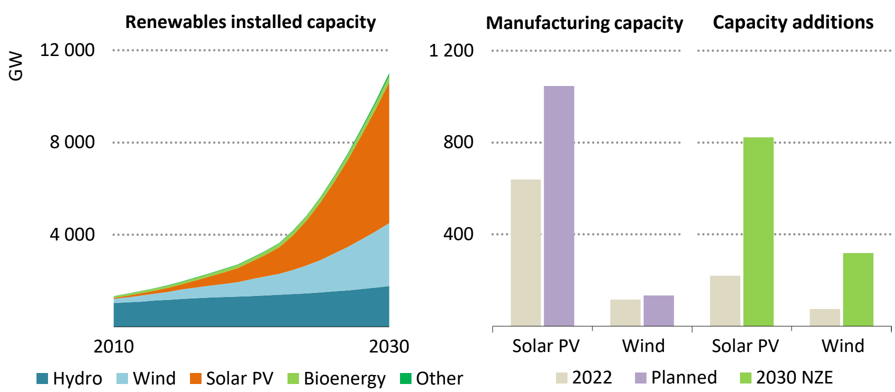
Technology options

Installed capacity of renewables-based electricity generation triples by 2030 to make the single biggest contribution to reducing global CO_2 emissions by 2030 in the NZE Scenario. Global installed capacity jumps from 3 630 gigawatts (GW) in 2022 to 11 000 GW in 2030, led by solar photovoltaics (PV) and wind (Figure 3.2).

Increasing renewables capacity threefold requires the annual pace of capacity additions to rise from 336 GW in 2022 to over 1 250 GW by 2030 – an annual average increase of 18%. Over the last decade, capacity additions more than quadrupled. Maintaining the recent pace of growth to 2030 would put the power sector on course to achieve what is needed in the NZE Scenario.

The share of electricity generation that comes from renewables rises from 30% in 2022 to almost 60% in 2030 in the NZE Scenario, with the combined share of solar PV and wind increasing from 12% in 2022 to 40% in 2030. The increase in renewables generation outpaces electricity demand growth, which cuts back unabated coal-fired generation and reduces its related emissions by half. In total, electricity sector emissions fall by about 6 gigatonnes of carbon dioxide (Gt CO_2) between 2022 and 2030, more than the current emissions of the electricity sector in China.

Figure 3.2 ▷ Global renewables installed capacity by technology, 2010-2030, and solar PV and wind manufacturing and capacity additions in the NZE Scenario, 2022 and 2030



Global renewables capacity triples by 2030 led by solar PV and wind, underpinned by rapid expansion of manufacturing capacity

Solar PV and wind lead the way in the NZE Scenario, together accounting for over 90% of the overall increase in renewables capacity to 2030 and 85% of the increase in renewable electricity generation. Solar PV and wind are the cheapest new sources of electricity in most markets today, are widely available, rapidly scalable and have policy support in over 140 countries. Global solar PV capacity additions increase from 220 GW in 2022 to 820 GW in 2030, of which about 60% is utility-scale projects and around 40% is distributed solar PV such as rooftop arrays on houses and businesses. Wind capacity additions rise from 75 GW in 2022 to 320 GW in 2030, with offshore wind accounting for around one-third of the total. The rapid expansion of solar PV and wind to 2030 would increase the amount of land occupied by these technologies by up to fourfold from today (Box 3.1). Other renewable energy technologies, including hydropower, bioenergy, geothermal, concentrating solar and marine power, boost annual capacity additions which together increase from 42 GW in 2022 to about 125 GW in 2030.

The global clean energy manufacturing industry is already gearing up to provide a huge increase in renewables capacity (see Chapter 1). If all the projects for manufacturing solar PV modules that have been announced go ahead, the capacity would be sufficient to meet the needs of the NZE Scenario in 2030. This is cause for optimism, but it cannot be taken for granted that they all will progress as planned. The outlook for global manufacturing capacity additions for wind is much less encouraging. If renewable power capacity is to triple by 2030, as envisaged in the NZE Scenario, stronger policies are needed in all jurisdictions to facilitate more rapid deployment of renewables, including through support for wind manufacturing capacity. In established markets, action to streamline permitting and land acquisition processes will be an essential element of stronger policy packages. In less developed markets, particularly in the emerging market and developing economies other than China, action to boost incentives to invest and reduce the costs of financing will be particularly important (IEA, 2023a). In all markets, boosting the flexibility of power systems, grids in particular, will be critical to successfully integrate rising shares of solar PV and wind (IEA, forthcoming). This points to the need for significant investment to expand and strengthen electricity grids (see section 3.2.4).

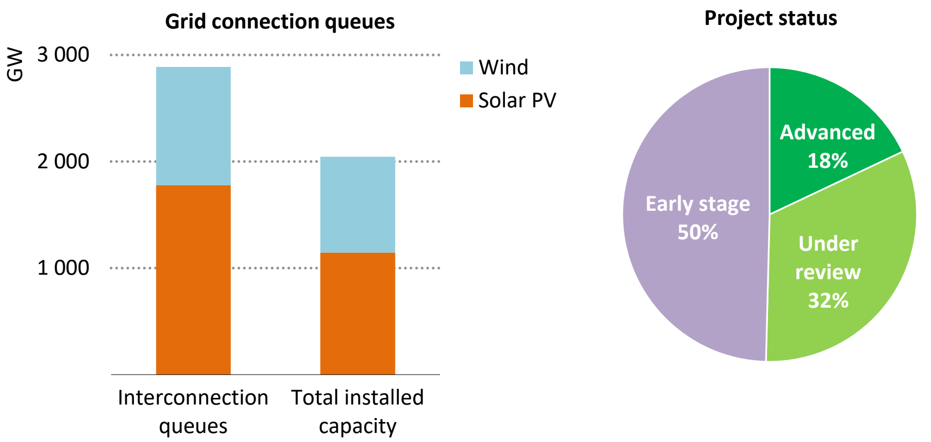
Permitting and grid connections

Increasing global renewables capacity threefold by 2030 in the NZE Scenario depends on expediting permitting and grid connections, and overcoming other challenges including social acceptance and limitations on available sites. Generation costs of wind and solar PV projects are already competitive in many countries, but permitting processes are slowing the pace of their deployment, as are delays in obtaining grid connections.

The size and importance of the issue underline the case for action. In Europe, today around 60 GW of onshore wind capacity – four-times the capacity commissioned in 2022 – is held up by various permitting procedures. Globally, around 3 000 GW of wind and solar PV projects in large renewable energy markets have applied for grid connections, which is slightly less than half the additional renewables capacity projected in the NZE Scenario by 2030 (Figure 3.3). Not all these projects are expected to come to fruition, but they give an indication of the scale of the issue.

The time required to obtain permits ranges from one to five years for ground-mounted solar projects, three to nine years for onshore wind, and nine years for offshore wind. The time required to obtain grid connections can also take several years and appears to be increasing rather than shrinking. These timescales are hindering current projects and risk choking off new ones.

Figure 3.3 ▷ Global grid connection queues for wind and solar PV by project status, 2022



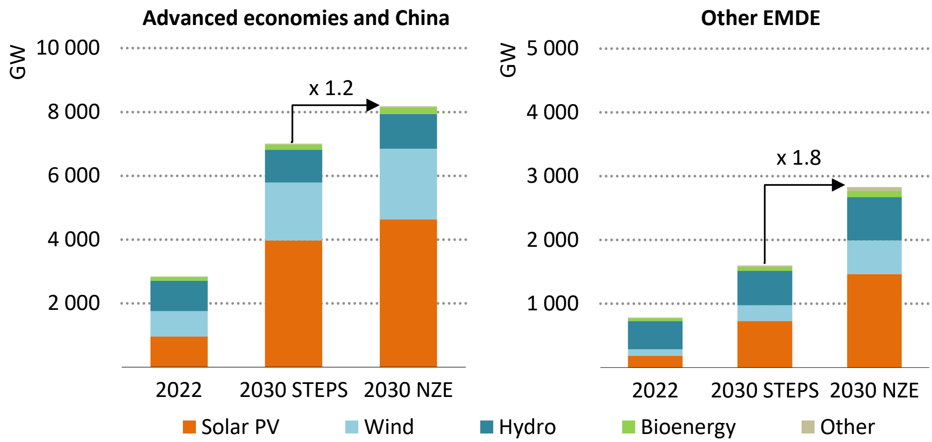
Achieving the net zero emissions pathway requires streamlining of permitting processes

Policy efforts to improve permitting procedures should be focussed on three areas: simplifying permitting procedures and/or setting clear permitting timelines; identifying preferential areas for renewable energy projects to fast track permitting; and removing certain permitting requirements for small renewable power projects and/or increasing the minimum capacity requirement for environmental impact assessments. These changes aim to reduce permit lead times and increase project bankability. Efforts to speed up grid connections for new renewables capacity should be focussed on ensuring that the relevant authorities view the provision of such connections as a high priority and are resourced to deliver what is required.

Boosting capacity in the emerging market and developing economies

China alone accounted for three-quarters of renewables-based power generation capacity additions in emerging market and developing economies over the last decade. Capacity additions in China during the last decade included three-times more solar PV and wind capacity than all other emerging market and developing economies combined. Clear and ambitious targets, strong policy support, mature local supply chains and low-cost financing were all key factors in this rapid expansion of renewables. This strong foundation has enabled China to reduce unit costs very rapidly, and it is now set to achieve its current Nationally Determined Contribution's target for installed wind and solar PV capacity by 2025, five years ahead of schedule.

Figure 3.4 ▷ **Installed renewables capacity by technology and economic grouping in the STEPS and NZE Scenario, 2022 and 2030**



Emerging market and developing economies other than China require the largest boost in the growth of renewables beyond the current pathway

Note: EMDE = emerging market and developing economies; STEPS = Stated Policies Scenario.

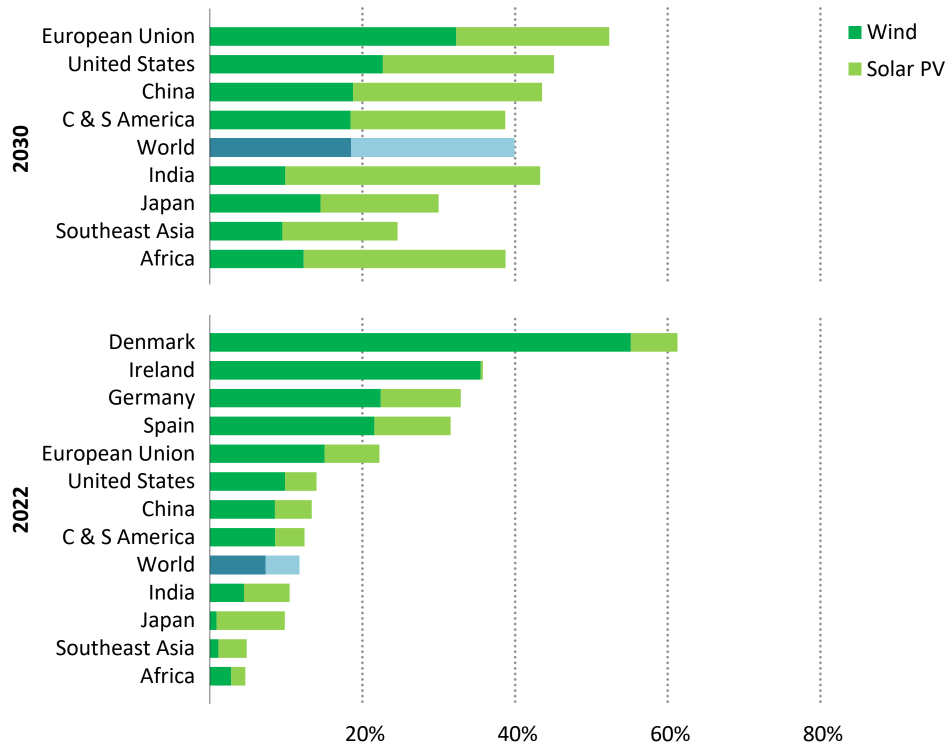
Other emerging market and developing economies also have significant potential to expand renewables cost effectively. They quadruple their total renewable capacity by 2030 in the NZE Scenario, with solar PV and wind providing over 80% of the increase (Figure 3.4). This is over twice the increase projected in the Stated Policies Scenario (STEPS). One of the main barriers to this faster growth of renewables capacity is the high cost of financing projects, which reflects project risk assessments that take account of issues such as policy uncertainties, weak financial health of off-takers, limited grid infrastructure and macroeconomic factors, including currency risks. The weighted average cost of capital (WACC) for renewables in emerging market and developing economies remain at least double those in advanced economies (see Chapter 4). Since every 1 percentage point increase in the WACC increases wind and solar PV generation costs by at least 7%, this makes an enormous difference to the prospects for renewables.

Appropriate policies are needed to address causes of the high cost of capital in these economies. Clear national targets with an annual implementation plan, for instance through competitive auctions, would be likely to increase investor confidence. In India, for example, an ambitious government target set for renewables capacity has been followed by central and provincial auction schedules with a transparent procurement process. The risks associated with the financial health of off-takers could be addressed through standardised power purchase contracts backed by government guarantees, especially for publicly owned utilities. India provides an example of policy action here too: its centralised large-scale auctions conducted by the Solar Energy Corporation of India (SECI) helped reduce project risks and lower the cost of capital for utility-scale solar PV and wind plants. Policies along these lines could also facilitate the availability of concessional financing from international and regional development banks, and this would further reduce the cost of capital.

Integration of variable renewables

While power systems have always had to accommodate the variability of electricity demand, the rapid expansion of solar PV and wind – both variable sources whose output depends on weather conditions – means that power system flexibility needs will increase. Since solar PV and wind do not contribute to grid stability in the same way as the fossil fuels which they increasingly displace in the NZE Scenario, new ways to ensure grid stability will also be needed.

Figure 3.5 ▷ Share of total electricity generation from wind and solar PV by selected country/region in 2022 and in the NZE Scenario in 2030



Integration of solar PV and wind is critical to the NZE Scenario, as their share in total generation in most regions reaches levels in 2030 seen only in a few countries today

Note: C & S America = Central and South America.

The rapid deployment of solar PV and wind in the NZE Scenario lifts their share of electricity generation in 2030 to over one-third in most regions of the world. Without effective action to ensure system flexibility, this could result in rising amounts of surplus solar PV and wind at times when output exceeds demand. Countries including Denmark, Ireland and Spain already produce one-third or more of their electricity from renewables and have managed the challenges of integration: other countries may be able to draw on the lessons they have learned (Figure 3.5).

Rising shares of variable renewables make electricity supply more weather dependent and leads to higher needs for flexibility across all timescales, ranging from hours to seasons and years. Varying wind patterns observed over weeks and seasons, for example, can contribute significantly to the increase of seasonal flexibility needs, while solar PV variability has the biggest impact on timescales ranging from hours to days.

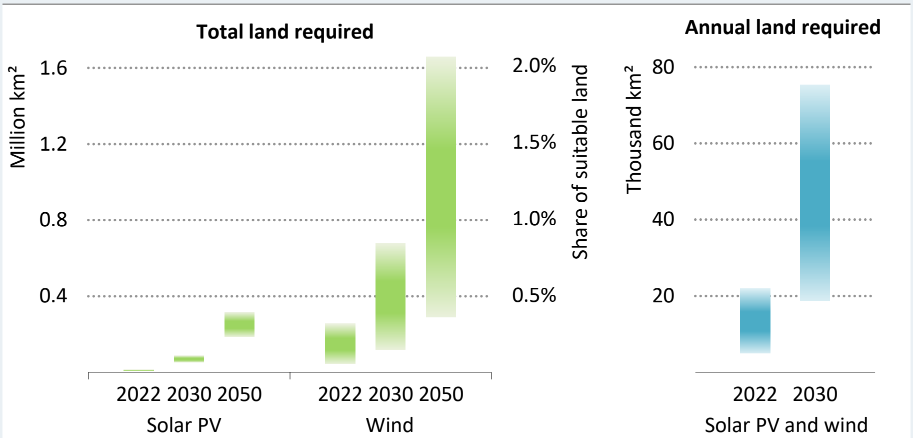
Successfully integrating these rising shares of solar PV and wind in electricity generation requires making the best use of existing and new sources of flexibility, and market and regulatory frameworks have a crucial part to facilitate this. Existing power plants, including natural gas- and coal-fired stations, can contribute while they remain in operation by focussing on flexibility rather than bulk electricity production. New sources of flexibility include energy storage technologies such as batteries and demand response help in particular to balance daily peaks and troughs, and between them they meet much of the short-term flexibility need in the NZE Scenario. Low-emissions dispatchable thermal power plants, including nuclear plants, reservoir and pumped storage hydro, grid-connected electrolysers and long-duration hydrogen storage all play a part in the delivery of longer term and seasonal flexibility.

Transmission and distribution grids need to be modernised and expanded to facilitate the integration of rising shares of solar PV and wind and the deployment of all sources of flexibility. This should be done in a way that facilitates demand response management, for example by providing incentives to use energy at times of high supply of renewable electricity, including through time-of-use tariffs (see section 3.2.4). Interconnections between regions are another option to provide flexibility: they allow for the pooling of flexibility resources and reduce the need for additional power system flexibility by balancing load, wind and solar production over large geographical areas. Measures to ensure system stability also need to be integrated into work to modernise and expand grids: they include the deployment of synchronous condensers, flexible alternating current transmission systems (FACTS), grid-forming inverters and fast frequency response (FFR) capabilities.

Box 3.1 ▻ Does the world have enough space for all the solar and wind in the NZE Scenario?

Based on a review of over 100 completed projects worldwide, we estimate that all the utility-scale solar PV and onshore wind projects in operation in the world in 2022 cover less than 0.2 million km^2 of land area. Solar PV installations in or on buildings are not included in this assessment as they rarely require additional land. We found that a utility-scale solar PV project of 100 MW generally occupies from 1 km^2 to 3 km^2. This is in line with other published estimates (NREL, 2021; A. Arvesen, 2018; Smil, 2010; UNECE, 2022). We also found that a 100 MW onshore wind turbine project generally covers from 5 km^2 to 30 km^2: here too our findings are consistent with other published estimates (NREL, 2021; Enevoldsen and Jacobson, 2021; Lovering et al., 2022). Wind projects require more land than solar projects per unit of capacity in part because the vast majority of utility-scale PV takes the form of solar panel arrays, where panels can be put close to one another, whereas wind turbines need a certain amount of space around them to optimise their performance. Variations in project size reflect a number of factors, including turbine design and the shape and geography of the site.

Figure 3.6 ▻ Total and annual land requirements for solar PV utility and onshore wind in the NZE Scenario, 2022, 2030 and 2050



The rapid expansion of solar PV and wind requires up to 2.0 million km^2 of land area by 2050 in the NZE Scenario, equivalent to up to 2.5% of global suitable land

Note: km^2 = square kilometres.

In the NZE Scenario, the tripling of renewables capacity by 2030 increases the global land area requirements for onshore wind and solar PV to up to 0.8 million km^2, which is more than four times the amount of land they use today. Wind power accounts for the majority of the land that is needed, though project requirements for a given output vary widely depending on the type of turbine used and on the nature of the project site. By 2050, total land requirements for onshore wind and utility-scale solar PV rise to up to 2.0 million km^2, or more than ten times the amount of land used today (Figure 3.6). On an annual basis, the land needed each year for new solar PV and onshore wind projects rises from 5-20 thousand km^2 in 2022 to 20-75 thousand km^2 in 2030. Achieving this scaling up requires action to overcome challenges related to land acquisition, permitting, local acceptance and grid development.

The requirement for land totalling up to 2.0 million km^2 for solar PV and wind in the NZE Scenario needs to be put into context. It is much less than the global requirement for land for crops in 2020 (12.2 million km^2) or for built-up areas in the same year (about 4.3 million km^2). But it is more useful to look at solar PV and wind requirements as a proportion of the land that is suitable for such projects, and we have attempted to do this. Suitable land in this analysis includes grasslands, shrub-covered areas, sparsely naturally vegetated areas, terrestrial barren land. It also includes most agricultural land on the basis that many projects have already demonstrated that farming activities can co-exist with onshore wind projects. However, it excludes artificial surfaces (including urban and associated areas), tree-covered areas, woody crops, mangroves, aquatic or regularly flooded areas, and permanent snow and glaciers.

This analysis results in about one-third of global land being ruled out as unsuitable for solar PV and wind, leaving just over 80 million km^2 as suitable, based on available land area data (FAO, n.d.). In the NZE Scenario, the global share of suitable land occupied by onshore wind and solar PV rises from about 0.2% in 2022 to up to 0.9% in 2030 and up to 2.5% in 2050, though the share varies widely by region. The increase in the land required for solar PV and wind in the NZE Scenario is certainly significant, but it is hard to argue that the world does not have the necessary space.

3.1.2 Double the rate of energy intensity improvements

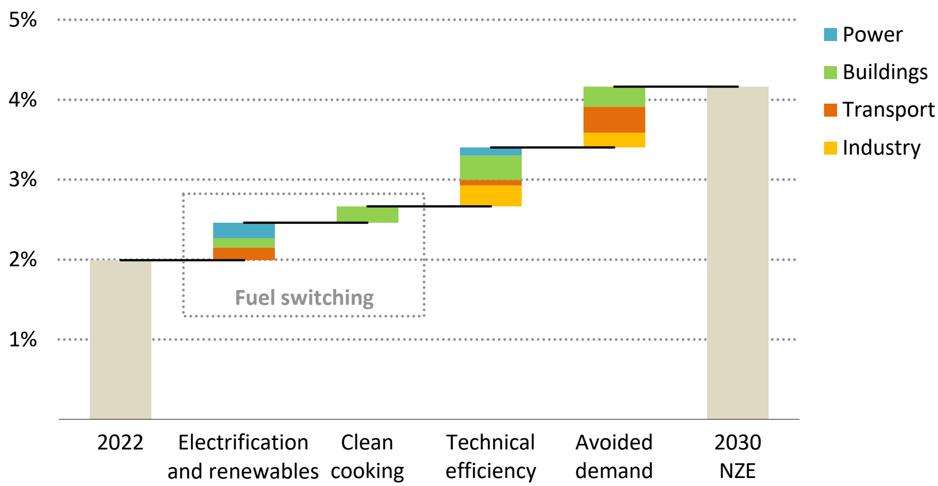
The annual rate of improvements in energy intensity – the amount of primary energy needed to produce a dollar of economic output – averages 4.1% through to 2030 in the NZE Scenario. This is double the rate achieved in 2022, which itself was nearly double the average rate achieved over the previous five years. One result of the rate of improvement achieved in the NZE Scenario is that energy demand in 2030 is nearly 10% lower than in 2022, even as the economy continues to grow. Reduced consumption means reduced emissions. It also brings energy security benefits and helps to make energy more affordable.

There are three main levers that double the rate of improvements in primary energy intensity in the NZE Scenario, each of which contributes roughly a third of the gains (Figure 3.7):

- A shift to more efficient fuels through electrification, renewables and universal access to clean cooking fuels.
- Technical efficiency measures in all sectors.

- Avoided energy demand through material and resource efficiency gains, including through behavioural change.

Figure 3.7 ▷ Rate of annual primary energy intensity improvements by lever in the NZE Scenario



More rigorous policies to boost fuel switching, energy and resource efficiency, and behavioural change are essential to double the rate of improvement in energy intensity

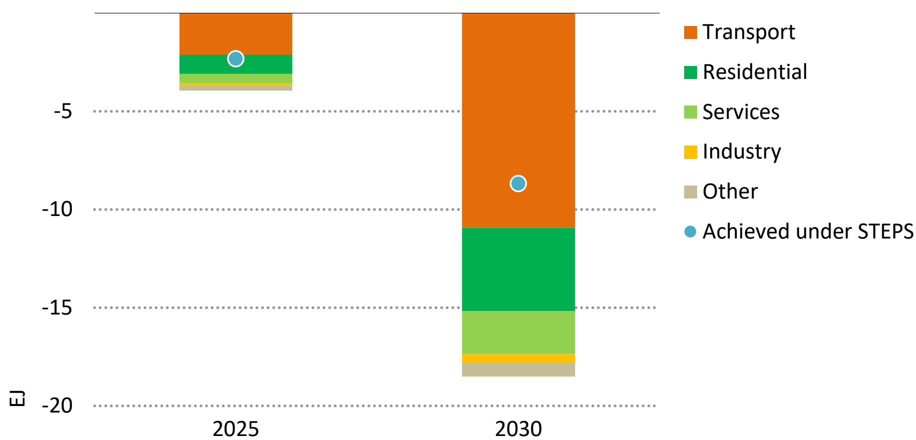
Notes: Avoided demand includes behavioural change. 2030 NZE refers to the average annual rate of energy intensity improvements between 2022 and 2030 in the NZE Scenario.

Switch to more efficient fuels: Role of electrification

Electrification is a major driver of the sharp fall in energy intensity in the NZE Scenario because electricity can be converted into energy services much more efficiently than incumbent fossil fuel-based technologies. Electric vehicles (EVs) are two- to four-times more efficient than current internal combustion engine (ICE) vehicles; heat pumps are three- to five-times more efficient than fossil fuel boilers, and induction stoves are about twice as efficient as gas stoves. In the NZE Scenario, a rapid shift to electricity across the energy system results in energy savings, reaching nearly 20 exajoules (EJ) by 2030, close to the combined current final consumption of Japan and Korea.

The majority of these savings are realised through the rapid uptake of EVs in transport and heat pumps in the residential sector (Figure 3.8). Both these technologies are already in use and are gaining ground, but the NZE Scenario speeds up their adoption and doubles the energy savings that they bring in the STEPS outlook (see section 3.1.3).

Figure 3.8 ▷ Annual energy savings from electrification in the NZE Scenario



Electrification results in annual energy savings of nearly 20 EJ by 2030, equivalent to the combined current final consumption of Japan and Korea

Technical efficiency measures: Improving the efficiency of appliances in buildings

Improvements in the unit energy consumption of appliances in recent decades have been impressive. Refrigerators purchased today consume less than half as much electricity as models sold 20 years ago; air conditioners have become over 40% more efficient in the same timeframe. These gains have been driven by a combination of technology improvements and policy measures designed to diffuse those improvements, notably through the widespread adoption of standards and labelling. Together they have reduced annual electricity consumption by around 15% in regions with long-standing policies. At the same time, appliances subject to standards and labelling programmes have become significantly less expensive (IEA, 2021a). Appliance standards are now in place in more than 110 countries and, for example, cover 90% of the energy consumption by refrigerators worldwide.

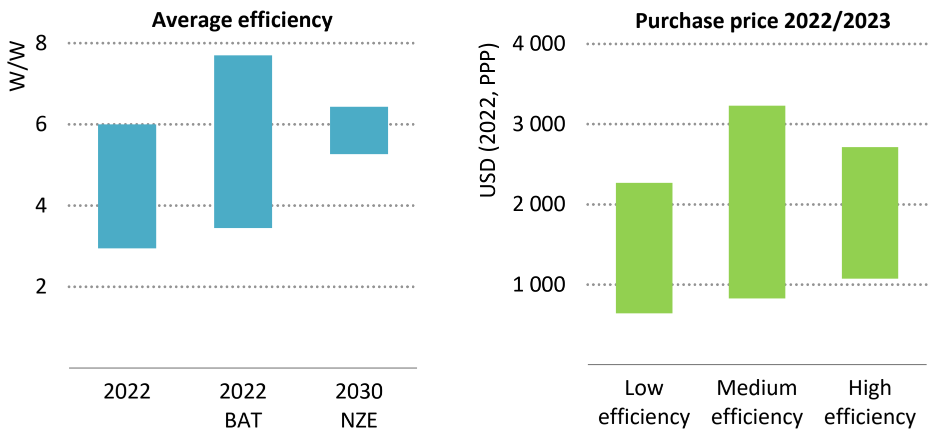
The NZE Scenario builds on the progress of such programmes but requires an increasing focus on best available technologies in all regions.[1] This is particularly important in emerging market and developing economies, where most appliance sales through to 2030 will be concentrated, and where efficiency policies are generally less stringent today than in advanced economies.

Air conditioners are particularly important in this context. The stock of air conditioners in emerging market and developing economies is set to double by the end of the decade

[1] The Super-Efficient Equipment and Appliance Deployment Initiative, a collaboration of the IEA with more than 20 governments and other partners, supports standards and labelling efforts by helping policy makers simplify regulation setting and compliance.

reflecting rising incomes and cooling needs. This presents enormous scope to increase the average efficiency of air conditioners. Highly efficient models are already available, but those sold today are on average just half as efficient as the best available technology in many markets. Thanks to standards and labelling programmes, average air conditioners sold in the emerging market and developing economies in 2030 in the NZE Scenario are at least 50% more efficient than today (Figure 3.9). More efficient models sometimes cost slightly more than the alternatives, but this is not always the case, and they save consumers money over their lifetime due to lower operating costs. Energy efficiency improvements of building envelopes (Box 3.2) as well as passive cooling strategies and behavioural changes such as higher air conditioner temperatures can also bring down energy bills and curb growth in electricity demand.

Figure 3.9 ▻ Average efficiency and purchase price of new air conditioners in emerging market and developing economies



Efficiency improvements are vital in the NZE Scenario, and efficient air conditioners today are not significantly more expensive than those with lower efficiency

Notes: W/W = Watt of cooling output per Watt of electricity input; BAT = best available technology; PPP = purchasing power parity. Based on data for wall air conditioners collected from Argentina, Brazil, Colombia, Ghana, Kenya, Panama and Vietnam in late 2022 and early 2023. Purchase prices are normalised to a cooling capacity of 12 000 British thermal units per hour. Low efficiency = below 4 W/W; medium efficiency = 4-5 W/W; high efficiency = above 5 W/W.

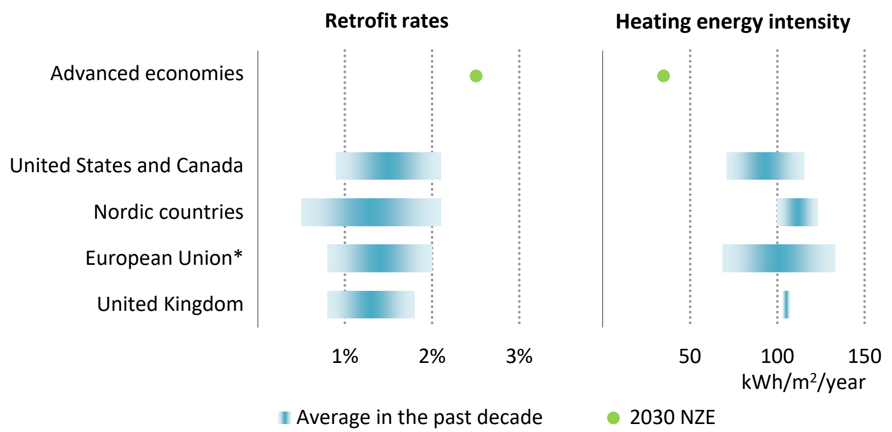
Box 3.2 ▻ A (retro) fitting solution to decarbonise buildings

Retrofitting is one of the main levers for decarbonising the buildings sector. Buildings in advanced economies have relatively long lifetimes, about 80 years on average. Over 90% of the buildings that will be in use in these countries in 2030 have already been built. In the NZE Scenario, 2.5% of buildings in advanced economies are retrofitted each year from

2030 onwards and all new buildings are zero-carbon-ready. Building energy codes and strong retrofit policies drive these developments, which together account for 40% of the emissions savings from efficiency measures in residential buildings.

In the past decade, between 2-14% of buildings a year in at least some advanced economies have undergone some kind of a retrofit, but fewer than 1.5% of buildings have been retrofitted sufficiently each year to lower energy demand by 30% or more (Figure 3.10). Achieving bigger energy savings from each retrofit will require consistent and robust policy support from governments.

Figure 3.10 ▷ Annual retrofit rates and space heating energy intensity of residential buildings in advanced economies



Annual residential building retrofit rates in advanced economies average less than 1.5% today; a step up to 2.5% by 2030 is needed in the NZE Scenario

*European Union here excludes Denmark, Finland and Sweden. These are included under Nordic countries.

Notes: kWh/m²/year = kilowatt-hour per square metre per year. Retrofit rates included here yield energy savings of 30% or more. The NZE Scenario 2030 target shows an average that varies depending on regional climate conditions and heating needs.

Sources: European Commission (2019), Olgyay (2010), US EIA (2018), and ZEBRA (2020).

Cost and convenience are the primary barriers to stepping up the rate and depth of retrofits. The cost of insulation materials has increased in recent years amidst supply chain disruptions and inflation. Retrofitting the average size home in advanced economies can cost thousands of USD, which can pose a significant financial barrier for lower income households (see Chapter 4). Deeper retrofits also often require additional time and cause extra disruption to occupants.

In recent years, numerous governments have offered grants, subsidies and tax credits to incentivise retrofits through programmes such as the US Inflation Reduction Act, the UK Greener Homes Grant, and the Superbonus in Italy. They have boosted retrofit rates substantially, but many incentives have expired or are due to expire soon. A number of governments have put strategies in place to standardise renovations, speed up retrofits and lower costs, and these could be replicated or adapted for use in other countries. For example, the Dutch Energiesprong programme relies on digital planning and prefabricated facades to deliver projects more quickly, while the Irish National Retrofitting Scheme emphasises one-stop shops so that homeowners can access complete renovation management and financing services via one counterpart. Legislative measures may also have a part to play. For example, the European Union is considering legislation to require retrofits of the least energy-efficient buildings in member states (European Parliament, 2023).

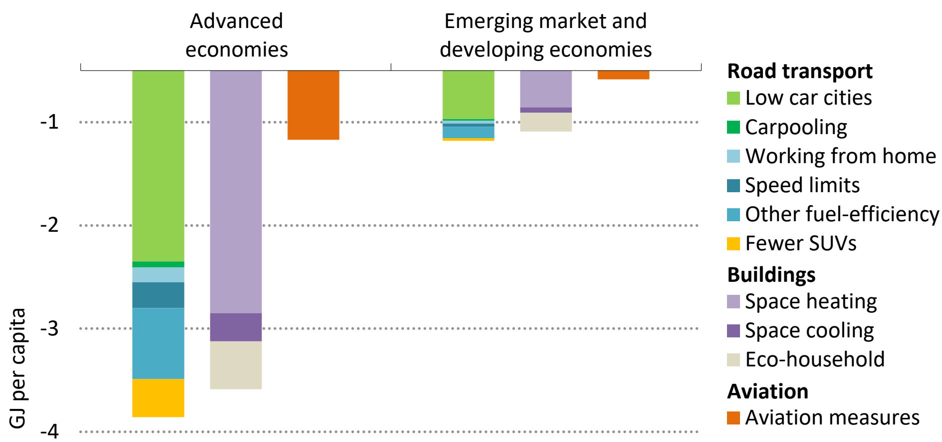
Avoided energy demand: Impact of behavioural change

Although technical options to reduce energy intensity are maximised in the NZE Scenario, the pace of turnover of the global stock of energy-related assets imposes constraints on what can be achieved by 2030. Consequently, behavioural changes – actions that consumers can take to reduce energy consumption – are needed to accelerate improvements in energy intensity. In the buildings sector, they include adjusting space heating and cooling temperatures. In the transport sector, they include more public transport and reduced car use in cities, eco-driving on highways and switching from planes to trains or videoconferencing. To bring about these changes, issues such as the high cost of train travel need to be addressed, and new financial incentives need to be introduced such as congestion charges in cities and levies on frequent flyers (IEA, 2023b).

Behavioural change in the NZE Scenario happens more quickly and to a larger extent in advanced economies than elsewhere. For example, demand for space cooling on a per capita basis is more than three-times higher in advanced economies even though emerging market and developing economies have around three-times more cooling degree days in a typical year. This means that raising space cooling temperatures generates far greater savings per capita in advanced economies than in emerging market and developing economies. In 2030, on a per capita basis, the energy savings in the NZE Scenario from behavioural changes in road transport and the buildings sector are about five-times higher in advanced economies than in emerging market and developing economies; in aviation they are about eight-times higher (Figure 3.11).

The reduction in energy demand from sustained behavioural changes in the NZE Scenario is significant, but it builds on the reductions achieved as a result of recent policy interventions related to the Covid-19 pandemic and energy crisis. For example, teleworking was still three-times more prevalent in 2022 than in 2019 (Parker, Horowitz and Minkin, 2022). The energy crisis of 2022 led to a number of measures designed to change behaviour, including national energy savings campaigns such as in Denmark, Germany, Ireland and Sweden. Among the Group of 20 (G20) nations, the number of policies supporting behavioural changes has more than doubled since 2021, and the G20 forum has recognised the importance of behavioural change with adoption of the High-Level Principles for Lifestyles for Sustainable Development.

Figure 3.11 ▷ Changes in energy consumption from behavioural measures in the NZE Scenario, 2030



Behavioural changes save five-times more energy per capita in advanced economies

Notes: Low car cities represent an urban model where planning and infrastructure reduce the dependence on cars to substantially improve public health, well-being and liveability, including a host of measures such as the phase-out of internal combustion engine cars from city centres, shared mobility or moderating urban speed limits. Other fuel efficiency includes reducing air conditioning temperatures in cars and eco-driving practices. Space heating/cooling includes limiting heating temperatures to 19-20 °C and cooling temperatures to 24-25 °C. Eco-household includes line drying clothes instead of machine drying, reducing laundry temperatures, switching off lights in unoccupied rooms, unplugging appliances not in use and reducing water heating temperatures. Aviation measures include a shift from short-haul flights to high-speed rail, reduction of business flights and imposition of a levy for frequent flyers.

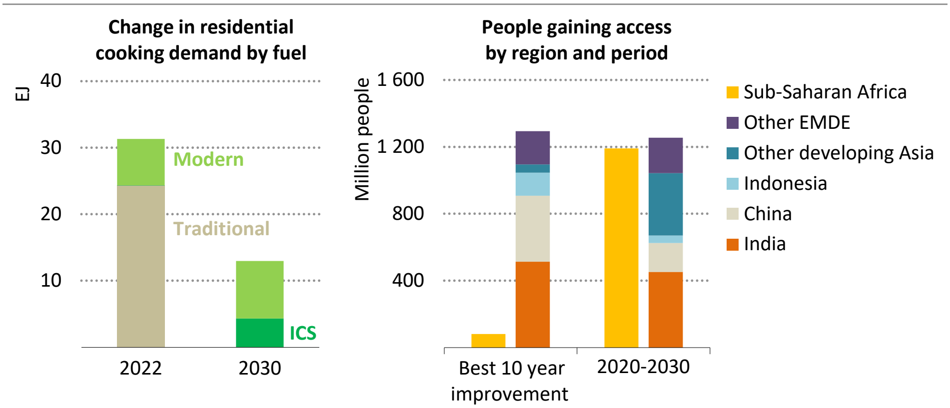
Behavioural change in the advanced economies reduces electricity demand in the buildings sector in 2030 by more than 6% and natural gas demand by around 15% in the NZE Scenario. Recent experience suggests that this is feasible: in Germany, households and small businesses cut natural gas consumption by up to 42% in 2022 in response to the energy crisis and public exhortations to save energy (Hirth, 2022). Similarly, driving in ICE cars drops by up to 14% from 2022 to 2030 with more use of public transport, cycling and walking. There are encouraging precedents here too: for example, London's congestion charge brought about an 18% drop in car traffic 20 years after its first adoption (Transport for London, 2023).

Switching to more efficient fuels: Role of access to modern energy

Accelerating access to modern energy helps drive down energy intensity more quickly in the NZE Scenario. Nearly 2.3 billion people in around 130 countries, mainly in Asia and sub-Saharan Africa, lack access to clean cooking today, while nearly 780 million people remain without access to electricity. In addition to its other benefits, access to modern energy improves energy efficiency. Despite considerable population growth, universal access to clean cooking cuts residential fuel demand for cooking in emerging market and developing economies by nearly 60% by 2030 in the NZE Scenario compared with today.

This is mainly due to switching from extremely inefficient traditional use of biomass to improved cookstoves (ICS). These stoves are more efficient, burn less wood and emit less smoke than traditional cook stoves. They allow poor households in rural areas to make a first step toward clean cooking without changing the fuel they use. For this to happen, investment in clean cooking stoves, equipment and infrastructure over this decade needs to reach about USD 8 billion annually – less than 1% of what governments spent in 2022 on measures to keep energy affordable for their citizens amidst the global energy crisis.

Figure 3.12 ⊳ Energy use for residential cooking and gains in access to modern fuels in emerging market and developing economies in the NZE Scenario



Universal access to clean cooking cuts residential fuel demand for cooking in emerging and developing economies by nearly 60% by 2030 relative to today

Notes: EJ = exajoules. ICS = improved cook stoves that use solid biomass as a fuel. Modern = modern fuels such as liquefied petroleum gas, electricity, biogas and ethanol. Traditional = traditional use of biomass, coal and kerosene. Best ten-year improvement bars reflect the single best historic year of providing clean cooking access for each country between 2000 and 2022, and assumes this is repeated for ten years as a representative point of comparison for the level of effort required to reach Sustainable Development Goal 7.

Achieving universal access to modern energy would involve an accelerated deployment of all available technologies, and an unprecedented reversal of current trends in sub-Saharan

Africa, where the population without access has climbed continuously in most countries. However, progress in other regions has demonstrated that it is possible to quickly provide access to clean cooking solutions (Figure 3.12). For example, in India, nearly half a billion people gained access within ten years thanks to a combination of subsidised refills of liquefied petroleum (LPG) cylinders, deposit-free LPG connections and a scheme allowing wealthier households to voluntarily renounce their access to LPG subsidies. Similar success stories from China and Indonesia showcase how strong national efforts can make an impact, with each country providing 2-3% of its population with clean cooking technologies every year (IEA, 2023c).

3.1.3 Accelerate electrification

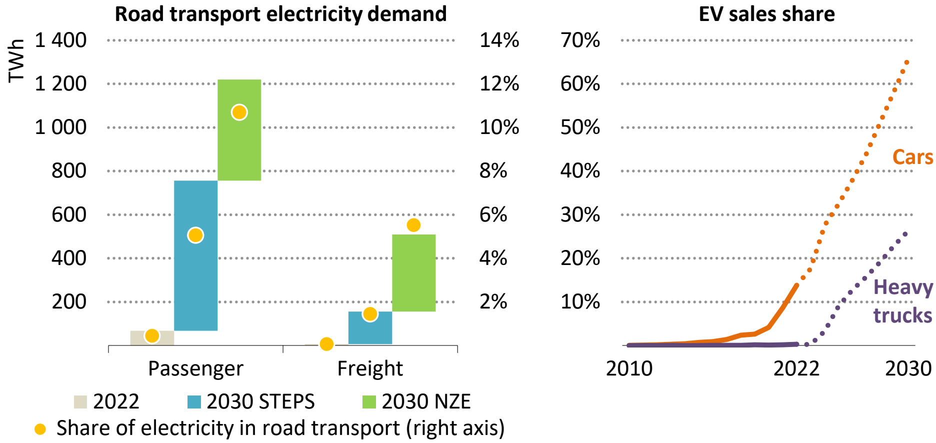
From 2023 to 2030, around one-fifth of the emissions reductions in the NZE Scenario result from electrification of end-uses that would otherwise have used fossil fuels. In transport, most of the gains come from the deployment of EVs. In the buildings sector, emissions reductions mostly come from the installation of heat pumps. In industry, there is potential for the electrification of low-temperature and some medium-temperature heat applications using highly efficient industrial heat pumps, with other electric heating technologies and thermal energy storage further extending electricity's reach. The electrification of heavy industries – steel, cement and chemicals – is critical to the achievement of the NZE Scenario, but these industrial branches reach lower levels of electrification to 2030. This is mainly due to the time needed to develop market-ready direct electrification technologies for certain applications, such as providing high-temperature heat in cement and chemical manufacturing, and the chemical reduction of iron ore in the steel making.

Electrification in transport

Electrification ramps up more quickly in transport than in other end-use sectors in the NZE Scenario. The share of transport energy consumption accounted for by oil falls from about 90% today to 80% in 2030; the share of electricity increases from 1% to almost 8% over the same period (Figure 3.13). More than 90% of this increase in electricity demand is attributable to the switch from ICE vehicles to EVs, and 50% of that in turn is attributable solely to electric cars. Electrification progresses in the STEPS too, reflecting rapid cost declines in recent years and strong policy support in major markets, but its pace is significantly faster in the NZE Scenario.

China and the advanced economies are expected to lead the way in the electrification of vehicle fleets, in which EV sales account for 80% of light-duty vehicles, 85% of buses and 55% of heavy trucks in 2030 in the NZE Scenario. As sales increase and costs decline, electrification follows in the other emerging and developing economies, where EV sales account for 40% of light-duty vehicles, 40% of buses and 7% of heavy trucks in 2030 in the NZE Scenario. This is supported by a rapid roll-out of charging infrastructure and associated investment in electricity grids.

Figure 3.13 ▷ Global electricity demand in road transport by scenario, 2022-2030, and EV sales shares in the NZE Scenario, 2010-2030



Electricity meets over 10% of energy demand in passenger road transport and electric cars are about 65% of all cars sales in 2030 in the NZE Scenario

Note: TWh = terawatt-hour.

Over the decade prior to 2022, global electric car sales increased at an average annual rate of over 50%; in the NZE Scenario, they increase on average by around 25% annually between 2023 and 2030, although from a higher base. Their share of total car sales reaches about 65% (compared with 14% in 2022). This suggests that electric car sales could meet or exceed what is called for in the NZE Scenario by 2030. There are currently about 500 electric car models available worldwide, and this is set to increase. For example, Volvo plans to sell only electric cars by 2030 and BYD, an automaker in China, has already stopped selling ICE vehicles. Investments in electric vehicle battery manufacturing are also picking up, with capacity increasing by almost 60% in 2022; announced expansions, if they proceed as planned, would deliver a throughput sufficient to meet the demand in 2030 in the NZE Scenario (see Chapter 1).

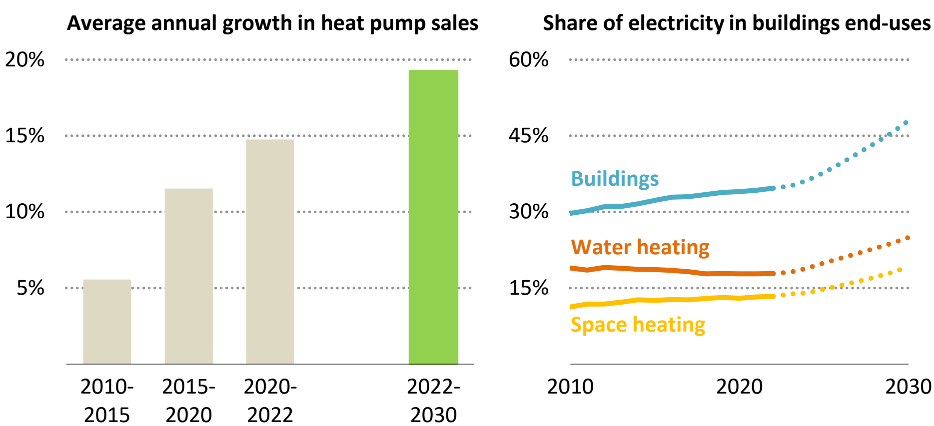
Electrification of heavier vehicle segments, such as trucks and buses, needs to accelerate faster to deliver what is required in the NZE Scenario. Electric buses increase their share of sales from 4% in 2022 to over 50% in 2030 in the NZE Scenario, and electric heavy trucks increase from 1% to 33% share. There are some encouraging signs that the pace of progress may increase. Truck and bus manufacturers are increasingly offering zero emissions vehicles. Electric buses and trucks are becoming increasingly competitive on a total cost-of-ownership basis. However, additional electricity demand by 2030 in the STEPS for heavy trucks and buses is only one-third of the level in the NZE Scenario, indicating that more needs to be done to accelerate uptake.

Currently, the most common policy measures to support EV deployment are fuel-economy and CO_2 emission standards, both for light- and heavy-duty vehicles, as well as financial incentives such as purchase subsidies and tax credits that make EVs more cost competitive with conventional ICE vehicles. Governments are also supporting the development of EV charging infrastructure, for example by offering financial incentives for public as well as private chargers and by stipulating infrastructure requirements in building codes.

Electrification in buildings

The share of electricity in energy use in the buildings sector worldwide rises from 35% today to nearly 50% in 2030 in the NZE Scenario, compared with 40% in the STEPS. The share of electricity in space and water heating increases by around 7 percentage points by 2030, mainly as a result of increased deployment of heat pumps, which are three- to four-times more efficient than electric resistance heaters. Heat pumps met around 10% of global heating needs in buildings in 2022, with more than 1 000 GW of capacity in operation for space (and/or water) heating. Sales of heat pumps are increasing rapidly: they rose by 11% in 2022, marking a second year of double-digit growth (IEA, 2023d). Growth is even faster in the NZE Scenario, with the stock almost tripling by 2030, by which time it meets over one-fifth of building sector heating needs. This implies average annual sales growth of almost 20% between 2023 and 2030 (Figure 3.14). In the European Union, the annual increase of heat pump sales has been over 35% since 2021, implying that the growth rates required in the NZE Scenario are feasible.

Figure 3.14 ▷ Global heat pump sales growth rate and share of electricity in buildings end-uses in the NZE Scenario, 2010-2030



Sales of heat pumps have surged since 2020, but need further growth to reach 2030 targets

In most markets, the upfront cost of a residential heat pump (including installation) is generally much higher than that of a fossil fuel boiler, though the extent of the cost gap varies widely within and across countries, even for the same technology. Nonetheless, in some mature markets, such as Norway, Denmark and Japan, the least expensive ductless air-to-air heat pump models have become cheaper than natural gas boilers for new installations in small houses, thanks primarily to reduced piping work and installation costs.

Financial incentives are currently available in over 30 countries around the world, covering more than 70% of today's heating demand (IEA, 2022). Many of these grants, tax rebates and low-interest loans for heat pumps in new buildings or as part of broader buildings renovations have been introduced or strengthened since the beginning of the energy crisis.

Other measures to support a more rapid uptake of heat pumps, as envisaged in the NZE Scenario, are new heat-as-a-service business models as well as revised building energy performance and clean heat standards. In addition, energy tariffs and taxes can be structured to favour cleaner and more efficient consumer choices. Addressing barriers such as a shortage of workforce for technology installation and restrictions or practical constraints for new installations becomes even more pressing as upfront costs come down.

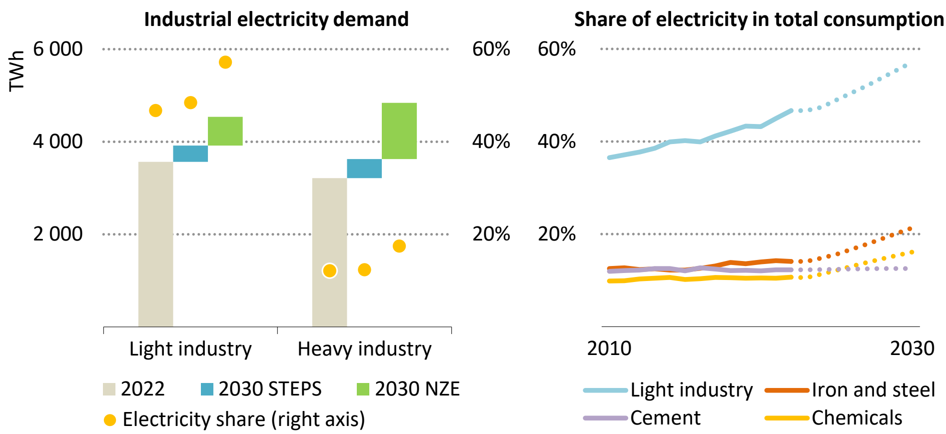
Electrification in industry

The industry sector currently accounts for more than 40% of global electricity demand. Electricity is versatile and provides a diverse array of energy services in industry, e.g. heating, cooling, lighting, electrochemical processes and motor drives. The production of steel recycled scrap and primary aluminium production all use electricity as the principal energy input today. In the STEPS, industrial electricity demand rises by around 15% by 2030 as demand for industrial outputs exceeds the rate of efficiency improvements. In the NZE Scenario, a concerted push to electrify processes across all sub-sectors leads to a much bigger increase in industrial electricity demand of 4 000 TWh, or 38% by 2030, 40% of which is in heavy industries (Figure 3.15).

Heating applications offer the largest scope for increasing electrification in the industry sector. Many of the technologies needed to substitute electricity for fossil fuels are already commercially available for low (<100 °C) and medium (100-400 °C) temperature heat. In light industries, more than 90% of total heat demand falls within these ranges. Heat pumps, electric boilers and resistance heaters – or combinations of all three – offer an efficient means of providing a wide range of temperatures for both direct heating and indirect heating using steam. In the NZE Scenario, electrification of heating applications accounts for 45% of the increase in electricity consumption in light industries to 2030.

Cost is the key potential barrier to achieving this. Fuel accounts for the majority of the total life cycle cost of heating equipment, and industrial end-user prices for fossil fuels tend to be substantially lower than electricity prices in most countries today. Industrial heat pumps, which are more efficient than fossil fuel heating units, are able to bridge the cost gap in some cases, especially when complemented with captive solar PV electricity generation. Thermal storage technologies that can deliver heat directly to industrial processes at high temperatures may be able to extend the reach of low-cost variable renewable electricity in the industry sector, by-passing the grid. Nevertheless, cost remains an obstacle.

Figure 3.15 ▷ Global electricity demand in industry by scenario, 2022-2030, and share of electricity in total energy demand by sub-sector in the NZE Scenario, 2010-2030



IEA. CC BY 4.0.

Electrification in industry must go far beyond what is projected under currently planned policies to be in line with the NZE Scenario

Electrifying the provision of high-temperature heat (>400 °C) in industry is more difficult. Electro-magnetic heating technologies, resistance heaters and electric arc furnaces are commercially available options for specific applications. For many key industrial processes, however, direct electrification technologies today generally are still at early stages of development. Examples include direct electrification of heating in cement kilns, electric steam crackers and electric iron ore electrolysis, the technologies for which are all at the prototype stage (IEA, 2023e). In the NZE Scenario, innovation efforts related to these technologies accelerate over the coming five years, with installation of the first commercial-scale plants projected in the early 2030s.

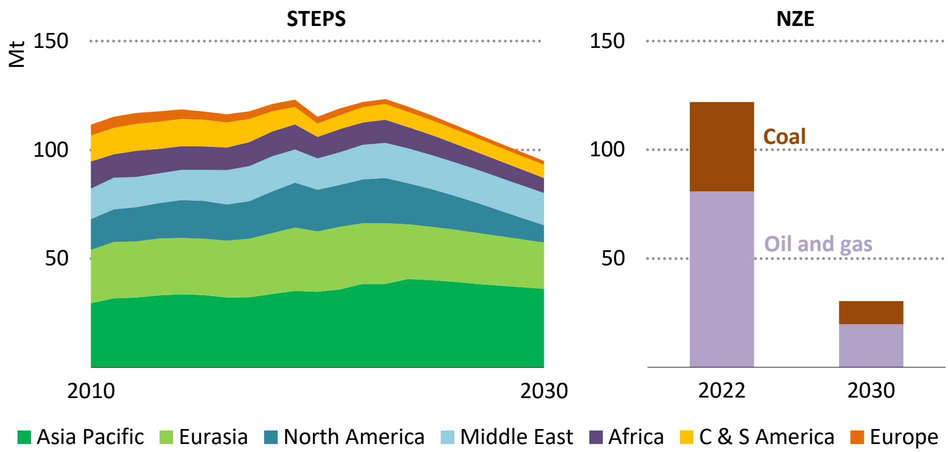
Energy performance standards and CO_2 pricing are the most common policy mechanisms currently employed to reduce industry sector emissions. These and similar measures can be instrumental to adjust the operational cost balance in favour of commercially available electrified equipment, notably industrial heat pumps. Various forms of policy support are needed to commercialise earlier stage technologies to electrify processes in heavy industries, such as grants for demonstration projects and concessional finance for initial deployment.

3.1.4 Reduce methane emissions

Rapid and sustained reductions in methane emissions are key to limit near-term global warming and to improve air quality. Methane emissions have an outsized impact on global temperatures in the short term, as methane is a short-lived climate forcer with powerful warming potential, albeit with a short atmospheric lifetime. Therefore, cutting methane emissions quickly would make a significant contribution to limiting the duration and magnitude of the temperature overshoot above 1.5 °C.

Methane is responsible for around 30% of the increase in global temperatures since the Industrial Revolution. After CO_2, cutting methane emissions has the single largest impact on limiting the temperature rise to 2050 in the NZE Scenario (IEA, 2023f). Around 150 countries have joined the Global Methane Pledge, which was launched at the Conference of the Parties 26 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, and it has the largest potential for abatement in the near term.

Figure 3.16 ▷ Methane emissions from fossil fuel operations by region in the STEPS and by fuel in the NZE Scenario



The gap in methane emissions between the STEPS and NZE Scenario reaches more than 60 Mt by 2030

Note: C & S America = Central and South America.

We estimate that fossil fuels were responsible for around 125 million tonnes (Mt) of methane emissions in 2022, a slight increase over 2021 (Figure 3.16). Coal, oil and natural gas were each responsible for around 40 Mt of emissions during production, processing, storage and transportation operations, and nearly 5 Mt of methane also leaked from end-use equipment. China accounts for over 50% of global coal supply and a similar share of coal mine methane emissions. The United States and Russia each emit nearly 14 Mt of methane emissions from oil and gas operations, or around 35% of the total from oil and gas operations between them. Many major emitters, such as China and Russia, have not yet pledged to act on methane.

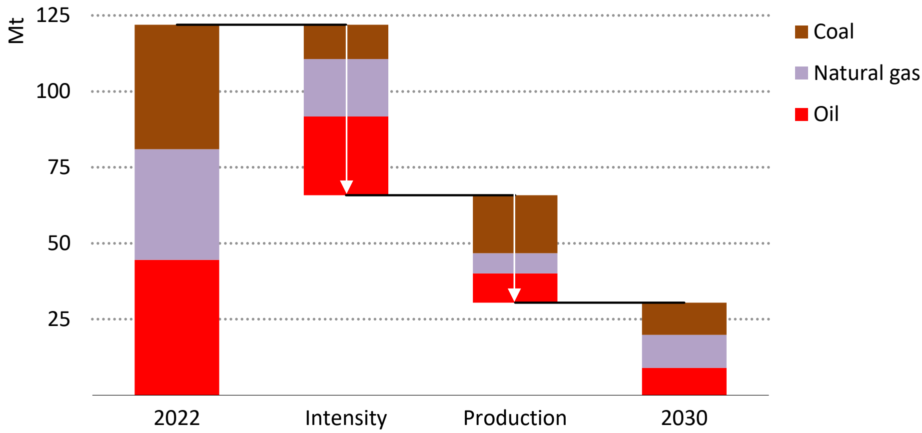
Methane emissions from fossil fuel operations fall by around 20% between 2022 and 2030 in the STEPS, mostly as a result of increasing political momentum to tackle these emissions and voluntary industry action. Efforts to curtail emissions are already leading to a reduction in the amount of methane that is emitted per unit of energy produced globally. Emissions from very large leaks detected by satellite fell by almost 10% in 2022 from the levels detected in 2021 and there was a nearly 5% reduction in natural gas flaring globally. We estimate that the global average methane intensity of oil and gas production has fallen by around 5% since 2019. But there is scope for much more to be done.

Several countries have released or are working on national methane action plans to support reductions. Many of them have recently published landmark policies on methane, including Colombia, Nigeria and the United States. Canada and the European Union are expected to issue new methane regulations in 2023. A number of oil and gas companies have set targets to limit emissions or reduce their emissions intensity. In 2022, the Oil and Gas Climate Initiative launched the Aiming for Zero Methane Emissions Initiative, a call for the industry to treat methane emissions as seriously as it already treats safety and to reach near zero methane emissions by 2030.

Methane emissions from fossil fuel operations fall by more than 75% by 2030 in the NZE Scenario, mainly as a result of the rapid deployment of emissions reduction measures and technologies (Figure 3.17). These include measures that put a stop to all non-emergency flaring and venting, and universal adoption of monthly or continuous leak detection and repair programmes. A fall in demand for fossil fuels also plays an important role, particularly in driving down coal mine methane emissions, though leaks from closed mines also need to be addressed. By 2030, all producers have an emissions intensity profile similar to that of the world's best operators today. By 2050, the drop in methane emissions from fossil fuels reaches 98% as a result of further technology development and demand reductions.

Methane abatement is very cost effective in the oil and gas sector. Based on average natural gas prices from 2017 to 2021, we estimate that around 40% of methane emissions from oil and gas operations could be avoided at no net cost because the outlays for the abatement measures are less than the market value of the additional gas that is captured. If the record natural gas prices seen around the world in 2022 are used for the calculations instead, we estimate that about 80% of the options to reduce emissions from oil and gas operations worldwide could be implemented at no net cost. In the NZE Scenario, around USD 75 billion in cumulative spending is required to 2030 to deploy all methane abatement measures in the oil and gas sector (IEA, 2023g). This is equivalent to just 2% of the net income received by the oil and gas industry in 2022. Even if there was no value to the captured gas, an emissions price of about USD 20/tonne CO_2-equivalent would make almost all available abatement measures cost effective.

Figure 3.17 ▷ Methane emissions from fossil fuel operations and reductions in the NZE Scenario, 2022-2030



By 2030, all fossil fuel producers have an emissions intensity profile similar to that of the world's best operators today

In the coal sector, wholesale methane reductions are generally more challenging than for oil and gas operations. Around two-thirds of the reductions in coal mine methane emissions in the NZE Scenario to 2030 come from a drop in coal consumption. Nonetheless, widespread deployment of abatement measures should still be a priority. More than half of methane emissions could be abated by making the most of coal mine methane utilisation, or by flaring or oxidation technologies when energy recovery is not viable. Mitigation action is particularly important for coking coal, mainly used in steel making, which tends to come from underground mines where abatement is more feasible.

Tackling emissions from fossil fuels is not the only opportunity to cut methane emissions from the energy sector. Achieving universal access to clean cooking and modern heating would cut the methane emissions that arise from the incomplete combustion of bioenergy as well as deliver numerous benefits for human health and well-being.

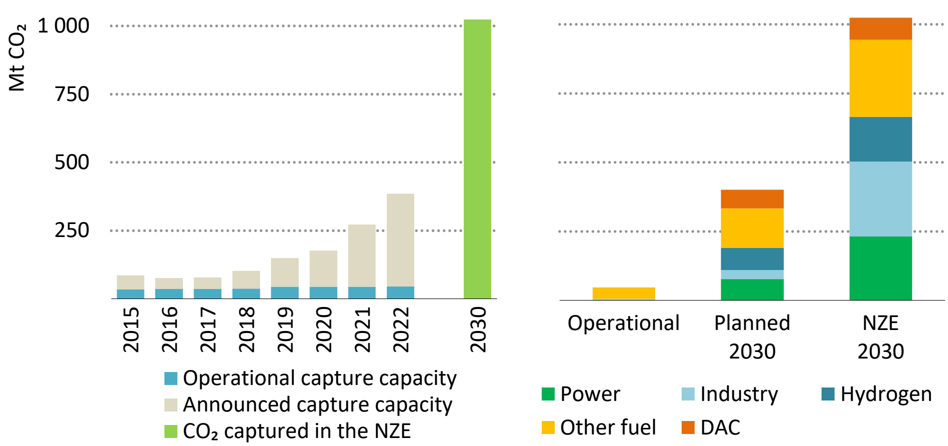
3.2 Accelerate long lead time options

3.2.1 Carbon capture, utilisation and storage

After years of underperformance, CCUS must now show it can deliver

CCUS is an important technology because it can reduce or eliminate emissions in areas where other options are limited, for example in the production of cement or synthetic kerosene and in the removal of CO_2 from the atmosphere. However, so far, the history of CCUS has largely been one of unmet expectations. Progress has been slow and deployment relatively flat for years. The current level of annual CO_2 capture of 45 Mt represents only 0.1% of total annual energy sector emissions. This lack of progress has led to progressive downward revisions in the role of CCUS in climate mitigation scenarios, including the 2023 NZE Scenario.

Figure 3.18 ▷ Global annual CO_2 capture capacity by status and sector in the NZE Scenario, 2015-2030



Planned CCUS projects, if brought to fruition, would increase capacity over eightfold, about one-third of needed requirements by 2030

Notes: Mt CO_2 = million tonnes of carbon dioxide; DAC = direct air capture. Includes all facilities with a capacity larger than 0.1 Mt CO_2 per year. Planned capacity for 2030 only includes projects with an announced operation date by 2030. Hydrogen includes low-emissions hydrogen production at dedicated facilities, including for use in ammonia manufacture. Captive low-emissions hydrogen production onsite at refineries and industrial plants are included in other fuel and industry categories.

Source: IEA CCUS Projects Database, (IEA, 2023h).

Since 2018, momentum on CCUS has increased on the back of stronger policies and improved market conditions. Today over 45 countries have CCUS projects in development. If all announced capture projects are built, around 400 Mt CO_2 could be captured every year globally by 2030 – more than eight-times current capacity. A number of capture projects are being developed for novel applications that are particularly important for reaching net zero emissions. Based on the current project pipeline, around 20% of capture capacity in 2030 would be for direct air capture (DAC), 20% for hydrogen production and 8% for industry (Figure 3.18). Planned capacities for CO_2 transport and storage have also increased. Based on the current project pipeline, CO_2 storage capacity could reach over 420 Mt CO_2 per year by 2030. However, only around 20 commercial capture projects under development had reached the stage of a final investment decision (FID) by June 2023; and even if all announced projects proceed, they would provide around 40% of the annual CO_2 capture of 1 Gt/year needed by 2030 in the NZE Scenario.

Learning from the past, planning for the future

CCUS appeared poised for a major expansion following the 2008-2009 global financial crisis, when more than USD 8.5 billion of public support was made available. Ultimately less than 30% of the funding was spent, and many CCUS projects could not advance fast enough to hit the near-term spending milestones required by the support programmes. Limited one-off capital grants, the absence of measures to address long-term liability for stored CO_2, high operating costs, limited social acceptability and vulnerability of funding programmes to external budget pressures all contributed to project cancellations. If CCUS is to make progress in line with the NZE Scenario, the industry needs to prove CCUS that can operate at scale. For their part, governments should develop effective support packages to help with operating as well as capital costs and find realistic ways of managing the long-term liabilities associated with CO_2 storage.

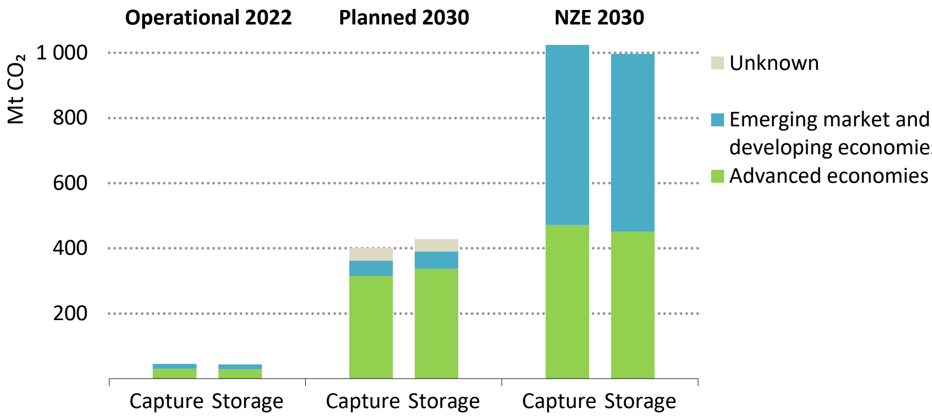
Achieving the 2030 level of global deployment of CCUS in the NZE Scenario also hinges on cutting project lead times, which currently average about six years.[2] Adoption of best practices could compress lead times to around three to four years, if CO_2 transport and storage infrastructure are already in place. Developing CCUS hubs could also help reduce lead times (Box 3.3). A lead time of four years for both capture and storage would mean that reaching 1 Gt CO_2/year of global capture capacity by 2030 in line with the NZE Scenario would require on average 160 Mt CO_2/year of capture capacity and 140 Mt CO_2/year of storage capacity to start the planning stage each year between 2023 and 2026. Project announcements in 2022 were just over this level for capture capacity and well above it for storage, which indicates that the level of global CO_2 capture and storage capacity required in the NZE Scenario by 2030 is not out of reach, provided that the necessary steps are taken to support it.

Unlocking CCUS deployment in emerging market and developing economies

There are few CCUS projects in development in emerging market and developing economies (Figure 3.19). This represents an important hurdle to achieve the NZE Scenario, given that emerging economies have large stocks of young emissions-intensive power plants and factories.

[2] Project lead time is defined here as the total time required between conception and commissioning of a facility.

Figure 3.19 ▹ CO_2 **capture and storage capacity by economic grouping in the NZE Scenario, 2022 and 2030**



Gap between the levels of planned CCUS deployment and what is needed by 2030 is the largest in emerging economies

Note: Planned capture and storage capacity include all facilities with a capacity larger than 0.1 Mt CO_2 per year as of June 2023, and projects with an announced operation date by 2030.

Source: IEA CCUS Projects Database (IEA, 2023h).

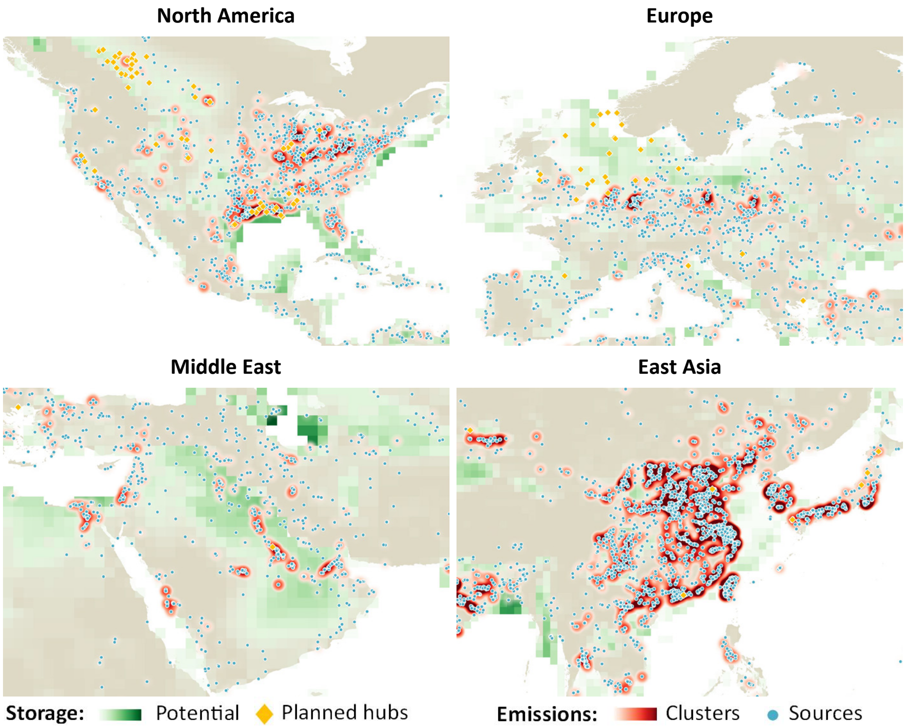
Some progress in CCUS has been made in emerging market and developing economies, e.g. around 20 new capture, transport or storage projects were announced in 2022 in Asia and the Middle East. China produces more than half the world's coal-fired power generation, steel and cement, but has less than 5% of the world's CCUS projects currently under development. China commissioned three projects in 2023 and has a project pipeline equivalent to a capture capacity potential of around 10 Mt CO_2/year. Indonesia finalised a legal and regulatory framework for CCUS in March 2023 – the first of its kind in Asia. The Middle East, the location of over 15% of global natural gas production, has unique opportunity to deploy CCUS for low-emissions fuel production, but currently accounts for less than 5% of global planned capture and storage capacity by 2030. Taken together, the announced projects would only meet a small fraction of what is needed by 2030 in the NZE Scenario.

Meeting NZE levels of CCUS deployment in emerging market and developing economies requires around 130 Mt CO_2/year of additional capture and storage capacity to start the planning stage annually from 2023 to 2026. Such a rate of deployment is ambitious given the current low number of projects in operation in those regions, but not unprecedented when compared to other sectors such as unabated cement production, coal power or oil and gas supply. Essential requirements for further progress include the development of legal and regulatory frameworks and the provision of incentives for the development of CCUS.

Box 3.3 ▷ Role of CCUS hubs to achieve net zero emissions

Most CCUS projects commissioned to date have been managed by a single operator to transport CO_2 from one capture facility to one injection site, which concentrates risks and costs on one developer. But CCUS projects are increasingly being developed as part of CCUS hubs, which consist of shared transport and storage infrastructure connecting multiple emitters, often as part of an industrial cluster. Today there are over 110 storage hubs in development, mainly in Europe and North America, with plans to sequester around 280 Mt CO_2 per year by 2030.

Figure 3.20 ▷ CO_2 emissions clusters and planned CCUS hubs in planning in North America, Europe, Middle East, and East Asia, 2022



Around 80% of global emissions from power plants, industrial facilities and refineries could benefit from shared infrastructure

Notes: Point sources and CO_2 emissions clusters include steel, cement, chemical, power generation and refining in facilities with total emissions larger than 0.1 Mt CO_2 per year. Sedimentary thickness (km) is used to indicate theoretical potential of CO_2 storage sites.

Sources: Analysis based on US EPA Office of Atmospheric Protection (2021); European Commission (2021); Kearns et al., (2017); S&P Global (2022); Global Energy Monitor, (2022); Global Cement, (2022).

The CCUS hub model spreads infrastructure costs between emitters and generates economies of scale, allowing smaller emitters and those located far from identified CO_2 storage sites to connect to shared infrastructure. Mainstreaming this model could help to reduce lead times, as new capture facilities could connect to an existing CCUS hub. In China, around 90% of emissions from steel, cement, power, chemicals facilities and refineries are within 30 km of large industrial clusters[3] which could benefit from shared infrastructure. In the United States the equivalent figure is around 70%, and around 60% in the Middle East and Europe.

3.2.2 Hydrogen and hydrogen-based fuels

Today hydrogen production is more of a climate problem than a climate solution. Demand for hydrogen is rising, reaching 95 Mt in 2022, but most of it is met by emissions-intensive supply, resulting in more than 0.9 Gt of direct CO_2 emissions in 2022. Production of low-emissions hydrogen from water electrolysis or from fossil fuels with high levels of CO_2 capture and storage amounted to less than 1 Mt in 2022 (IEA, 2023i).

There has been significant progress on policy and investment in low-emissions hydrogen since the 2021 version of the NZE Scenario (IEA, 2021b). Billions of dollars of support for project developers have been budgeted by governments in a wide range of countries, and the world's largest installed electrolyser facility is more than ten-times bigger than the largest one at the start of 2021. There is now enough confidence in the market to support several investment decisions of more than USD 0.5 billion for low-emissions hydrogen production projects. Included are three projects that together will produce ammonia from 0.2 Mt of hydrogen from electrolysis from 2026 (91% in Saudia Arabia, 8% in Oman and 1% in the United States). Despite the high expectations that have developed around hydrogen recently, more action is urgently needed from policy makers and industry to deliver the requirements of the NZE Scenario.

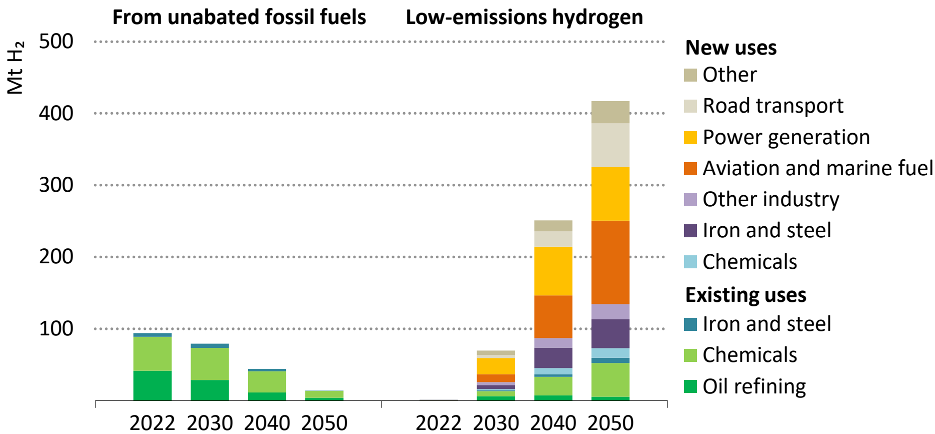
Creating demand for low-emissions hydrogen

In the absence of robust demand for low-emissions hydrogen, the current race to secure market share for equipment such as electrolysers will have no winners. The NZE Scenario sees demand scaled up first in existing applications where large quantities of low-emissions hydrogen can be integrated with minimal plant modifications and little need for new infrastructure. This builds on recent experience: to date, most of the world's largest financed projects for hydrogen production from electrolysis or with CCUS have been designed to serve existing demand, such as for fertiliser plants. But the level of demand for low-emissions hydrogen in existing applications is insufficient to reach the level called for by 2030 in the NZE Scenario (Figure 3.21). New sources of demand are needed. Recently, some developers have secured provisional agreements with prospective buyers, but announced plans for

[3] Emitting at least 5 Mt CO_2 per year.

production of low-emissions hydrogen indicate that there is a risk of supply capacity outstripping demand.

Figure 3.21 ▷ Global hydrogen demand in the NZE Scenario, 2022-2050



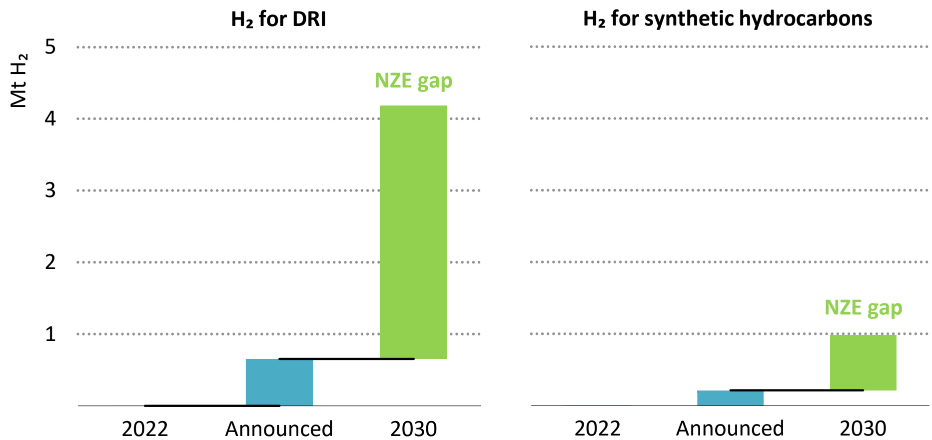
Use of low-emissions hydrogen rises significantly to 70 Mt by 2030 and extends to new applications such as in aviation and shipping

Notes: Mt H_2 = million tonnes of hydrogen. Unabated fossil fuels include hydrogen produced with CO_2 capture for utilisation without storage, such as in urea synthesis. Demand for aviation and marine fuel and power generation includes hydrogen that is converted to make low-emissions hydrogen-based fuels.

New applications represent more than four-fifths of low-emissions global hydrogen demand in 2030 in the NZE Scenario. These are at early stages of development or deployment today yet are targeted by the expanding pipeline of announced projects. The largest sources of demand, ranked by size, are power generation (including storage), low-emissions hydrogen-based transport fuels, and iron and steel production. While hydrogen and ammonia are used in just 1% of power generation in 2030, the sector represents a significant source of demand due to its sheer size and the high value of clean, storable and flexible fuel to occasionally balance the grid. In the longer term, increasing use of low-emissions hydrogen in aviation, shipping and to a lesser extent heavy trucks means that transport becomes the largest source of hydrogen demand, and industry overtakes power generation as the second-largest source of demand.

In the industry sector, iron and steel production represents one of the important sources of low-emissions hydrogen demand despite there being no such plants in operation today. In the NZE Scenario, hydrogen-based direct reduction of iron (DRI) – a means of processing iron ore without fossil fuels – leads to just over 4 Mt of low-emissions hydrogen demand by 2030. The attainability of this scale-up is supported by an increase in new project announcements for hydrogen-based DRI since 2021, when only one was in development. Some of these have been successful in securing provisional agreements with prospective buyers. Nonetheless, the 2030 level in the NZE Scenario is more than six times the implied demand of the current project pipeline (Figure 3.22).

Figure 3.22 ▷ Global low-emissions hydrogen demand from announced fuel and iron and steel projects in the NZE Scenario, 2022-2030



Announced projects that stimulate demand for low-emissions hydrogen are expanding rapidly, though they fall short of 2030 needs in the NZE Scenario

Notes: DRI = direct reduced iron. NZE gap = the difference between the sum of announced projects and deployment needs in 2030 of the NZE Scenario. Synthetic hydrocarbons include low-emissions hydrogen-based fuels that are drop-in replacements for oil products.

In aviation, synthetic kerosene derived from hydrogen and CO_2 has considerable potential as a drop-in fuel. From negligible quantities of production in 2022, this new application increases in the NZE Scenario to more than 2 billion litres per year in 2030 (still less than 1% of aviation demand). This creates 1 Mt of hydrogen demand. Announced demand commitments from the aviation industry to purchase volumes of this fuel fall far short of the levels projected in the scenario, in part due to the lack of installed capacity. Trial operation of the first synthetic kerosene plant is expected in 2023, with first commercial-scale plants due in 2025. The lead time to build a synthetic kerosene plant is two to four years. Nevertheless, it will be challenging to build up capacity, secure supplies of carbon neutral CO_2 and low-emissions hydrogen, and establish off-take commitments in line with the NZE Scenario.

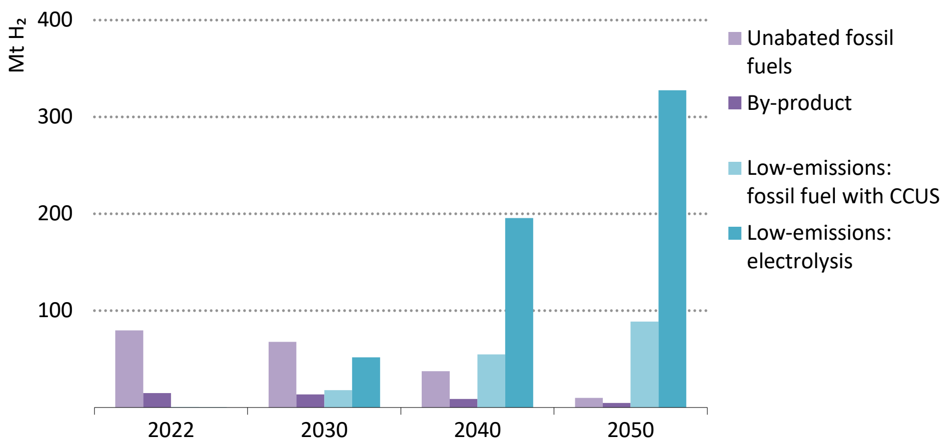
In shipping, the use of ammonia or methanol as fuel for maritime vessels requires engine modifications and fuel supply system development. While today there are no commercial ships operating on ammonia, engine manufacturers have successfully tested the technology, and around 150 ammonia-ready vessels were on order at the end of 2022. These ships present an opportunity to rapidly develop the associated safety protocols. In the

NZE Scenario, orders of ammonia-ready vessels increase from the 2022 level on average by about 20% per year to 2030, representing about 15% of typical annual vessel orders. Agreements between shipping operators and ammonia and methanol producers will be necessary to bring supply and demand into line and to enable the use of low-emissions hydrogen in shipping to rise as rapidly as envisaged in the NZE Scenario.

Scaling up production

Meeting projected demand for low-emissions hydrogen in the NZE Scenario entails a rapid change in how hydrogen is produced and a massive scaling up of production from the less than 1 Mt of low-emission hydrogen produced in 2022 (Figure 3.23). The current shortage of equipment manufacturing capacity, production capacity, infrastructure, end-user systems and market standards represent a series of obstacles to progress, as does the challenge of matching supply to demand during a period of rapid growth in production. There have been some notable steps forward since 2021, especially in relation to water electrolysis, but much remains to be done.

Figure 3.23 ▷ Global hydrogen supply by source in the NZE Scenario, 2022-2050



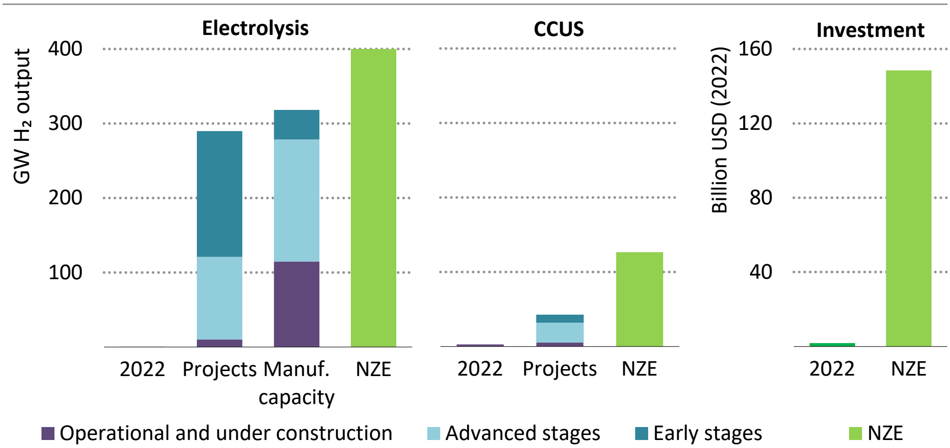
Low-emissions hydrogen production rises rapidly to reach 45% of total hydrogen supply by 2030

Note: Other sources of low-emissions hydrogen, including from biomass, amount to less than 1% of the total and are not shown here.

The pipeline of projects for the deployment of electrolysis capacity looks encouraging, though there is still a long way to go. If all announced projects come to fruition, more than 400 GW of electrolysis could be operational by 2030, which is around 70% of what is required in the NZE Scenario. However, more than half of the announced capacity corresponds to projects that are at very early stages of development and less than 4% are under construction or have reached FID. The availability of renewable electricity is one potential constraint that could hinder the rate at which projects start construction.

There have also been some encouraging signs in the outlook for manufacturing of the electrolysers on which the increase in electrolysis capacity depends (Figure 3.24). If all announcements from the private sector are realised on time, manufacturing capacity could reach 155 GW per year by 2030, with cumulative production by this date of more than 450 GW of electrolysers. However, only 8% of these announcements of electrolyser manufacturing capacity expansions have reached a FID and started construction. If permitting processes run smoothly, as assumed in the NZE Scenario, it takes two to three years to build a gigawatt-scale plant for manufacturing electrolysers and a further year or two to install the electrolysers, so a rapid increase in manufacturing capacity is not out of reach. Supportive government policies have been broadened to boost manufacturing capacity as well as low-emissions hydrogen demand and deployment, including the US Inflation Reduction Act, Europe's Important Projects of Common European Interest and the European Hydrogen Bank, and the UK Low-Carbon Hydrogen Business Model.

Figure 3.24 ⊳ Potential low-emissions hydrogen supply capacity from electrolyser and CCUS projects and investments in the NZE Scenario, 2022 and 2030



Announced projects for electrolysis deployment account for around 70% of the 2030 needs in the NZE Scenario, but less than 4% of them have reached a final investment decision

Notes: Projects in this figure represent the capacity of electrolysis and CCUS that could be installed by 2030 if all the announced projects to produce low-emissions hydrogen are realised on time. Manuf. Capacity represents the maximum capacity of electrolysis that could be installed by 2030 if all announcements to expand manufacturing capacity of electrolysers are realised on time. To facilitate comparison between electrolysis and CCUS-equipped capacity, values are shown in GW of installed capacity of hydrogen output, which for electrolysis is 31% lower in 2030 than the equivalent value based on electricity input.

There has also been some progress with low-emissions hydrogen production from natural gas with CCUS, but here again there is much further to go. The five plants that have started construction in North America since 2021 between them represent production capacity of 0.5 Mt each year, 70% from just two projects that are both incorporating over 90% CO_2 capture and are equivalent to more than all the electrolyser capacity currently in operation. However, slower progress in Europe, China and the Asia Pacific has led to a downward revision of the contribution of low-emissions hydrogen from fossil fuels with CCUS in the 2023 version of the NZE Scenario. It still calls for CCUS-equipped hydrogen projects representing an annual production capacity of 17 Mt to reach FID by around 2026 for operation by 2030, which requires an increase in the size of the current pipeline as well as faster progress of projects through to FID.

The use of hydrogen envisaged in the NZE Scenario depends on investment in the production, transmission and distribution of low-emissions hydrogen and hydrogen-based fuels. This currently stands at around USD 1 billion per year and needs to increase to USD 150 billion by 2030 to meet NZE levels, plus at least USD 100 billion in dedicated renewable electricity capacity. Delivering this increase depends on getting the regulatory framework right and on creating as much certainty as possible about future demand growth. Stimulating investment in low-emissions hydrogen in emerging market and developing economies is likely to be especially challenging. This group accounts for around one-quarter of announced projects, but the majority of their projects are at very early stages of development and are struggling to access finance. Multilateral development banks have started to provide funding for hydrogen projects, with programmes worth around USD 4 billion announced in 2023, but this still accounts for just 3% of the investment needed by 2030 in the NZE Scenario (IEA, 2023j). More will need to be done if emerging market and developing economies (excluding China) are to account for around 40% of cumulative investment in low-emissions hydrogen between now and 2050, as envisaged in the NZE Scenario.

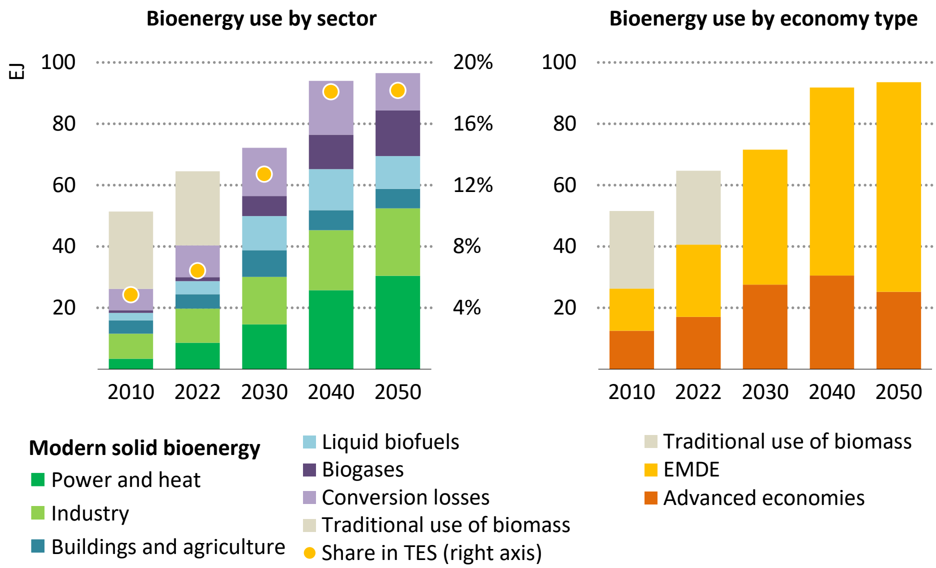
3.2.3 Bioenergy

Role of modern bioenergy

Modern bioenergy is one of the pillars of the clean energy transition, growing from 6% of total energy supply today to 13% in 2030 and 18% in 2050 in the NZE Scenario. All of the increase comes from sustainable sources, which minimises impacts on biodiversity, water resources and soil health, and helps to safeguard energy access and affordable prices for agricultural outputs. One of the main advantages is that bioenergy is compatible with existing infrastructure. Biomethane for instance is compatible with natural gas infrastructure, while solid bioenergy can be used in industries such as cement and power generation with relatively few modifications. In addition, the raw materials used to make bioenergy, such as agricultural and forestry residues, are broadly distributed across the world.

Most of the growth in modern bioenergy use in the NZE Scenario comes from the emerging market and developing economies, where it almost doubles by 2030, growing at a rate that is around one-third faster than in advanced economies (Figure 3.25). The main driver is the growth in liquid biofuel production, mostly consumed by the transport sector in developing economies but also exported to advanced economies. Another key driver is the phase-out of the traditional use of biomass in inefficient open cookstoves, which are replaced with modern energy alternatives, including bioenergy used in more efficient cookstoves. The rich biomass resource potential in emerging economies also helps drive growth in modern bioenergy uses in industry and the electricity sector. While bioenergy is used in a number of sectors, it plays a particularly important role in the transport sector, where its share of demand for liquid fuel transport increases from almost 4% today to over 10% by 2030. This is driven primarily by demand in passenger cars, heavy-duty trucking, long-haul aviation and international shipping.

Figure 3.25 ⊳ Primary bioenergy use by sector and economic grouping in the NZE Scenario, 2010-2050



Modern bioenergy use in emerging market and developing economies almost doubles to 2030, rising 30% faster than in advanced economies

Note: TES = total energy supply.

Ensuring a sustainable supply of bioenergy

The expansion of modern bioenergy involves trade-offs between bioenergy supply, sustainable development goals and other land uses, notably food and feed production. The maximum level of bioenergy used in the NZE Scenario (100 EJ) takes these trade-offs into consideration and is based on assessments of the global sustainable bioenergy potential (Creutzig, 2015; Frank, 2021; IPCC, 2014; IPCC, 2019; Wu, 2019).

There is a shift in the NZE Scenario from conventional feedstocks towards advanced bioenergy feedstocks to avoid land-use conflicts. Advanced feedstocks from waste and residues such as agricultural residues, forest and wood residues and the organic fraction of municipal solid waste do not require dedicated land use. From 2030 onwards, a growing reliance on advanced feedstocks means that over half of the total biomass feedstock supply comes from sources with no dedicated land use.

The remaining feedstocks – for both conventional and advanced bioenergy – do require dedicated land use, but can still be produced in a sustainable way. Modelling done in collaboration with the International Institute for Applied Systems Analysis[4] indicates that the requirement for bioenergy crops in the NZE Scenario could be met without encroaching on forested land, and that by 2050 there is no overall increase in cropland[5] use for bioenergy production from current levels. Total land use for bioenergy in the NZE Scenario is well below estimated ranges of potential land availability that take full account of sustainability constraints, including the need to protect biodiversity hotspots and to meet the UN Sustainable Development Goal 15 on biodiversity and land use. The certification of bioenergy products and strict control of what land can be converted to expand forestry plantations and woody energy crops nevertheless is critical to avoid land-use conflict issues.

Short-rotation woody energy crops provide a steadily growing share of bioenergy supply in the NZE Scenario, providing just under 40 EJ of bioenergy in 2050: these crops are cultivated on cropland previously used for conventional biofuels, pastureland and marginal lands and can produce twice as much bioenergy per hectare as many conventional bioenergy crops. The remaining modern bioenergy comes from sustainably managed forest plantations and sustainable tree planting integrated with agricultural production via agroforestry systems: these do not conflict with food production or biodiversity.

How quickly can the use of biofuels expand?

The prospects for demand for liquid biofuels depend largely on policy mandates. Most biofuels can be blended at high rates with relatively few modifications. In the case of renewables diesel, no blending is required as it can be used interchangeably with conventional, oil-based diesel. However, in most countries, blending rates are low, due to the high cost of liquid biofuels and limited policy support. More than 80% of biofuels are currently used in the United States, Brazil, Europe and Indonesia, where a mix of regulations, financial incentives and technical standards have supported their expansion. However, the supportive policy frameworks in these regions need to be strengthened to help expand demand, which more nearly triples by 2030 in the NZE Scenario. They also need to be replicated elsewhere, especially in emerging market and developing economies where

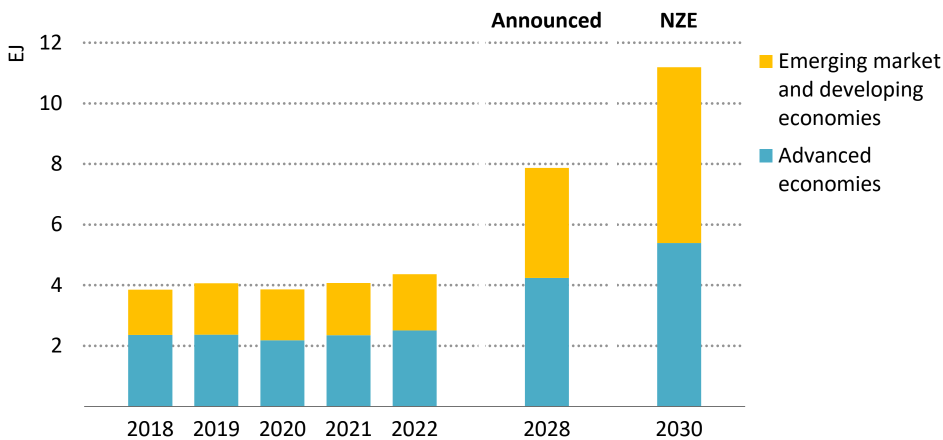
[4] IEA model results have been coupled with the International Institute for Applied Systems Analysis (IIASA) Global Biosphere Management Model (GLOBIOM) to provide data on land use and the greenhouse gas emissions from bioenergy production.

[5] Cropland here refers to agricultural land used for food, animal feed and bioenergy production but excludes short-rotation woody crops not established on existing agricultural cropland.

biofuel demand rapidly increases in the NZE Scenario**.** The volumetric share of ethanol in gasoline jumped in India from 4% in 2019 to more than 10% in 2022, which provides an example of what can be done.

Global liquid biofuel production is not currently on track to deliver what is required by 2030 in the NZE Scenario, based on current market trends and policies. Output has increased on average by 4% per year over the last five years, but it needs to increase by an average of 13% per year to reach the 11 EJ projected for 2030 in the NZE Scenario (Figure 3.26). Biomass-based diesel, for instance, has expanded at an average of 9% worldwide for the past five years. Existing and announced projects would cover half of the increase in demand, assuming they all go ahead, but new facilities take only around two to three years to build, which means that there is still time for additional projects to fill the gap.

Figure 3.26 ▷ Liquid biofuel production by economic grouping in the NZE Scenario, 2018-2030



Liquid biofuel output in both economic groupings more than doubles by 2030 of which the existing project pipeline could cover 50%

A key barrier to raising liquid biofuel output is the limited availability of sustainable feedstocks. The total potential resource base of all kinds of sustainable bioenergy (solid, liquid and gaseous) is estimated at around 100 EJ, of which only 10 EJ (including conversion losses) is currently used to make biofuels. However, the pace and scale of expansion in the NZE Scenario is contingent on producing biofuels from a broader set of feedstocks than those used today. In 2030, 40% of production is based on what are known as advanced feedstocks, i.e. materials that do not compete with food and feed production. These advanced feedstocks include crops grown on marginal land, agricultural and forestry residues and residue oils, fats and grease. By 2050, their share of total production reaches 75%. Advanced feedstocks today support 12% of biofuel production and come primarily from residue oils, fats and grease such as used cooking oil. But the existing project pipeline would use more than 90% of the estimated supply of these residues. Achieving the increases in supply projected in the NZE Scenario therefore requires higher reliance on other kinds of advanced feedstocks, in particular agricultural and forestry residues.

Box 3.4 ▹ Expanding access to feedstocks is key to increasing biofuels

Biofuel producers and governments have an opportunity to expand the feedstock base used to make liquid biofuels. This requires a focus on five broad areas:

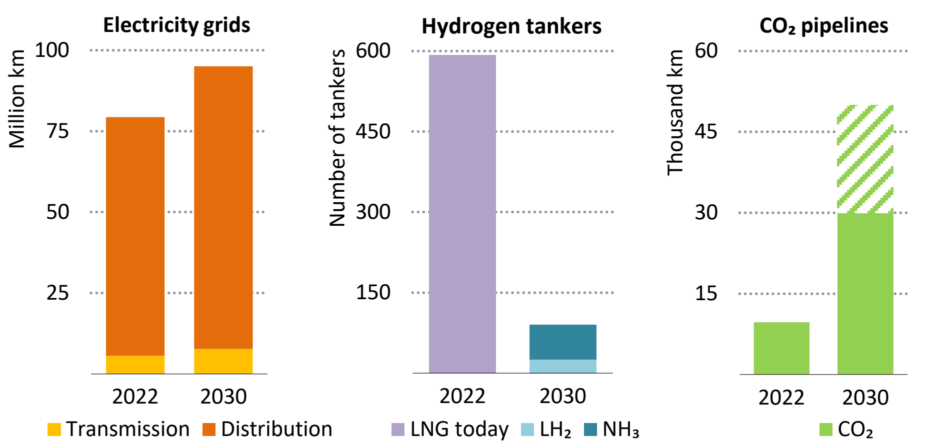
- **Enhance land productivity**: Intercropping, cover crops, growing crops on marginal land and improving crop yields all hold potential to expand supply of feedstock. For instance, woody short-rotation coppice can produce twice as much bioenergy per hectare as conventional bioenergy crops. Over the past two years, seven major energy companies, including ExxonMobil, Eni, Chevron Corporation and BP have announced projects and partnerships to develop these feedstocks.
- **Improve waste and residue collection:** An estimated 20 Mt of residue oils, fats and grease are generated each year that are compatible with commercial biodiesel and renewable diesel production technologies, and which could be directed towards biofuel production. Companies are already working to gather these wastes. Additional efforts are also needed to access woody residues from agriculture and forestry. Collection can be facilitated by building facilities close to sources of supply, as companies are doing at some sugar mills in Brazil and India, and at some forestry plantations in the United States. Improved data, co-ordination and business models can help with efforts to collect dispersed residue feedstocks.
- **Deploy technologies that can process various feedstocks:** Global efforts are needed to commercialise and expand technologies that can convert the feedstocks to biofuels at scale. Some efforts are underway. For example, Brazil and India are building seven cellulosic ethanol projects that use agricultural residues to create ethanol, while a plant that converts forestry residues into biojet kerosene is being built in the United States.
- **Reduce the life cycle emissions intensity of biofuels:** CCUS, facility improvements, and taking account of the life cycle carbon intensities of various feedstocks (including carbon sequestered in soil) all offer pathways to reduce greenhouse gas emissions from every litre of biofuels produced. For instance, in the United States CO_2 transport pipelines are planned that would connect around 30 ethanol facilities with CO_2 storage.
- **Develop and implement performance-based sustainability frameworks:** Efforts to expand feedstock supplies need to be accompanied by performance-based sustainability frameworks which include carbon assessment methodologies. The development of such frameworks will play a critical role to ensure that efforts to expand biofuels are both effective and sustainable.

3.2.4 Infrastructure

Rapid expansion of existing infrastructure plus development of new infrastructure for emerging technologies are both required

Electricity networks – the backbone of power systems – are central to clean energy transitions. Increasing population, rising incomes and electrification of more and more end-uses that previously used fossil fuels combine to considerably push up demand for electricity. Rapid growth in the share of electricity generated by variable renewables, in particular solar PV and wind, bring new challenges to ensure power system flexibility and stability. Significant electricity grid changes are needed, particularly as storing electricity is challenging and costly. New transmission and distribution lines will have to be built. In 2022, the length of electric transmission and distribution lines worldwide totalled around 80 million km. This needs to expand 20% by 2030 in the NZE Scenario (Figure 3.27). Digitalization, smart systems and advanced semiconductor technologies each play a crucial role to ensure and improve control and stability of power flows, and will have to be factored into plans for new lines as well as to be integrated into existing grids. Grids also play a pivotal role in enhancing the flexibility of the power system, enabling the integration of variable renewable and distributed energy resources (see section 3.1.1). Energy transitions could be stifled if the current pace of grid development does not accelerate, slowing the uptake of renewables, raising fossil fuel use and associated CO_2 emissions (IEA, forthcoming).

Figure 3.27 ▹ Global infrastructure needs for electricity, hydrogen and CO_2 storage in the NZE Scenario, 2022 and 2030



Infrastructure to transport and store electricity, hydrogen and CO_2 is an often overlooked but critical enabler of clean energy transitions

Notes: LNG = liquefied natural gas; LH_2 = liquefied hydrogen; NH_3 = ammonia. The hatched area for CO_2 pipelines represents the NZE Scenario range of 30 000-50 000 km.

Today hydrogen is mostly produced close to where it is used. As demand increases in the NZE Scenario, it is likely to become cheaper to produce some low-emissions hydrogen in areas with good renewable energy resources and transport it to demand centres. Pipelines can transport large volumes of hydrogen efficiently over hundreds of kilometres, and these could include repurposed natural gas pipelines. For longer distances, hydrogen may need to be converted into a denser form, either through liquefaction (LH_2) or conversion into a chemical carrier that can be easily shipped, e.g., ammonia, methanol, synthetic fuels or a liquid organic hydrogen carrier. Increasing demand for low-emissions hydrogen means that more than 20 000 km of pipelines are needed by 2030 in the NZE Scenario, compared with 5 000 km today, together with around 25 LH_2 tankers (160 000 m^3), up from zero today, and around 70 new ammonia tankers, up from the current 40 tankers that carry ammonia year round.

CCUS deployment is hindered by a lack of available CO_2 storage sites. Assessing and developing potential sites, including saline aquifers and depleted oil and gas fields, is often a time-intensive and expensive process, but it is vital: without appropriate storage sites it will be much harder to develop other parts of the value chain, including CO_2 pipelines. CO_2 storage capacity expands in the NZE Scenario from less than 50 Mt today to around 1 Gt by 2030 – a more than a 20-fold increase – while CO_2 pipeline infrastructure expands from around 9 500 km today to between 30 000-50 000 km by 2030.

How feasible is the ramp-up of infrastructure to 2030 in the NZE Scenario?

The rapid ramping up of infrastructure requirements envisioned in the NZE Scenario is technically feasible, but nonetheless represents an enormous undertaking.

Electricity grids are already accelerating. Over the past five years, the transmission and distribution grids worldwide expanded by 1.9 million km each year – a rate of increase about 9% higher than experienced in the 2013-2017 period. The pace picks up in the NZE Scenario as grids expand by around 2 million km each year to 2030 (Figure 3.28).

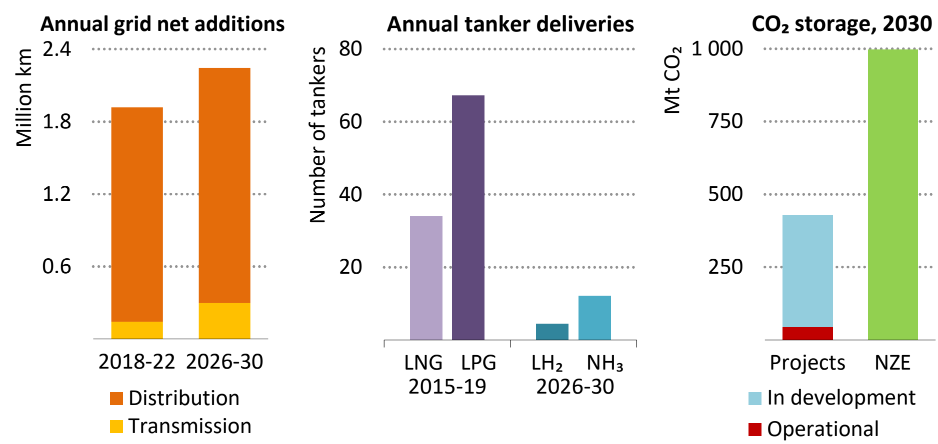
The deployment of transport and storage infrastructure for hydrogen and CCUS depends on a number of factors, including how quickly technologies that are still at the demonstration stage can achieve commercialisation, e.g. LH_2 shipping, ammonia cracking, as well as development of regulatory frameworks, permitting rules and public acceptance. If lead times for hydrogen and CCUS infrastructure projects are roughly on a par with those for previous natural gas infrastructure projects, infrastructure development may hinder the production and demand projects to which they are linked. Repurposing existing oil and gas assets, including natural gas networks, shipping terminals and offshore platforms, could help to fast track the deployment of hydrogen and CO_2 infrastructure, reduce lead times and investment costs.

In the case of hydrogen, the fertiliser industry already ships ammonia in tankers designed to carry liquefied petroleum gas (LPG), but dedicated LH_2 tankers are not yet commercially available, and some innovation will be required to overcome the additional challenges of the lower boiling point of hydrogen compared with natural gas, and the use of hydrogen boil-off as fuel. The projected pace of global expansion in LH_2 and ammonia shipping in the

NZE Scenario is similar (in energy terms) to the speed of LNG expansion during its first decade of development. How quickly LH_2 tankers can be deployed is uncertain, as the technology is not mature, but the NZE Scenario only calls for around 4 LH_2 tankers by 2030, around a tenth the number of LNG tanker deliveries in a given year with a similar size in volumetric terms.

In the case of CCUS, there are ample potential global CO_2 storage resources, but further resource assessment is required to develop sites. Based on current project pipelines, CO_2 storage capacity could reach more than 420 Mt CO_2 per year by 2030, around 40% of what is required in the NZE Scenario. CO_2 pipelines currently under development would provide around 30-50% of what is needed in the NZE Scenario, with around 15 000 km under development worldwide. This could increase as projects move forward since not all announced projects have specified pipeline lengths yet.

Figure 3.28 ▻ Annual global deployment of additional electricity lines, hydrogen tankers and CO_2 storage in the NZE Scenario compared with historic trends

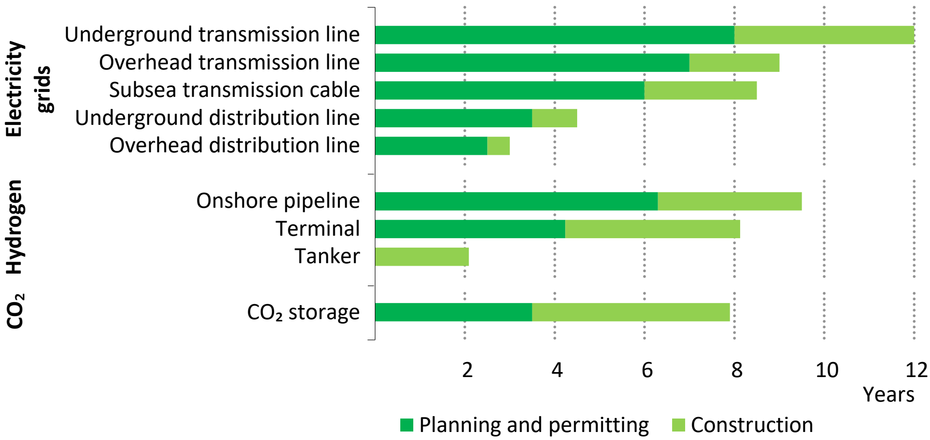


Grid additions to 2030 are close to historic rates; roll-out of liquefied hydrogen tankers and CO_2 storage relies on emerging technologies and available resources

Notes: LNG = liquefied natural gas; LPG = liquefied petroleum gas; LH_2 = liquefied hydrogen; NH_3 = ammonia; NZE = Net Zero Scenario. CO_2 storage project capacity in 2030 includes projects currently in operation plus those in development.

The planning and permitting processes for major new clean energy infrastructure typically take three to eight years to complete before construction can start and could be longer for first-of-a-kind projects (Figure 3.29). In the case of electricity lines and pipelines, line route plans may need to be assessed by a multitude of regulatory authorities, jurisdictions and other stakeholders. When involving new types of infrastructure, such as storage sites for CO_2, it is not always clear which regulator should be in charge of the permitting process. As large infrastructure projects often cross or impact multiple landowners, early and frequent stakeholder engagement and an appropriate communication strategy are required to minimise potential increases in lead times due to public opposition. As highlighted in the IEA Special Report on Grids (forthcoming), there is evidence of permitting bottlenecks forcing the delay of some large electric transmission line projects. However, there are some signs of recognition of the urgent need to expedite permitting of clean energy infrastructure.

Figure 3.29 ▷ Typical lead times for selected infrastructure projects



On average, construction takes between one to four years, while planning and permitting may take three to eight years and can create bottlenecks and cause delays

Notes: Electricity grid lead times are based on average lead times in Europe and United States. Transmission refers to extra-high voltage, ranging from 200-765 kV. Hydrogen terminal lead times are based on average lead times for LNG terminals in Europe and Asia. Hydrogen tanker lead times are based on lead times for an LNG tanker.

3.3 Consequences of further delays for the clean energy transition

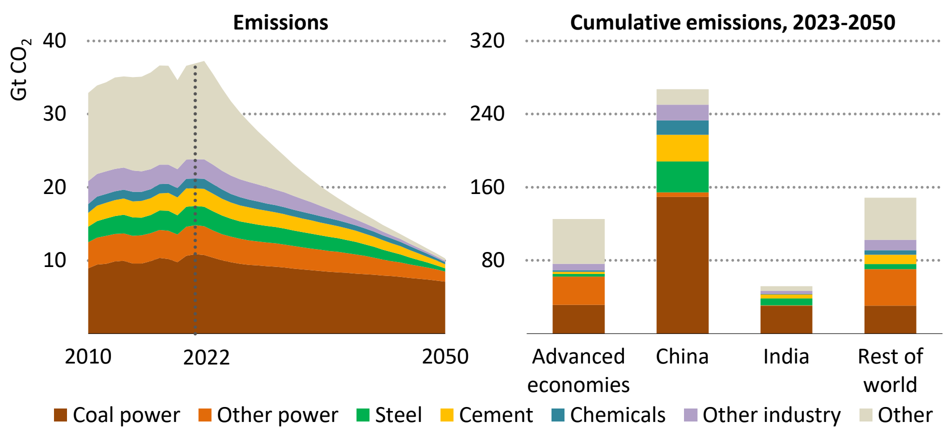
Failure to accelerate the clean energy transition along the lines of the pathway depicted in the NZE Scenario would virtually guarantee a high overshoot of the 1.5 °C limit,[6] with serious consequences for humans, ecosystems and climate tipping points. In such circumstances, returning the global average temperature rise to below 1.5 °C by 2100 would require a large and costly deployment of CO_2 removal technologies and would not avoid the need to reduce fossil demand substantially in this decade. Raising climate ambitions and ensuring effective implementation must remain critical priorities.

[6] High overshoot refers to an increase in global average temperature above 1.6 °C but below 1.8 °C above pre-industrial levels and a subsequent fall to below 1.5 °C. (IPCC, 2023).

3.3.1 The world has already delayed too long to avoid hard choices

The NZE Scenario can only be achieved with substantial changes to operating patterns and the early closure of some existing fossil fuel-based infrastructure. If current energy sector assets were to be operated until the end of their normal technical and economic lifetimes, and in the same manner in which they have been operated, they would generate further cumulative emissions of around 600 Gt CO_2 over the period 2023 to 2050 (Figure 3.30). This is far more than the estimated remaining CO_2 budget to remain below 1.5 °C. This has implications for China given that it accounts for 45% (270 Gt CO_2) of the emissions from existing assets over this period, primarily owing to its large fleet of relatively young coal-fired power plants and the size of its industrial base, which has the capacity to produce more than half the global demand for crude steel and cement. It also has implications for those countries, including India among others, that have significant additional emissions-intensive capacity under construction or planned to come online in the next few years. But it is also an issue that all countries worldwide will need to confront if they intend collectively to get to global net zero emissions by 2050. On the supply side, the rate of reduction in oil and gas demand necessary to reach net zero emissions by 2050 is now so fast that it may imply the early closure of some existing oil and gas fields.

Figure 3.30 ▷ Global energy sector CO_2 emissions from existing assets by sub-sector and region assuming no early retirements or modifications



Absent early retirement or modifications in operations, existing assets would emit 600 Gt CO_2 in the 2023-2050 period, dashing any hope of staying below 1.5 °C

Note: AE = advanced economies.

Further delaying the hard choices necessary to reach global net zero emissions by 2050 would make the problems substantially worse, and much harder to solve. Between 2023 and

2035, cumulative investments in fossil fuel supply, fossil-based power generation and end-uses are currently planned to be USD 3.6 trillion higher than in the NZE Scenario, despite current net zero emissions pledges. Much of this investment would be for assets with long lives in which operations would need to be curtailed or lifetimes shortened if the goal of returning the temperature increase to below 1.5 °C is to be achieved.

3.3.2 Implications of not raising climate ambitions to 2030

The net zero emissions pledges that have been announced by countries around the world – even if they are all implemented in full and on time – would make it impossible to limit global warming to 1.5 °C without high overshoot (see Chapter 1). This raises the question of whether global warming could be brought back to below 1.5 °C after a high overshoot, and if so, at what cost. In order to explore this question, the IEA developed the Delayed Action Case. It assumes that all countries that have announced net zero emissions pledges implement policies in the period to 2030 that enable achievement of their pledges. This is in line with the IEA Announced Pledges Scenario (APS). In fact, the policies that have been put in place are not sufficient to achieve the APS, and moreover we cannot be sure that all the policies that have been put in place will be maintained and fully implemented. Therefore, the starting point of the Delayed Action Case is more optimistic than current policy settings and Nationally Determined Contributions. The findings discussed in this section in terms of the challenges of bringing global warming back below 1.5 °C need to be seen in that context.

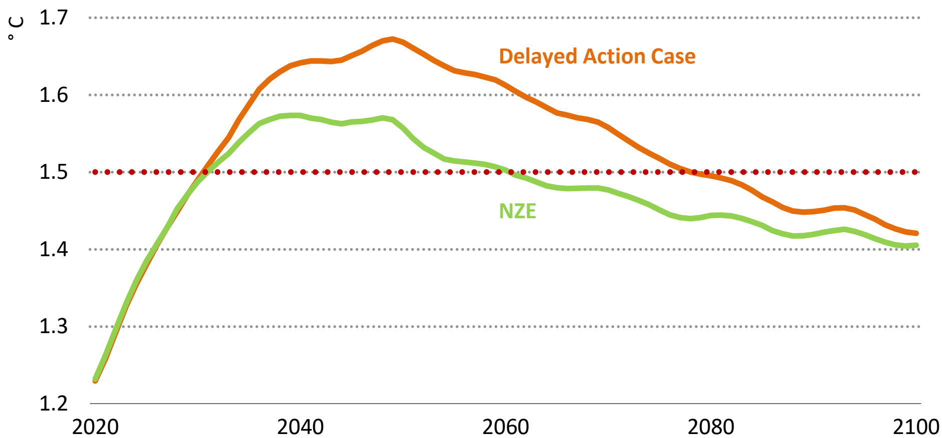
In the Delayed Action Case, countries are assumed to undertake actions that go beyond what is currently factored into the APS and accelerate their implementation of more ambitious climate policies after 2030, particularly where they have significant technological and financial capacities. This reduces global energy sector CO_2 emissions by just over one-third by 2035, relative to the 2022 level. This compares with the nearly two-thirds reduction projected in the NZE Scenario over the same period. Although policies become increasingly stringent over time, the delayed and uneven actions across sectors and regions mean that energy sector CO_2 emissions reach net zero only by the middle of the 2060s. As a result, the global temperature rise climbs to a peak close to 1.7 °C around 2050. After this time, the temperature falls by about 0.05 °C per decade due to net CO_2 removals from BECCS and DACS, cuts to methane emissions in the previous decades, and a reduction in atmospheric CO_2 due to natural processes (see Chapter 2). This brings warming to below 1.5 °C by 2100 (Figure 3.31).

The rise in temperature in the Delayed Action Case exceeds 1.6 °C for about 25 years and 1.5 °C for almost 50 years, which has a number of potentially serious consequences for vulnerable populations, ecosystems and climate tipping points. According to the Intergovernmental Panel on Climate Change (IPCC), if a temporary overshoot of the 1.5 °C threshold occurs, then there is high confidence[7] that "…many human and natural systems will face additional severe risks, compared to remaining below 1.5 °C". These risks are mainly

[7] High confidence = 80% chance.

associated with irreversible changes to ecosystems and with the release of additional greenhouse gases (IPCC, 2023).

Figure 3.31 ▷ Median global temperature rise in the Delayed Action Case and the NZE Scenario



IEA. CC BY 4.0.

Even a small delay in stronger action to cut emissions beyond current pledges would cause global temperature to exceed 1.5 °C for almost 50 years

Source: IEA analysis based on outputs of MAGICC 7.5.3.

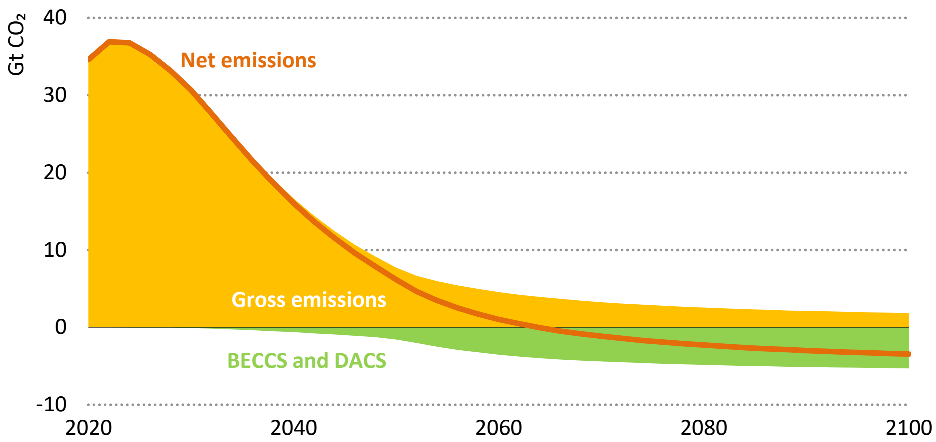
Threats to ecosystems and biodiversity are likely to persist for many decades after temperatures start to decline. In more than one-quarter of global locations the chances that animal and plant species can return to pre-overshoot "normal" are either uncertain or non-existent (Meyer et al., 2022).

Additional global warming comes with heightened risks of triggering tipping points in the earth system, i.e., large scale, irreversible events such as the melting of ice sheets or the abrupt dieback of the Amazon rainforest (Wunderling et al, 2022). The risks of positive feedback loops in the climate system, combined with inherent uncertainties in the earth's response to future greenhouse gas emissions and net CO_2 removals, mean that there is a one-third chance of the temperature rise exceeding 1.8 °C in the Delayed Action Case.

3.3.3 What would it take to bring temperatures back below 1.5 °C?

In the Delayed Action Case, bringing the global increase in average temperatures back down to below 1.5 °C would require scaling up CO_2 removal from the atmosphere through bioenergy equipped with CCUS (BECCS) and direct air capture and storage (DACS) to over 5 Gt CO_2 every year during the second-half of this century (Figure 3.32). This is equivalent to the annual energy sector emissions of the United States today and compares with projected removals which reach 1.7 Gt in 2050 in the NZE Scenario. The Delayed Action Case assumes that this requirement is split between BECCS, which delivers 2 Gt a year in 2100, and DACS, which delivers 3.3 Gt a year in 2100.

Figure 3.32 ▷ Global gross and net energy sector CO_2 emissions in the Delayed Action Case



Delaying the achievement of net zero emissions to after 2060 would mean that up to 5 Gt per year of CO_2 removals would be needed to bring temperatures to below 1.5 °C

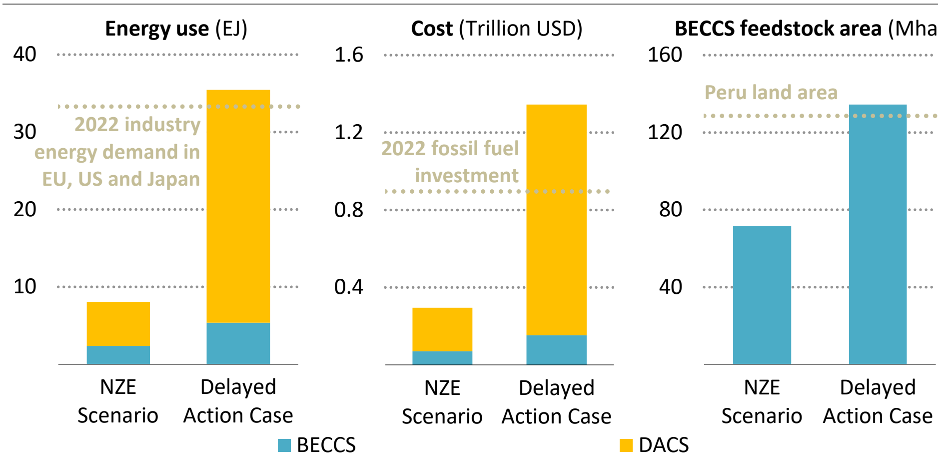
The 2 Gt CO_2 removal each year through BECCS required in the Delayed Action Case is twice the amount required in the NZE Scenario. The extent to which BECCS can be increased is constrained by limits on sustainable bioenergy supply as well as by the economic and logistical challenges of deploying infrastructure to connect bioenergy facilities, often very dispersed, with large-scale CO_2 storage sites. Capturing 2 Gt CO_2 per year from bioenergy facilities would require gathering, processing, combusting, capturing, transporting and storing the emissions from bioenergy produced on roughly 135 million hectares (Mha)[8] of land – slightly less than the total land area of Peru, the 20th largest country in the world (Figure 3.33). As sustainable bioenergy feedstock is spread thinly and widely, so are bioenergy facilities, and connecting them with CO_2 transport infrastructure and suitable storage sites would be a huge challenge in logistical terms.

While the deployment of DACS is not restricted by the availability of feedstock or suitable sites, it is much more energy intensive and costly than BECCS. This is mostly due to the low concentration of CO_2 in the atmosphere, which requires huge volumes of air to be treated

[8] Estimated by applying the share of bioenergy feedstock used in facilities equipped with CCS to total bioenergy land use. Land use for bioenergy includes cropland for first- and second-generation energy crops, and sustainably managed forest land for bioenergy estimated on a pro rata basis (i.e., the proportion of feedstocks used for bioenergy production out of total forest harvest).

for CO_2 separation. Capturing around 3.3 Gt CO_2 directly from the atmosphere as required in the Delayed Action Case by 2100 would require filtering 0.1% of the earth's atmosphere every year. At this scale, DACS would consume around 30 EJ of energy annually, just below than current total energy consumption in the industry sector in the European Union, Japan and United States combined. If the energy required for the deployment of DACS was provided by solar PV, this would require around 4.5 Mha of land for solar PV and DACS facilities, which is roughly equivalent to the land area of Denmark. While this is orders of magnitude lower than the land and water footprints typically associated with bioenergy production, it would put further strains on an already resource-constrained energy system.

Figure 3.33 ▹ Global annual energy use, annual carbon removal costs and land requirements for carbon removal technologies in the Delayed Action Case, 2100



Heavier reliance on Carbon Dioxide Removal in the Delayed Action Case would have huge implications for energy use, economic costs and resource use

Notes: EJ = exajoules; Mha = million hectares; EU = European Union; US = United States; BECCS = bioenergy equipped with CCUS; DACS = direct air capture and storage. Energy and costs for BECCS are for the carbon capture unit only. Cost corresponds to the levelized cost of carbon capture. BECCS feedstock area refers to the land area from which BECCS feedstock must be collected. The Delayed Action Case assumes that total sustainable bioenergy limit does not increase from the NZE Scenario (100 EJ), but the share of bioenergy combined with CCUS increases.

There is also the question of cost to consider. Removing 2 Gt with BECCS and 3.3 Gt with DACS each year by the end of the century would cost around USD 1.3 trillion per year (in 2022 dollars), 50% more than was invested in fossil fuel supply in 2022. Organising this scale of resource mobilisation would be a major challenge requiring close international co-operation.

SPOTLIGHT

Status of direct air capture and storage technology

Direct air capture and storage is a promising technology for net zero emissions pathways, but it cannot substitute for deep reductions in emissions or delays in developing and deploying the technologies that can reduce or avoid emissions in the first place. The industrial, infrastructure and cost challenges of scaling up direct air capture and storage to the degree in the Delayed Action Case highlight the need to minimise its use as much as possible by prioritising direct reductions of emissions from fossil fuel combustion and non-combustion applications alike, as in the NZE Scenario.

Even with the very rapid emissions reductions built into the NZE Scenario, DACS plays an important role in balancing the last remaining residual emissions. It also plays an important role in capturing CO_2 directly from the atmosphere that provides the necessary and irreplaceable climate neutral carbon feedstock for low-emissions fuels such as synthetic aviation kerosene (given constrained sustainable bioenergy resources), which play a vital part in the aviation sector. Policy makers should support faster innovation in and deployment of DAC technologies, even as they prioritise the deployment of clean technologies across the energy system.

Two technological approaches are currently being used to capture CO_2 from the air: solid DAC (S-DAC) and liquid DAC (L-DAC). Solid DAC operates at ambient to low pressure and medium temperature (80-120 °C), while liquid DAC operates at high temperature (300-900 °C). These technologies are currently at the prototype (L-DAC) and demonstration (S-DAC) stages and need to be scaled up dramatically to play the role envisaged in the NZE Scenario (see section 3.2.1).

Other interesting DAC technologies are emerging such as electro-swing adsorption, zeolites and passive DAC. While these DAC technologies are now at early stages of development, they offer the possibility of lower costs (passive DAC could cost less than USD 100/t CO_2 compared with USD 1000/t CO_2 for the DAC technologies at a more developed stage today), lower energy intensities (electro-swing DAC needs only around one-third of the energy per tonne of CO_2 compared with more developed technologies) and abundant sorbent availability (global zeolites production in 2022 was equivalent to around 1 Mt).

Growing commercial interest in the L-DAC and S-DAC technologies, as well as the innovation potential of emerging DAC technologies, suggests that DAC technologies could be scaled up to the levels seen in the NZE Scenario, provided that appropriate policies are in place. At the same time, policy makers and industry need to be realistic about the role that DACS and other carbon dioxide removal technologies can play in robust net zero emissions strategies, and about the risks involved in making assumptions about their future development. Time is not on our side. Even with substantial innovation and deployment, these technologies must be seen as a way of complementing, not replacing, a focus on reducing emissions.

3.3.4 Implications for the oil and natural gas industry

With continuing investment in existing and approved sources of supply, but without any new conventional oil and gas project approvals, oil and gas production would decline by around 2% each year on average to 2030 and by 4-5% each year on average from 2030 to 2050.

In the NZE Scenario, a rapid and sustained surge in clean energy investment and a variety of other measures lead to reductions in demand for oil and gas that broadly match the projected fall in production from existing sources of supply. As a result, there is no need for the approval of any new long lead time upstream conventional oil and gas projects.

In the Delayed Action Case, clean energy investment takes place less rapidly and measures designed to reduce emissions progress more slowly. As a result, oil and natural gas demand fall by around 0.5% on average each year to 2030. After 2030, oil and gas demand declines at a rate closer to 4% per year on average through to 2050. To ensure a smooth match between supply and demand there would need to be continued investment in existing sources of oil and gas supply, and some new sources of supply would need to be approved for development over the next few years. However, accelerating the decline in demand for oil and gas after 2030 in the Delayed Action Case means that no new long lead time oil projects would need to be approved for development from the late 2020s onwards, and this in turn means that there is no need to explore for new oil and gas fields from now on. The projects that are developed over this period would have to prioritise low-emissions technologies across the full supply chain. This means minimising methane leaks and flaring, electrifying facilities using low-emissions electricity and integrating the use of CCUS where feasible. After the late 2020s, oil and gas investment globally would shift entirely to maintaining production at existing fields and minimising the emissions intensity of operations.

Secure, equitable and co-operative transitions

Faster together

SUMMARY

- The clean energy transition brings new energy security risks. Although capital spending on critical minerals saw a 30% increase in 2022 and exploration spending rose by 20%, announced critical mineral mining projects are not sufficient to meet the needs of the Net Zero by 2050 Scenario (NZE Scenario) in 2030. Bridging this gap requires a focus on investment, recycling, technology innovation and behavioural change.
- More traditional energy security risks do not disappear. Global oil and gas markets reduce in volume terms in the NZE Scenario, but production becomes concentrated in a small number of producers, with the share of the Middle East rising from 25% today to 40% in 2050.
- The NZE Scenario sees a huge increase in clean energy investment and a rapid decrease in fossil fuel investment. Ensuring a smooth transition requires the two to be carefully synchronised. In the NZE Scenario, the key requirement is a massive and rapid increase in clean energy investment.
- Today more than 80% of clean energy investment is taking place in advanced economies and China; more is needed in emerging and developing economies. The NZE Scenario sees clean energy investment increasing nearly threefold from the current level by 2030, but fivefold in emerging market and developing economies other than China. Around USD 80-100 billion in annual concessional funding is needed by the early 2030s to lower the cost of finance and mobilise private capital in lower income countries.
- Affordability of energy is a key concern. A people-centred transition requires measures to ensure that the least well-off in all societies are able to benefit from the lower operating costs of clean and energy-efficient technologies. In overall terms, clean energy investment in the NZE Scenario is outweighed by declines in spending on fossil fuels, with worldwide net energy spending savings equalling USD 12 trillion to 2050.
- The Global Stocktake needs to provide a clear signal about the ambition and urgency with which countries are preparing their new Nationally Determined Contributions – the key vehicle for collective action under the Paris Agreement.
- International co-operation is central to develop agreed standards, to diversify clean energy supply chains in a way that avoids undermining the benefits of global supply chains, to ensure that rapid scale up can be achieved, and to share lessons learned from clean energy demonstration projects to accelerate innovation.

4.1 Introduction

The IEA *Net Zero by 2050: A Roadmap for the Global Energy Sector* in 2021 concluded that without fair and effective international co-operation the transition to net zero emissions would be delayed by decades (IEA, 2021a). Today, the world faces sharper geopolitical fractures, heightened concerns about energy security, more intense competition for clean energy supply chains and technologies, and tighter financial and fiscal conditions particularly in many emerging market and developing economies. These conditions may make international co-operation more difficult, but it is just as important now as in 2021.

Achieving the outcomes set out in the NZE Scenario requires international co-operation in several areas. Energy security is an important concern for all countries and needs to be actively managed both within and between governments, whether it is a question of a traditional issue such as the security of oil and gas supplies or an emerging issue such as the adequacy and security of critical minerals supplies (section 4.2). Today, emerging market and developing economies, other than China, are lagging significantly behind in the deployment of clean energy technologies. Reversing this imbalance and ensuring that the benefits and costs of the clean energy transition are distributed fairly must be a critical focus (section 4.3). Among other issues, this entails addressing the investment gap in clean energy technologies across emerging market and developing economies, including through the provision of more concessional finance to mobilise private capital (section 4.4). The Global Stocktake under the Paris Agreement needs to provide a clear signal about the ambition and urgency with which all countries are preparing their next round of Nationally Determined Contributions – the key vehicle for collective action under the Paris Agreement. Innovation in novel clean energy technologies needs to accelerate to support progress towards the goals of the Paris Agreement, and international co-operation has a role to play here in respect of issues such as cross-border infrastructure and the development of international standards (section 4.4).

4.2 Energy security

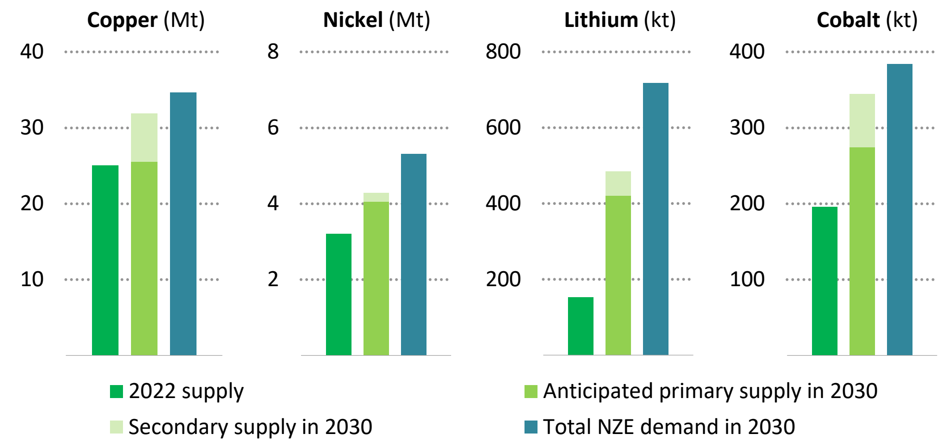
Managing traditional security risks related to fossil fuel supply will remain important during the transition to clean energy systems. However, as the transition advances, new risks arise, including some related to the supply of critical minerals needed for clean energy technologies, and others that relate to the adequacy and reliability of electricity systems that will form the backbone of the new energy economy. This section looks at both new and traditional risks and considers what approaches can reduce or mitigate them.

4.2.1 Bridging the gap between critical mineral supply and demand

The rapid deployment of clean energy technologies puts strains on supply chains, notably for critical minerals. The development of clean energy technology supply chains has made impressive progress since 2015. However, the expected pace of growth in critical mineral supplies does not yet match that of manufacturing capacity additions for clean energy technologies, posing challenges for scaling up clean energy deployment at the required pace to support net zero emissions transitions.

Demand for critical minerals for clean energy applications quadruples between 2022 and 2030 in the NZE Scenario. Electric vehicles (EVs) and battery storage are the main drivers of demand growth, but demand from low-emissions power generation and electricity networks also increases. As demand for clean energy applications rises faster than it does for other uses, the share of clean energy in total demand for key minerals increases considerably. For example, the clean energy sector represents nearly 90% of total lithium demand by 2030 in the NZE Scenario, up from 60% today, and clean energy technologies overtake stainless steel as the largest consumer of nickel around 2030.

Figure 4.1 ▷ Anticipated supply and projected demand for selected minerals in the NZE Scenario, 2030



While investments in new projects are increasing, meeting requirements of the NZE Scenario requires further efforts to boost investment, recycling and technology innovation

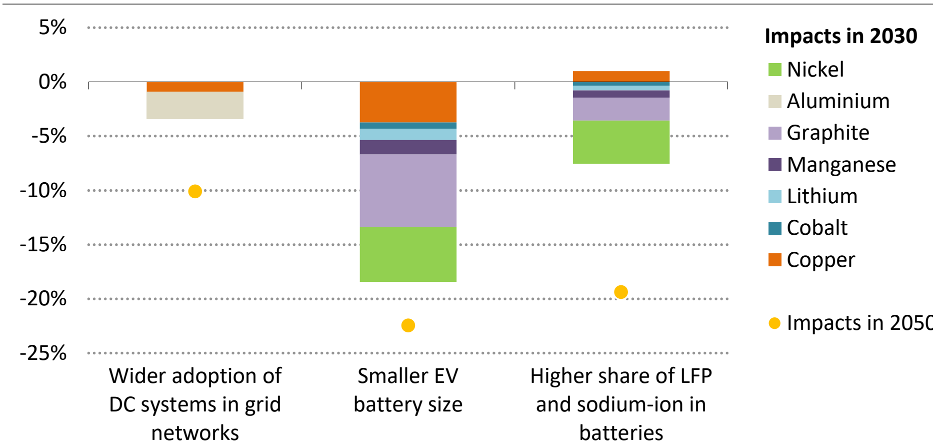
Notes: Mt = million tonnes; NZE = Net Zero Scenario. Anticipated supply is expected future production based on assessment of announced projects. Secondary supply refers to supply from recycled materials.

Despite increases in recent years, the anticipated supply from the current project pipeline still falls short of the requirements in the NZE Scenario (Figure 4.1). Expanding investment in new mining and refining facilities is crucial to avoid the risk of supply shortages slowing energy transitions or raising their cost. Encouragingly, many countries have recently introduced new policies to boost investment in new supplies. Our latest assessment indicates that capital spending for critical minerals development rose 20% in 2021 and by a further 30% in 2022 (IEA, 2023a). Exploration spending also rose by 20% in 2022, driven by record growth in lithium exploration. But more needs to be done, and the lack of progress on diversifying supply sources remains a concern. The share of the top-three producers of some critical minerals in global supply remains very high and has not changed from 2019 levels, notably for nickel and cobalt. For refining and processing operations in particular, most planned projects are being developed in incumbent producers, with China holding half of planned lithium refining projects and Indonesia representing nearly 90% of planned nickel smelting facilities.

An increase in recycling rates would help to reduce the pressure on primary supply and would also bring energy security benefits, especially to regions with higher deployment of clean energy technologies and limited resource endowments. For bulk materials such as steel and aluminium, recycling practices are relatively well established, but this is not yet the case for many energy transition minerals such as lithium and nickel. Waste regulations should be updated to ensure that they cover emerging waste streams from new clean energy technologies, backed by support for the construction of new recycling facilities. In the NZE Scenario, secondary supply from recycling meets 10-20% of total demand for key energy transition minerals in 2030, and there is scope for this share to increase significantly as the amount of equipment reaching its end of life expands in the longer term.

Technology advances also have a major role to alleviate potential supply strains. For example, significant reductions in the use of silver and silicon in solar cells over the past decade have contributed to a spectacular rise in deployment of solar photovoltaics (PV). Embracing a higher share of high-voltage direct current transmission lines in electricity networks has the potential to curtail their material demand by 3% in 2030 and 10% in 2050, and a wider adoption of lithium-iron phosphate chemistries and sodium-ion batteries could reduce mineral demand for EV batteries by 7% in 2030 and almost 20% in 2050.

Figure 4.2 ⊳ Impacts of technology and behavioural changes on material demand in the NZE Scenario, 2030 and 2050



Technology innovation and consumer behaviour provide scope to alleviate potential supply strains by reducing demand

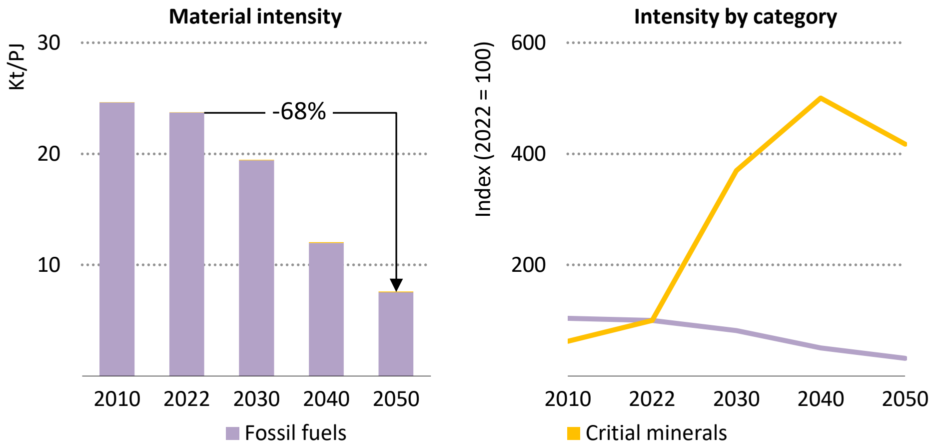
Note: DC = direct current; LFP = Lithium-iron phosphate.

Changes in consumer behaviour also play a part. The NZE Scenario assumes, for example, that targeted measures reduce the appetite for sport utility and other large vehicles, cutting mineral demand for EV batteries by 18% in 2030 and around 20% in 2050 (Figure 4.2).

Addressing the potential gaps between supply and demand is a significant challenge, but recent trends such as increased capital investment in new supplies, increased recycling facilities and the emergence of new technology options provide grounds for cautious optimism. To sustain this momentum, it is imperative to bolster international co-operation in order to stimulate investment, foster technology innovation and promote recycling practices. This should be accompanied by increased international co-operation on the social and environmental impacts of mining to improve performance, for example by harmonising standards and strengthening data collection and reporting mechanisms.

While the demand for critical minerals increases significantly in the NZE Scenario, clean energy transitions require significantly fewer extractive resources in aggregate than today's energy system. Decarbonisation means a major reduction in the overall materials intensity of the energy system, given that increased demand for critical minerals is accompanied by a massive decrease in extraction of fossil fuels. The net result is that for every unit of energy delivered in 2050, the energy system consumes two-thirds less in materials (fossil fuels and critical minerals combined) than it does today (Figure 4.3).

Figure 4.3 ▷ Material intensity of the global energy system in the NZE Scenario, 2010-2050



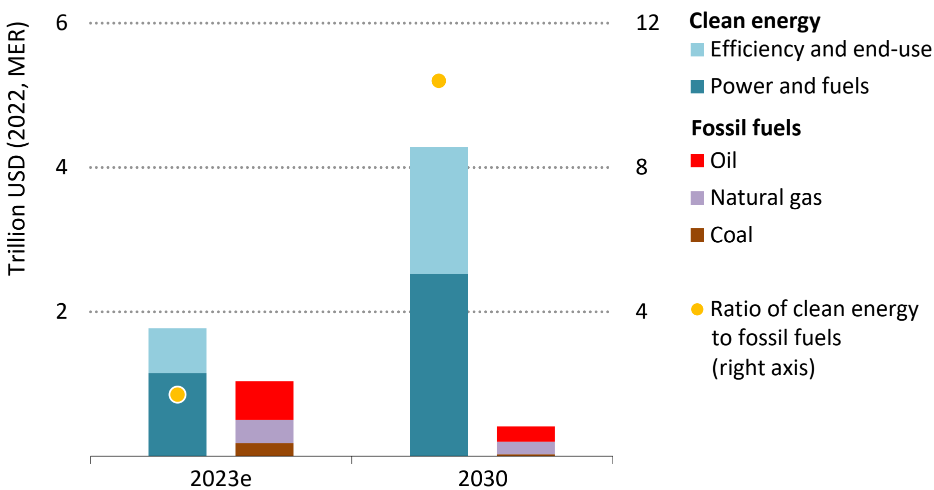
Overall intensity of materials to support the global energy system drops by more than two-thirds by 2050

Notes: Kt/PJ = thousand tonnes per petajoule. Critical minerals do not include steel and aluminium. The intensity for critical minerals does not include the amount of waste rock that occurs during mining activities.

4.2.2 Scaling up clean energy technologies and scaling back fossil fuels need to be well synchronised

Efforts to ensure energy security have so far focussed on adding new infrastructure to ensure uninterrupted access to energy supplies. However, net zero emissions transitions require a winding down of high carbon energy systems alongside major investment in new clean energy infrastructure. Ensuring a smooth transition requires these two movements to be carefully synchronised.

Figure 4.4 ▷ Global investment in clean energy and fossil fuels in the NZE Scenario, 2023-2030



IEA. CC BY 4.0.

A massive scale up in clean energy investment is key to ensure smooth transitions, but the shift in energy investment needs to be carefully synchronised

Notes: MER = market exchange rate. Power and fuels also includes investment to reduce emissions from fossil fuel supply.

Global investment in clean energy is set to outstrip investment in fossil energy by a factor of 1.8 to 1 in 2023. This ratio rises to 10 to 1 in 2030 in the NZE Scenario, when around USD 2.5 trillion is invested in clean electricity and low-emissions fuels and around USD 1.8 trillion in energy efficiency and end-uses, while investment in fossil fuel supply falls to around USD 0.4 trillion (Figure 4.4). The sequencing of the shift in energy investment is important. Running ahead on scaling back fossil fuel investment before clean energy investment ramps up would push up prices and risk price spikes, and this would not necessarily advance secure transitions. The key requirement for the achievement of the NZE Scenario is a massive and sustained increase in clean energy investment. The faster clean energy investment and deployment takes place, the faster the transition away from fossil fuels will be.

Even with the ambitious and rapid clean energy transition in the NZE Scenario, some elements of fossil fuel infrastructure continue to contribute to the secure operation of the overall energy system for many years to come. The role of gas-fired power plants in power system reliability, or of refineries in providing for the residual fuel needs of the internal combustion engine (ICE) fleet, are cases in point. Unplanned or premature retirement of this infrastructure could have negative consequences for energy security. There is also scope to reuse or repurpose some existing infrastructure. For example, some parts of natural gas networks could be used to transport low-emissions fuels such as biomethane and hydrogen, refineries could be converted to produce biofuels, and natural gas storage facilities could be repurposed to store hydrogen.

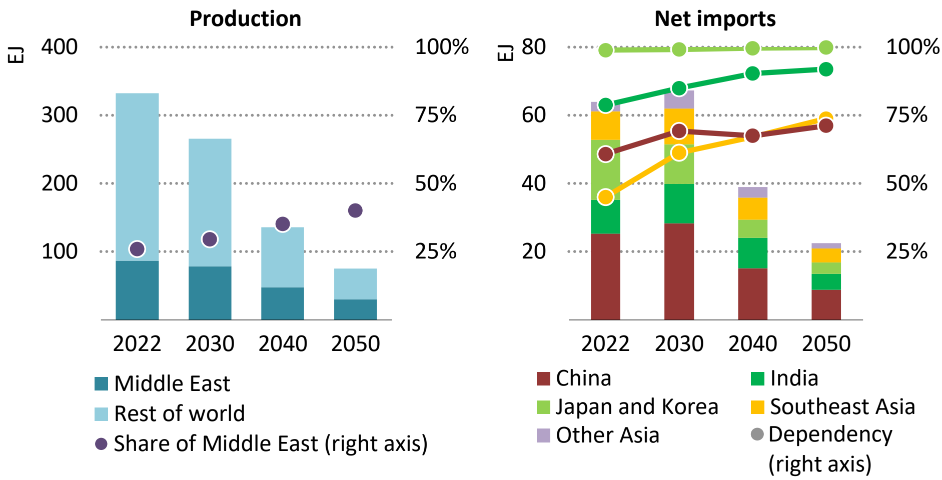
4.2.3 Fossil fuel markets shrink, but vigilance is still needed

Achieving net zero emissions goals brings energy security benefits as reliance on fossil fuels decreases, but concerns about the security of oil and gas supplies do not disappear in the NZE Scenario. Given the demand trajectory, the risks in this scenario do not relate to the adequacy of investment: global demand falls sufficiently fast that no new oil or gas field developments are needed, although continued investment in existing fields is still required. But as energy transitions progress and demand falls, oil and gas supplies become increasingly concentrated in a small number of low cost producers, and the Organization of the Petroleum Exporting Countries (OPEC) share of world oil production rises from 36% in 2022 to 52% in 2050 – a level higher than at any point in the history of oil markets since the first oil shock.[1] Oil import dependency also remains high for many countries, notably in emerging Asian economies. The Middle East plays an outsized role in serving these import needs, with its share in total crude oil exports rising from 45% in 2022 to 65% in 2050 (Figure 4.5). Import dependency in Asia also rises for natural gas from 27% in 2022 to 45% in 2050. In the NZE Scenario, importers therefore remain exposed to risks arising from geopolitical events and physical disruptions in the Middle East or accidents near trade chokepoints, even as the total volume of imports and the size of the oil and gas market falls.

The major hydrocarbon producers, notably in the Middle East, are also set to face economic challenges as revenues from oil and gas sales decline with the shift towards clean energy. In the NZE Scenario, governments in net exporting regions collect USD 380 billion from the production of oil and gas in 2030, around 50% below the average between 2017-2021, and this falls further to less than USD 90 billion by 2050. While producer economies have taken steps to diversify their economic structure, progress has been limited in most cases. Producer economies have also made limited progress in diversifying their energy sector away from fossil fuels and the share of low-emissions sources in their energy systems is among the lowest in the world.

[1] Supply trajectories and sensitivities for the NZE Scenario are examined in more detail in a forthcoming WEO special report on the Oil and Gas Industry in Net Zero Transitions, which will be released in November 2023.

Figure 4.5 ▹ Middle East share of global oil and gas production, and oil and gas net imports in Asia in the NZE Scenario, 2022-2050



Oil and gas supplies are increasingly concentrated in a small number of low cost producers; Asia's import dependency continues to rise

Note: EJ = exajoules.

The NZE Scenario charts an orderly process of change, but this is far from guaranteed in practice. Some importing countries might look to conclude new supply arrangements in the interest of energy security, even while seeking to reduce domestic fossil fuel use. Exporters or potential exporters might also be keen to exploit untapped oil and gas resources and some large, low cost producers might choose to expand production to capture a bigger market share, even if that pushes prices down; others might seek to restrict production to keep prices high. All these options would come with risks. New projects would risk locking in emissions that push the world over the 1.5 °C threshold. They would also face major economic and financial risks if the world is successful at scaling up clean energy in line with the NZE Scenario. A higher degree of supply concentration among a small number of countries would mean increased import dependency risks for importing regions, and restrictions on production by exporting countries to keep prices high could pose financial strains on importers.

Net zero transitions are more likely to proceed smoothly if countries work together constructively to minimise these risks. That is easier said than done, of course, but there are various ways in which exporting and importing countries could build up shared interests to avoid pitfalls. For example, they could work together on technology demonstration and joint R&D projects to harness the potential for low-emissions energy in producer economies; co-operate to facilitate investment in low-emissions fuel trade; and strengthen bilateral and multilateral engagement on a variety of energy-related issues. It is ultimately in everyone's interests that the transition to clean energy systems should be a smooth one.

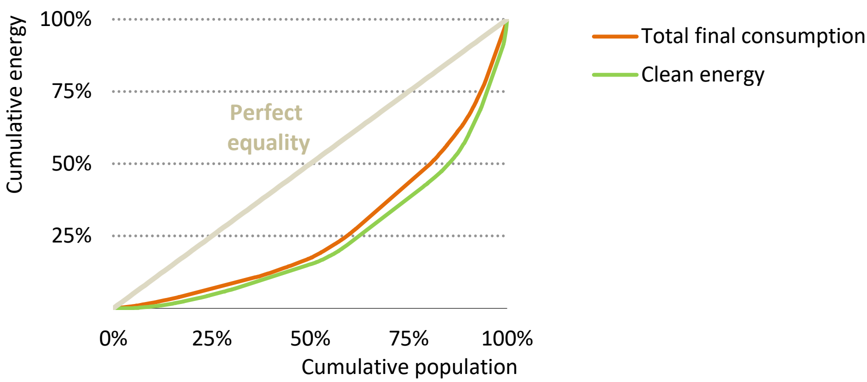
4.3 Equity

Achieving net zero emissions by 2050 requires every country, every organisation and every individual around the world to contribute to the clean energy transition. Yet today, the pace of deployment of clean technologies remains highly uneven, with advanced economies and China pulling far ahead while other emerging market and developing economies lag behind. Within societies, there is a risk that the less well-off will see fewer benefits from the transition unless supportive policies are put in place for a people-centred transition. This section explores the drivers of disparities in clean energy deployment and ways forward for bringing clean energy to all (section 4.3.1), the affordability of energy in the NZE Scenario (section 4.3.2), and the best ways to manage the impact of a rapid transition on energy sector employment (section 4.3.3).

4.3.1 Accelerating clean energy deployment in emerging market and developing economies

Energy consumption per capita is highly unequal across countries, and clean energy consumption even more so. Among the countries for which IEA has comprehensive energy statistics, the current Gini coefficient[2] of energy inequality is 0.39 for all sources of energy consumption and 0.46 for clean energy. Half of all the clean energy supplied is used by 15% of the global population, the majority of whom live in advanced economies (Figure 4.6).

Figure 4.6 ▷ Distribution of total final and clean energy consumption across the global population, 2022



Energy use per capita is highly unequal across countries, and clean energy consumption even more so, reflecting differences in income and wealth

Notes: The figure shows Lorenz curves; the closer the curve is to the 45-degree line, the more equal values are among countries. Clean energy excludes the traditional use of biomass.

[2] The Gini coefficient is a measure of inequality typically used to measure income inequality, which has been adopted in this section to evaluate inequality in energy consumption. 1 indicates perfect inequality (where one group or one individual consumes or receives all the resources) while 0 indicates perfect equality.

Figure 4.7 ▹ Clean energy technology deployment normalised for population and households by region, 2022

Clean energy technologies are deployed at a higher rate in advanced economies and China than in other emerging market and developing economies

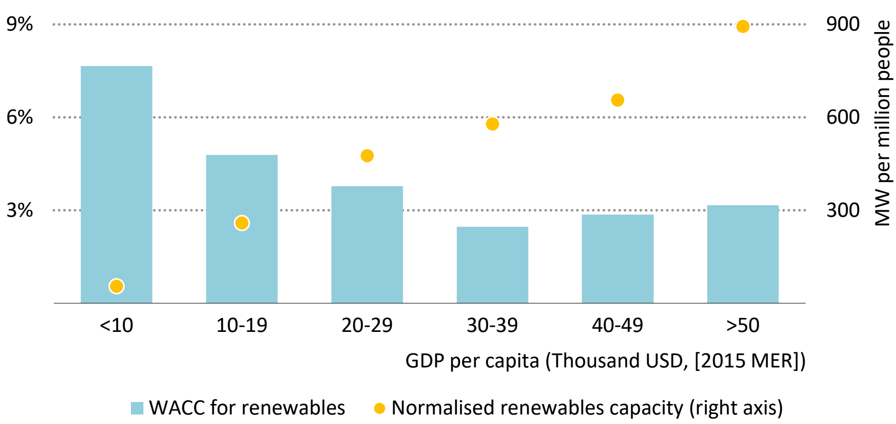
Note: BAT = best available technologies; AE = Advanced economies; C & S America = Central and South America; MENA = Middle East and North Africa.

Differences in access to clean energy vary markedly across technologies. Today, advanced economies and China combined have nearly 2.5-times more solar PV and wind capacity in operation per person than the global average (Figure 4.7). Wind and solar deployment per capita are particularly low in Africa. In 2022, the Netherlands had more solar PV capacity installed than the whole of Africa, for example. More capital-intensive and less mature technologies such as battery storage are the most unevenly deployed across regions. Less capital-intensive technologies such as best-in-class efficient appliances and light-emitting diode (LED) lighting systems are more evenly deployed. The disparities are not only a legacy of the earlier start in the deployment of clean energy technologies by advanced economies: similarly strong disparities are seen in recent capacity additions and new sales.

Concerted action at international and national levels is needed to address these disparities. The main barriers include:

- **Access to finance**: Capital costs for renewables-based projects in emerging market and developing economies remain at least double those in advanced economies (Figure 4.8). This reflects the relative lack of experience with clean energy technology in those economies and their constrained policy and regulatory capacity in comparison with advanced economies. It also reflects wider real or perceived macroeconomic risks. The higher financing costs that these economies face perpetuates a lack of experience with clean energy technologies, which creates a vicious circle of under deployment. Financial support, for example through Just Energy Transition Partnerships, will be necessary, but is not sufficient to help overcome these barriers. (Concessional finance, de-risking instruments and other solutions are discussed in section 4.4.1.)

Figure 4.8 ▷ Weighted average cost of capital for renewables and renewables capacity per capita versus GDP per capita, 2022



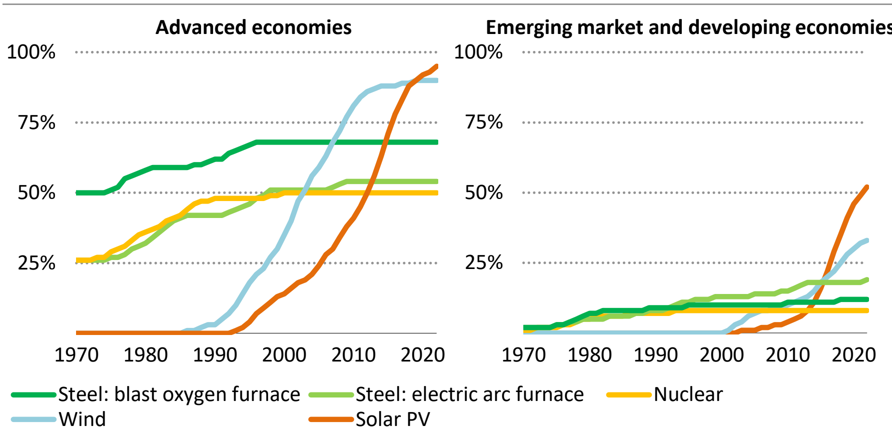
The cost of financing for renewables is more than two-times higher in the lowest income countries than in high income countries, correlating with lower deployment per capita

Note: WACC = weighted average cost of capital; MER = market exchange rates.

Source: IEA analysis based on IRENA (2023).

- **Policy environment**: Supportive policies are vital to expand clean energy. Economic and regulatory instruments such as standards and codes have been shown to boost the adoption and utilisation of clean energy solutions (Nepal et al., 2018; Pfeiffer and Mulder, 2013), and well-designed government policies play a central role in altering incentive structures for private actors and encouraging the uptake of new technologies. Many emerging market and developing economies have been less able to move forward in these areas than advanced economies, often because of competing political priorities including economic development and poverty alleviation, and this gap is visible in the different ambition levels set out in their Nationally Determined Contributions (section 4.4.2).
- **Innovation ecosystems**: So far, few clean energy innovations have originated in developing economies. Emerging market and developing economies other than China accounted for only 5% of global public energy R&D funding, 3% of corporate energy R&D funding and 5% of energy venture capital funding in 2022 (IEA, 2023b), while 90% of patents for low-emissions energy between 2000 and 2020 were from advanced economies and another 8% from China (IEA, 2021b). Although energy technologies diffuse across country borders over time, there can be delays of over a decade between early and late adopters, and much longer in some cases (Figure 4.9). Lowering barriers to trade and foreign direct investment can help to foster technology diffusion, as can increased engagement between countries in early-stage technologies (section 4.4.3).

Figure 4.9 ▷ Share of countries adopting selected technologies, 1970-2022



First adoption of energy technologies in emerging market and developing economies in some cases has lagged over a decade behind advanced economies

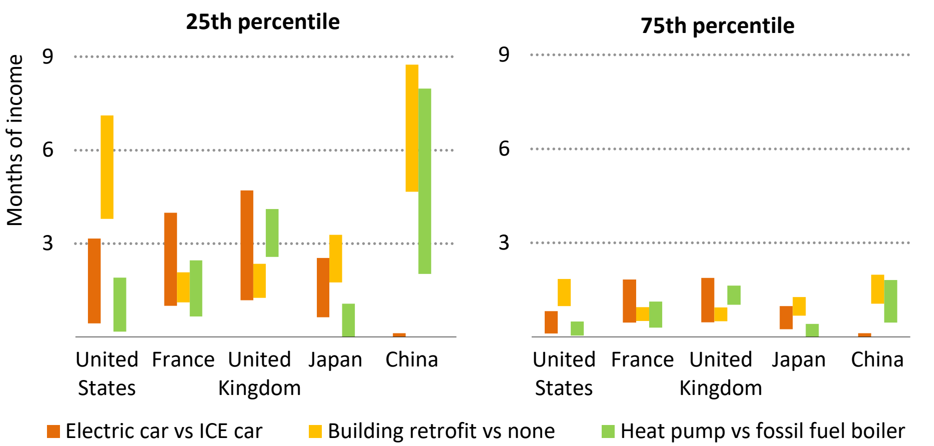
Note: Power technologies are counted as adopted when at least 10 MW of capacity have been installed.

- **Market size and conditions**: In countries where market size is limited, economies of scale are difficult to achieve and technology costs may remain high. In countries where societal awareness and demand from consumers for clean energy is less pronounced, companies have fewer incentives to invest in or switch to cleaner technologies (Suzuki, 2015; Zeng et al., 2022).

4.3.2 Enhancing clean energy affordability

Domestic trends mirror disparities at the international level. Even in countries that have achieved relatively high rates of clean technology deployment, there remain large groups of people who cannot afford the upfront premium of some clean energy technologies. Although technology purchase costs decline over time as their scale of deployment increases – as has been the case in China, where EVs are now often cheaper than ICE cars – there often remains a significant "green premium" even for relatively mature technologies, and that can be prohibitive for lower income or even median income households (Figure 4.10). As an example, for Chinese or US households in the 25th percentile, a deep building retrofit – an integrated set of energy conservation measures to significantly improve overall building performance – of an average size home can cost four to nine months of income, compared with one to two months for households in the 75th percentile. In advanced economies, the cost premium of buying a heat pump as opposed to a fossil fuel boiler is up to four months of income for households in the 25th percentile.

Figure 4.10 ▷ Purchase cost premium for clean energy technologies in months of household income in selected countries, 2022



IEA. CC BY 4.0.

While often affordable for the rich, the cost premium of low-emissions efficient technologies can be equivalent to several months of income for lower income households

Notes: Subsidies are not accounted for here. Costs are shown for average size cars, residential dwellings and heat pumps. In China, electric cars on average are cost-competitive with ICE cars.

Sources: IEA analysis based on World Inequality, (2022) for income; JATO, (2021) for vehicle costs.

This green premium can prevent low income households from benefiting from the lower operating costs that come with clean and energy-efficient technology options. For example, heat pumps are three- to five-times more efficient than fossil fuel boilers, while induction stoves are two- to three-times more efficient than gas stoves, and a household retrofit which is deep enough to reduce energy consumption for space heating and cooling by 50% can lower annual energy bills by more than 25% for an average family in the United States. The poorest households would benefit most from these savings on operating costs because they spend more of their income on energy than richer households, even though their emissions footprints are much smaller: the poorest 10% of the global population are responsible for a mere 0.2% of energy sector CO_2 emissions, while the richest 10% are responsible for nearly half (IEA, 2022a).

Poorer households need to be given careful consideration as clean technologies are rolled out if countries are to achieve just transitions, and if national decarbonisation targets are not to be at risk from lack of broad societal support. To help the poorest households afford efficient low-emissions technologies, governments can build measures to address inequalities into the design of climate policies. For example, grants and fiscal support for clean technologies can be means-tested by income (Table 4.1).

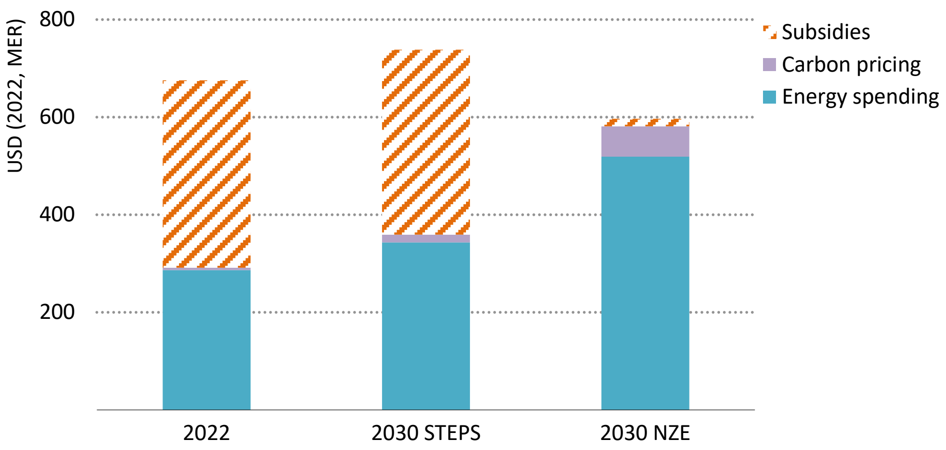
Table 4.1 ▹ Means-tested clean technology household grant programmes

Country	Programme	Technology target	Means testing criteria
Canada	Oil to Heat Pumps Affordability Program	Residential heat pumps	Post-tax household income must be at or below national median.
Ireland	Fully funded energy upgrades	Residential efficiency improvements including improved insulation	Households receiving welfare payments are eligible.
France	Vehicle conversion premium	Lower carbon, more efficient vehicles	For households with income below EUR 22 983.
	MaPrimeRénov	Residential efficiency improvements	The amount of the grant is scaled based on income.
United Kingdom	Home Upgrade Grant	Energy efficiency upgrades for off-gas-grid homes	Funding is only available for low income households.
United States	Inflation Reduction Act Clean Vehicle Credit	New electric vehicles	Household income must be below USD 300 000 for couples or USD 150 000 for individuals.
	Weatherization Assistance Program	Residential energy efficiency improvements	Households must be at or below 200% of the US poverty income guideline.

The costs of the clean energy transition are understandably a concern for all countries. In advanced economies, technology upgrades and energy efficiency retrofits translate into substantial savings on energy bills. In emerging market and developing economies, households also benefit from the more efficient use of energy, though modern energy consumption increases as rising incomes allow for larger residences and more appliances. New appliances need to meet ambitious energy efficiency standards in emerging market and developing economies, where the coverage and stringency of these policies is lower today than in advanced economies. In the NZE Scenario, over a billion people gain access to modern energy by 2030, particularly in sub-Saharan Africa. While this results in new expenditure on electricity and other modern fuels, it saves time previously spent on fuel wood collection in rural areas and money previously spent on expensive charcoal in cities.

Carbon pricing policies and the phase-out of fossil fuel subsidies raise fuel costs. These policy changes need to be carefully designed and implemented to limit impacts on household budgets and to sustain support for the clean energy transition. Fossil fuel subsidies reached record levels in 2022 but are largely removed by 2030 in the NZE Scenario (Figure 4.11). This has the benefit of lowering the burden on government budgets compared with the Stated Policies Scenario (STEPS), and does not prevent the provision of targeted support for the energy costs of low income households through direct payment schemes or other means. Targeted measures cost much less than across-the-board subsidies, not least because wealthier households consume more energy than poorer ones and therefore benefit disproportionately from subsidy schemes. New and expanded carbon tax and emissions trading systems provide important additional sources of revenue as the clean energy transition progresses: these could be used in part to help low income households to afford clean and more energy-efficient technology options and reduce their energy bills.

Figure 4.11 ▷ Annual cost of residential energy per household in emerging market and developing economies in the STEPS and NZE Scenario, 2022 and 2030



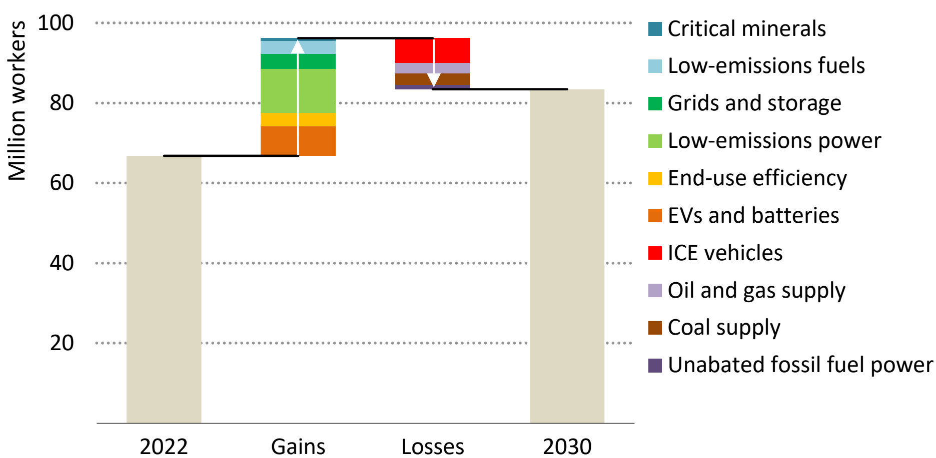
Phasing out energy subsidies and carbon pricing policies in emerging economies need to be carefully designed and implemented to avoid negative impacts on consumers

Note: Energy spending includes other taxes and levies on fuels in addition to carbon pricing and excludes transport fuel spending.

4.3.3 Managing the employment transition

The changes between now and 2030 in the NZE Scenario imply a rapid transformation in energy employment, with the demand for workers in clean sectors rising much faster than the fall in fossil fuel-related jobs. Today, around 65 million people work in energy or key energy-related sectors such as energy efficiency and vehicle manufacturing, and half of these jobs are already focussed on clean energy.[3] In the NZE Scenario, 30 million new clean energy jobs are added by 2030 while close to 13 million jobs in fossil fuel-related industries are lost, meaning that around two clean energy jobs are created for every fossil fuel-related job lost (Figure 4.12).

Figure 4.12 ⊳ Energy employment changes by sector in the NZE Scenario, 2022-2030



Approximately two clean energy jobs are created for every fossil fuel-related job lost between today and 2030

Note: ICE = internal combustion engine; EVs = electric vehicles.

Employment in low-emissions electricity sees substantial growth in the NZE Scenario, with solar PV and wind power adding around 3 million jobs each and employing a combined 11.5 million workers by 2030. The better-established end-use efficiency and electricity grid labour forces also continue to expand throughout the decade, employing around 14 million and 11.5 million people respectively in 2030, whereas emerging technologies such as low-emissions hydrogen production or concentrating solar power see job opportunities increase sharply by 2030.

[3] See IEA *World Energy Employment Report 2023*, (forthcoming) for more detailed information on energy employment by sector and region.

The sectors likely to see larger job losses, including fossil fuel supply and ICE vehicle manufacturing, need to carefully plan for the changes ahead. This magnitude of job losses is not unprecedented – in China, the number of coal mining workers has nearly halved over the last two decades due to labour productivity improvements (IEA, 2022b). In some cases, workers in activities that stand to lose jobs already possess skills and know-how that overlap with growing energy sectors. Coal miners have many of the skills needed for the extraction and processing of critical minerals, for example, while people working in conventional vehicle manufacturing can apply their experience to EV manufacturing and battery assembly. Workers leaving the oil and gas workforce are already highly sought-after by the chemical industry and others. In many cases, however, the jobs created by the energy transition will not be in the same place, require the same skills, or pay the same wages as the jobs lost, such that policies could play a role to support the workers and communities whose livelihoods may be affected.

4.4 International co-operation

The IEA's 2021 *Net Zero by 2050* report concluded that a lack of fair and effective international co-operation would push back the date by which global net zero emissions are achieved by decades (IEA, 2021a). The report included the Low International Co-operation Case which explored the implications of failing to co-operate on finance, trade and supply chains, technology innovation and CO_2 removal. This section builds on this case and explores several areas in which international co-operation needs to be strengthened.

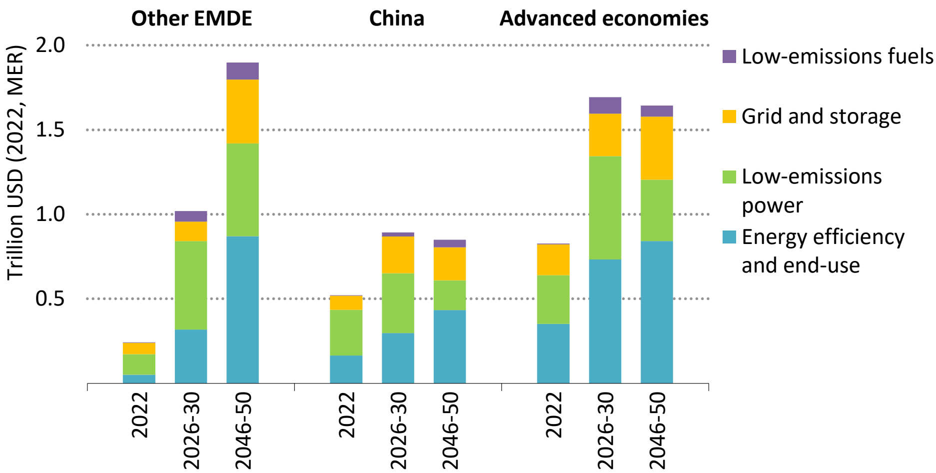
4.4.1 Addressing financing barriers in emerging economies

Investment needs for net zero emissions

Recent trends in clean energy spending provide some encouraging signs at the global level. Investment in clean energy outpaces investment in fossil fuels: for each USD 1 invested in fossil fuels in 2023, we estimate that USD 1.8 will be invested in clean energy. Clean energy investment today is dominated by the advanced economies and China. Some large economies such as India and Brazil have recently seen strong growth in clean energy investment, but it continues to lag investment in fossil fuels in other emerging market and developing economies, with an estimated USD 250 billion set to be invested in clean energy in 2023 compared to nearly USD 450 billion invested in fossil fuels.

While the recent global shift in investment towards clean energy shows that the transition is well and truly underway, a much faster shift is needed to get on track for net zero emissions by 2050, with an average of USD 10 needing to be invested in clean energy for each USD 1 invested in fossil fuels by 2030. In total, annual clean energy investment reaches USD 4.5 trillion by the early 2030s and USD 4.7 trillion by 2050 in the NZE Scenario, compared with USD 1.6 trillion in 2022 (Figure 4.13). Most of the increase in clean investment is in the emerging market and developing economies (other than China), where it rises fivefold in the second half of the current decade compared with 2022, and more than sevenfold in the second half of the 2040s.

Figure 4.13 ▷ Clean energy investment needs by region/country in the NZE Scenario, 2022-2050

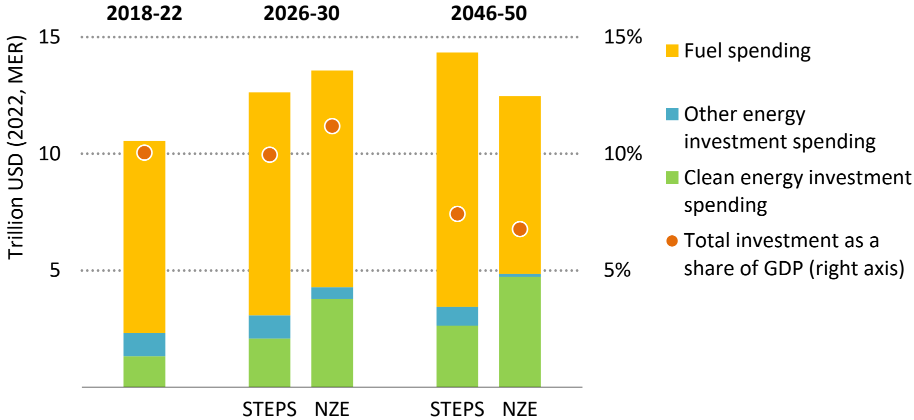


The bulk of increased investment in clean energy is needed in emerging economies, other than China; it rises more than sevenfold in the second half of the 2040s relative to 2022

In China and advanced economies, investment in low-emissions power has been rising strongly because of supportive government policies and rapid cost declines in solar PV and wind which have made those technologies attractive to investors. Investment in electricity networks and storage has not risen as quickly, and now needs to accelerate in order to meet rising demand, modernise systems and ensure reliable service. Raising the level of investment is a tougher undertaking in many developing economies, where state-owned utilities are struggling to raise affordable capital as a result of rising interest rates, high levels of existing debt and cash flow pressures related to electricity subsidies. Risks associated with timely grid connections and curtailment are often cited by investors as barriers to developing new renewables projects in these countries. The introduction of cost-reflective tariffs would be particularly helpful in this context.

Global investment spending on clean energy peaks in the NZE Scenario at USD 4.8 trillion per year between 2036 and 2040. This very high level of investment leads to significant savings in fuel purchases, which fall from an average of about USD 8.2 trillion per year in 2018-2022 to USD 7.5 trillion in 2050 (a third lower than in the STEPS) (Figure 4.14). Total fuel and investment spending as a share of GDP peaks during the 2026-2030 period at 11.2% before falling to 6.4% in 2050. Cumulative savings on fuel spending exceed additional capital investment by 40% from 2031 through 2050, with net undiscounted savings equalling USD 12 trillion. The benefits of clean energy transitions would be even higher if the benefits associated with improved air quality and lower frequency of extreme climate events were also taken into consideration.

Figure 4.14 ▷ Global energy investment and spending on fuels in the STEPS and the NZE Scenario, 2018-2050



Higher capital investment in clean energy in the NZE Scenario more than pays off in reduced fuel spending with net undiscounted savings equalling USD 12 trillion

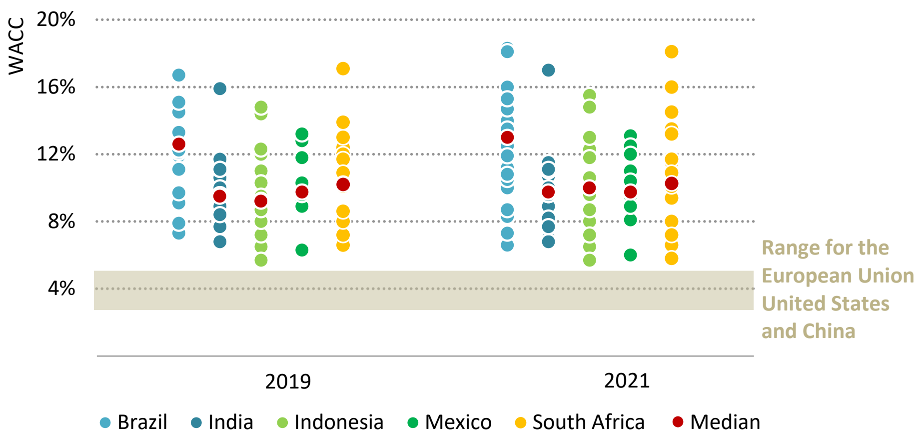
International co-operation to scale finance for clean energy

Many emerging market and developing economies struggle to finance new projects due to rising debt levels and tightening fiscal conditions. Some have seen access to external financing closed off. Large emerging economies such as Brazil, India, Indonesia, Mexico and South Africa can raise capital, but it costs two- to three-times more than in advanced economies (Figure 4.15).

Closing the financing gap will require increased international co-operation between countries and more active engagement with financial stakeholders to better understand the barriers faced by emerging market and developing economies and the impact on the cost of capital of the risks that investors are most concerned by. This would help to better target policy interventions and inform the design and prioritisation of blended finance – the strategic use of development finance and philanthropic funds to mobilise private capital flows to emerging market and developing economies. The knowledge and experience gained from successful projects could also be shared more widely with the aim of helping other countries, while more standardisation in project structuring and preparation would facilitate the development of new projects and ease due diligence processes. Stronger efforts will also be needed to improve the availability and quality of data necessary for financial investors to better assess and hence manage risks. The provision of capacity building support by the international community would help.

Closing the gap will also require the appropriate package of support. There are two important points here. First, there is no single instrument on which to rely; a mix of concessional finance (below market rate loans), grants for project structuring and project preparation, guarantees and other de-risking instruments (including to lower the cost of currency hedging) is needed.[4] Second, reaching scale will require a shift from direct financing of projects towards more project de-risking with the aim of leveraging much higher multiples of private finance and maximising the use of limited public funds. International co-operation and engagement with investors will be vital in this context.

Figure 4.15 ▷ Cost of capital for various solar PV projects in selected countries, 2019 and 2021



Cost of capital for large emerging economies is two- to three-times higher than in advanced economies, undermining the financial viability of new projects

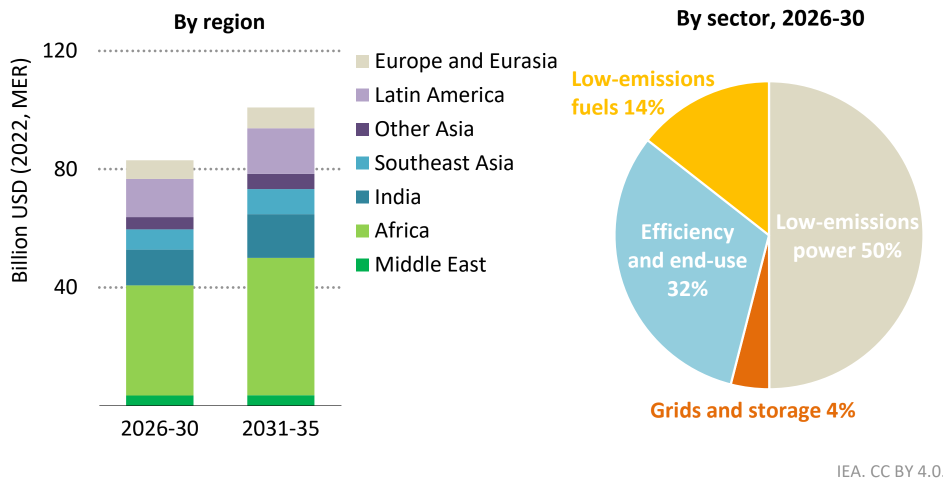
Notes: WACC = weighted average cost of capital. Each dot corresponds to individual utility-scale projects.

Of course, there is also the question of how much support is needed. Analysis undertaken by the IEA with the International Finance Corporation estimates that the NZE Scenario would require USD 80 to 100 billion in annual concessional funding by the early 2030s to improve risk adjusted returns to mobilise private capital at scale for clean energy investment (IEA and IFC, 2023). This is less than a fifth of what was spent in 2022 by governments in advanced economies on measures to lower energy bills during the energy crisis (IEA, 2023c). Africa would require the largest share of support, accounting for 45% of estimated concessional funding needs, followed by India and Latin America, which would each account for about 15% (Figure 4.16). Half of all concessional funds would support investment in low-emissions power, and a third would support investment in end-use energy efficiency and electrification. Low-emissions hydrogen, bioenergy and carbon capture and storage (CCUS) together account for 14%, or almost twice their share in overall investment, reflecting difficulties in

[4] Not all investment will require concessional finance, nor will blended finance structures be appropriate in all cases. Clean energy technologies such as solar PV and onshore wind already can be financed commercially in several emerging economies.

obtaining commercial financing for such large-scale immature technologies. Electricity networks and storage account for just 4%, which is less than their share in overall investment, reflecting the fact that some state-owned utilities with high debt levels and/or low credit ratings face significant difficulties to access private capital.

Figure 4.16 ▷ Concessional funding needs for clean energy in selected emerging market and developing economies and by sector in the NZE Scenario



Africa requires the largest share of concessional funding; low-emissions power accounts for half of all concessional funding needs

Note: Low-emissions fuels include bioenergy, low-emissions hydrogen and CCUS.

At the Conference of the Parties (COP) 15 in 2009, developed countries committed to a collective goal of mobilising USD 100 billion per year by 2020 (extended to 2025 at COP 21) to support climate action in developing countries. In 2020, public climate finance for energy, transport and industry reached USD 31 billion and mobilised USD 9 billion in private capital (OECD, 2022). In 2020, each USD 1 of public climate finance in the sector leveraged just USD 0.3 of private finance. Average leverage ratios for private capital mobilisation need to reach USD 6-7 by the early 2030s in the NZE Scenario.

Therefore, much more is needed to deliver on the commitment made at COP 15 and to provide what is needed in the NZE Scenario to put the world on course to global net zero emissions by 2050. Moreover, considerable additional funding will be needed so that state-owned enterprises that cannot at present access commercial capital are able to fund projects such as electricity network upgrades or energy efficiency improvements in public buildings.

A new collective quantified goal on climate finance (NCQG), is intended to be agreed by 2024 and to supersede the USD 100 billion target agreed at COP 15. Whatever is agreed will have major implications for the journey towards global net zero emissions by 2050. Negotiations on the NCQG should take account of the need to rapidly scale up the amount of public climate finance provided to emerging market and developing economies and the need to increase the amount of private capital mobilised. Carbon credit financing could complement other sources (Box 4.1). It will also be important for providers to carefully consider how best to allocate and target their contributions.

Box 4.1 ▹ How can carbon markets contribute to scaling up nascent clean energy technologies?

Nascent technologies and fuels such as direct air capture and storage (DACS), sustainable aviation fuels and low-emissions hydrogen play an important role in the NZE Scenario. However, securing financing for demonstration and first-of-a-kind projects is hindered by their high initial costs. Initial projects may not offer the prospect of a short-term commercial return, but they are needed to bring down costs through learning and economies of scale, and thus to accelerate deployment.

Policy support for these technologies in the form of tax credits, advanced market commitments, concessional loans and loan guarantees is gaining momentum. That support is essential, but it may be insufficient to guarantee that planned projects are implemented and new projects come forward. Private capital is also needed. Carbon credit markets offer a potential means of providing it.

An example is DACS for which the current price of removing one tonne of CO_2 is in the range USD 600-2 500, but it is clearly an important technology for the future and its costs will come down as lessons are learned from initial projects. Today voluntary carbon markets are underpinning most DACS projects, with growing purchases of DACS credits by firms and advance purchase commitments by demand aggregators such as Frontier.[5]

Sustainable aviation fuels (SAF) offer a second example. Producers of SAF today rely mainly on off-take agreements for their revenues, but demand has been low because SAF prices are three- to four-times higher than those of conventional jet fuel. SAF credits could help to bridge the price gap premium, and a start on this is being made. For instance, a pilot project was launched in July 2022 by GenZero, an investment company, Singapore Airlines and the Civil Aviation Authority of Singapore to advance the use of SAF. A total of 1 000 SAF credits were made available for sale, generated from the 1 000 tonnes of SAF to be used at Singapore Changi Airport. Each credit purchased will reduce CO_2 emissions by 2.5 tonnes. In the European Union, there are plans to make available 20 million allowances under the EU Emission Trading System, with a market

[5] Frontier, a demand aggregator, is an advance market commitment to accelerate the development of carbon removal technologies set up in early 2023 by a consortium comprising Stripe, Alphabet, Shopify, Meta and McKinsey Sustainability. In June 2023, it announced its first purchases from six projects on behalf of Stripe worth up to USD 7.8 million (Frontier, 2022).

value around EUR 2 billion, to cover some or all of the price gap between fossil kerosene and SAF for the period 2024-2030. A clear framework to account for the overlap of direct GHG emissions from fuel combustion of airlines (or Scope 1 emissions) with indirect GHG emissions from private and business travel (or Scope 3 emissions) would be important for ensuring that SAF credits are used credibly to effectively reduce emissions from air travel.

Carbon credits could complement other sources of financing of low-emissions hydrogen projects. The complexity of the supply chains involved means that it has not yet proven possible to establish such credits, but the Hydrogen for Net Zero (H2NZ) Initiative is currently seeking to develop new crediting methodologies for the voluntary carbon market aimed at unlocking carbon finance for hydrogen projects (South Pole, 2023).

The credibility of carbon credits has suffered in recent years as a result of market design imperfections and some cases of abuse. It is essential to ensure that carbon credits are generated from real, verified, additional and permanent emissions reductions or removals. Applying industry guidelines such as those of the Integrity Council for the Voluntary Carbon Markets Core Carbon Principles[6] and following guidance under Article 6 of the Paris Agreement should help in this respect. There also needs to be more transparency on the actions taken by corporations in pursuit of their net zero emissions strategies and other pledges, including their use of carbon credits, and more guidance on how to formulate a CO_2 removal strategy. The Voluntary Carbon Markets Integrity Initiative[7] could be helpful here: among other things, its Claims Code of Practice should help reduce instances of greenwashing.

4

4.4.2 Enhancing ambitions through the United Nations Framework Convention on Climate Change and Global Stocktake

Under the 2015 Paris Agreement, countries agreed to co-operate to collectively limit the global increase in temperature to well below 2 °C and to pursue efforts to limit it to 1.5 °C above pre-industrial levels. Progressive strengthening of national climate goals and collective action is central to the Paris Agreement. Its ratchet mechanism requires Parties to communicate new or updated Nationally Determined Contributions (NDCs) of increasing ambition every five years from 2020, based on the capability and capacity of each country, and informed by the Global Stocktake of progress between cycles (Figure 4.17).

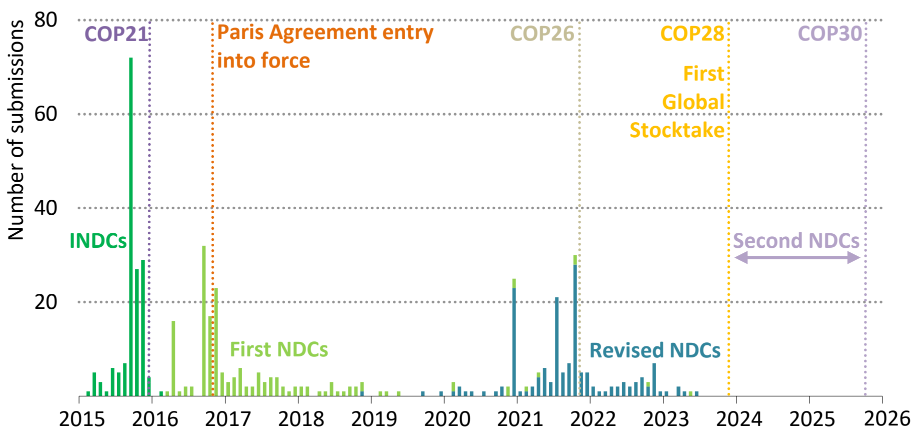
The five-year cycle between each round of NDC submissions is intended to strike a balance between the need to give time to countries to formulate, implement and learn from their NDCs, and the need for the level of ambition to be increased in the light of the urgent requirement to tackle climate change. This urgency is reflected in the decisions taken at

[6] https://icvcm.org/the-core-carbon-principles

[7] https://vcmintegrity.org/

COP 26 in 2021 and COP 27 in 2022, which invited countries to strengthen their current NDCs, rather than wait for the first Global Stocktake in 2023 before doing so, as requested in the Paris Agreement. The response to these calls to strengthen ambitions of existing NDCs was underwhelming (see Chapter 1). It is therefore critical that the next round of NDCs should represent a true step-change in ambition and that a key outcome of the Global Stocktake should be a requirement for all countries to submit more ambitious NDCs for the next cycle.

Figure 4.17 ▹ Timeline of Nationally Determined Contribution submissions, 2015-2026



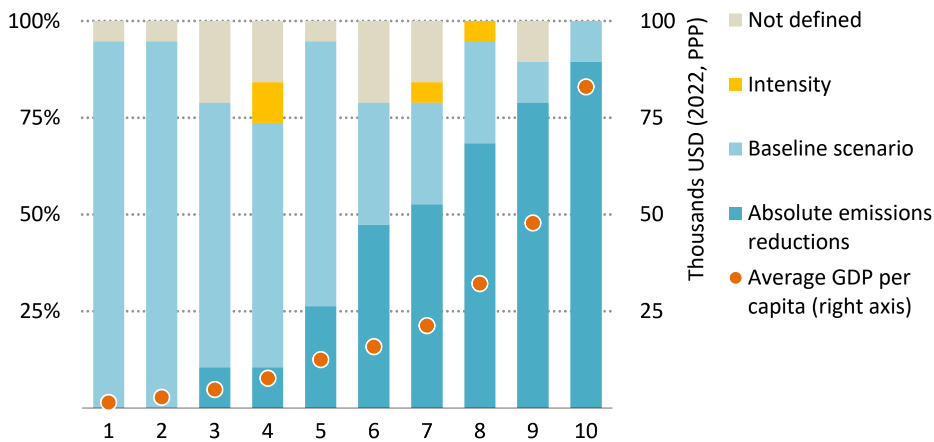
168 NDCs, representing 195 countries, had been submitted to the UNFCCC by September 2023, of which nearly 90% had been revised

Note: INDCs = Intended Nationally Determined Contributions; NDCs = Nationally Determined Contributions; COP = Conference of the Parties.

Transparency is also an important component of the co-operative framework of the Paris Agreement. Before COP21, fewer than 80% of draft NDCs contained a quantified mitigation target. As of September 2023, this share had increased to 91% in revised NDCs, significantly facilitating the assessment of collective progress.

The Paris Agreement requests developed countries to adopt absolute emissions reduction targets, while developing countries are only encouraged to do so in recognition of the fact that for many of them, the NDC process was the first time they may have set mitigation targets. To date, most NDCs from developing countries use either baseline scenario targets, which mitigate emissions against a forward-looking counterfactual business-as-usual baseline, or emissions intensity targets, which are relative to an economic or operational variable such as GDP. As of September 2023, countries with low to medium income per capita have mostly set baseline scenario targets, whereas countries with higher income per capita have mostly adopted absolute emissions reductions targets (Figure 4.18). However, a number of higher income countries have either not elaborated NDCs at all or have adopted intensity or baseline NDCs that are not commensurate with their level of development. In the next round of NDCs, it is hard to see a good reason why any high-emitting, higher income country should fail to adopt an absolute reduction target.

Figure 4.18 ▷ Mitigation target types of current NDCs by country development level



Most high income countries have set absolute emissions reductions targets; for the second-round of NDCs, all high-emitting, high income countries should do so

4.4.3 Accelerating clean energy technology deployment

International co-operation will need to play a major role in accelerating the development and diffusion of clean energy technologies around the world. We highlight the importance of co-operation in three key areas: set standards for near zero and low-emissions materials and fuels; diversify clean energy technology supply chains; and step up clean energy demonstration projects.

Definitions and standards for clean products and fuels

Definitions and standards embodying measurement protocols and environmental performance thresholds can help to establish a common view of the way forward for various technologies and sectors. For heavy industry and long-distance transport, they are needed in particular to underpin policies designed to tackle hard-to-abate emissions. A package of policy measures may include “demand pull” measures, for example to establish differentiated markets for products and fuels produced with substantially fewer emissions than those produced with incumbent technologies, to develop clean public procurement[8] protocols, and to define clean technology mandates. All of these depend on the existence of agreed standards. It may also include "supply push" measures, for example to make it possible to evaluate through the use of agreed standards whether a given technology or measure to reduce emissions deserves financial support, and if so to what extent.

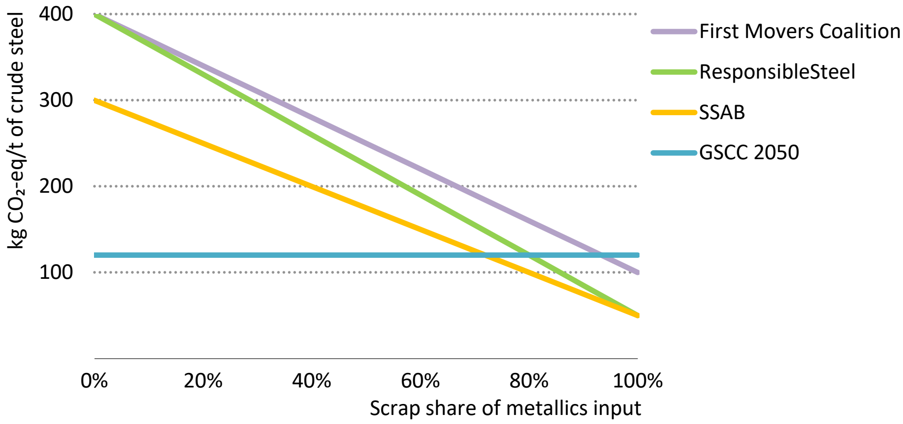
Once emissions have been measured, thresholds can be used to differentiate production, products and fuels according to their environmental footprint. Such thresholds should be designed to be stable, absolute and sufficiently ambitious to be compatible with a trajectory for the global energy system that reaches net zero emissions by mid-century. They also need to take account of the specific characteristics of each sector, material and fuel, such as the limited availability of certain inputs like scrap metal for recycling. Interim measures that substantially lower emissions intensity but fall short of desired higher performance thresholds should be recognised, but only in the context of longer term plans to reach those higher thresholds. The IEA has recently put forward, as inputs to ministerial discussions among the Group of 7 (G7) members, common definitions for near zero emissions steel and cement production as well as frameworks for measuring and collecting data on low-emissions hydrogen (IEA, 2022c; IEA, 2023d).

Several regulatory frameworks and certification systems defining the environmental performance of fuels and materials are currently being developed in parallel (Figure 4.19); between which there are inconsistencies of approach. There is a significant risk that a lack of co-ordination may lead to a proliferation of varying standards, resulting in market fragmentation, excessive administrative burden for companies, and a confusing landscape for customers and suppliers. The IEA has proposed net zero principles for emissions measurement methodologies for materials production that aim to guide revisions to existing methodologies and promote convergence and interoperability in the medium term (IEA, 2023e). These principles stipulate that an emissions measurement methodology should allow for comparison between production from all facilities. Emissions boundaries and scope should cover all major contributions to production and product emissions. Accounting rules for emissions credits and co-products should be compatible with a net zero emissions energy system. In addition, methodologies should incentivise, wherever possible, the use of site- and product-specific auditable, measured data, as opposed to generic emissions estimates or factors.

Stronger international co-operation is vital to limit the proliferation of multiple, competing standards that risk slowing the clean energy transition. By aligning standards, countries can help create larger, shared markets for lower emissions fuels and materials, thus accelerating cost reductions. The newly established IEA Working Party on Industrial Decarbonisation, the International Partnership for Hydrogen and Fuel Cells in the Economy, and the Clean Energy Ministerial Hydrogen Initiative are relevant fora in which governments can collaborate on this topic.

[8] Clean procurement entails the procurement of goods and commodities that are produced and delivered in ways that are compatible with clean energy transitions. The term green procurement is often used.

Figure 4.19 ▷ Emissions intensity thresholds for near zero and low-emissions steel production as a function of the proportion of scrap used



While there are significant differences between the emissions intensity thresholds proposed by various institutions, their long-term ambitions are very similar

Notes: kg CO_2 -eq/t = kilogramme of carbon dioxide equivalent per tonne. GSCC 2050 refers to the 2050 value of the Steel Climate Standard produced by the Global Steel Climate Council, an association of steel producers. The other thresholds are static over time and thus are not associated to a particular year. They correspond to the SSAB fossil-free standard developed by the steel producer SSAB, the ResponsibleSteel International Standard developed by the non-profit multistakeholder certification initiative ResponsibleSteel (the threshold is equivalent to and constitutes a public endorsement of the threshold put forward by the IEA to the G7 Ministers in 2022), and the procurement requirements outlined by the First Movers Coalition, an initiative that promotes private procurement in support of clean energy technologies.

Sources: ResponsibleSteel (2022); First Movers Coalition (2022); SSAB (2023); GSCC (2023).

Recommended policy actions to advance international co-operation in setting standards and definitions include (IEA, 2022c; IEA, 2023c; IEA, 2023d):

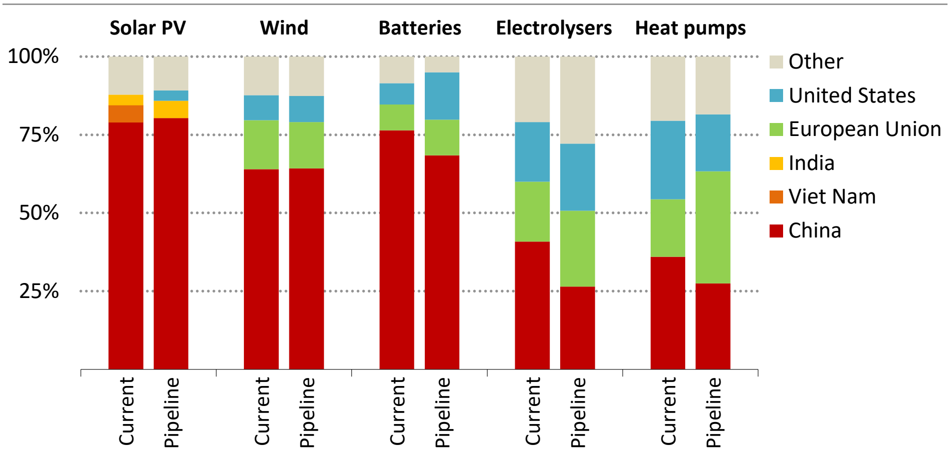
- **Avoid the creation of new emissions measurement methodologies** for materials and fuels emissions intensity and focus efforts to tailor existing international protocols.
- **Engage in the amendment and revision processes** for existing emissions measurement methodologies wherever possible.
- **Engage in inclusive technical dialogues and co-ordination activities for measurement methodologies and data collection** for the emissions from materials and fuels production.
- **Engage in constructive dialogue about definitions that differentiate according to emissions performance** to identify areas of common understanding and establish ways to make definitions interoperable, as well as to share knowledge on their potential use in policy instruments.

Diversify clean technology supply chains

Many supply chains for clean energy technologies are characterised by a high degree of concentration, and this entails major risks for security of supply. Concentration at any point along a supply chain makes the entire chain vulnerable to disruption arising from individual country policy choices, company decisions, natural disasters or technical failures. Disruption of this kind is very likely to drive up prices of intermediate and final products and hamper clean energy transitions.

Clean energy technology supply chains today are generally more geographically concentrated than those of fossil fuels. Today just three countries account for about 90% of global lithium mining output; the equivalent figures for cobalt, nickel and copper are 75%, 65% and 45% respectively. When it comes to production of key clean energy mass-manufactured technologies – solar PV modules, wind turbine nacelles, EV batteries and electrolysers – just three countries account for 80-90% of global capacity (Figure 4.20) (IEA, 2023f). In the case of solar PV, some individual manufacturing plants in China can produce more modules than entire countries. For instance, the LONGi plant in Taizhou – the largest operating plant in China – could have supplied half of the capacity additions of solar PV modules in the European Union in 2022 (38 GW).

Figure 4.20 ▷ Current and projected geographical concentration of manufacturing operations for selected clean energy technologies



Announced projects – if all realised – will alter the global distribution of manufacturing capacity for batteries, electrolysers and heat pumps

Notes: Wind refers to onshore wind nacelles in this figure. For electrolysers, it only includes projects for which location data were available. Shares are based on manufacturing capacity. Current refers to installed capacity data for 2022 and first quarter 2023 where available. Pipeline refers to the sum of current installed capacity and all announced manufacturing capacity additions (as of end of first quarter 2023) through to 2030. Other refers to the aggregate of all capacity besides that of the top-three countries/regions for each technology and timeframe. See *The State of Clean Technology Manufacturing* (IEA, 2023f) for more details.

The pipeline of announced projects for mass manufacturing of clean energy technologies points to a limited fall in geographical concentration of some but not all clean technologies in the coming years. If all solar PV and wind projects that have been announced come to fruition, concentration among the top-three producers would remain similar to current levels by 2030 (85-90%), with China's share remaining virtually unchanged (80% for solar, 65% for wind). By contrast, if all announced manufacturing projects for batteries, electrolysers and heat pumps come to fruition, the shares of the top-three producers would change, though China would still maintain a strong position. For example, the share of global battery manufacturing capacity in China would fall to around two-thirds, while that of the United States would jump to 15% and the European Union to 11%.

Policy makers need to balance the need to address overdependence on a limited range of sources of materials and technologies on the one hand with the benefits of an open international trading system on the other. Dominance of clean energy technology supply chains by a handful of countries presents obvious security concerns and will inevitably invite policy reactions from other countries. At the same time, overzealous moves to de-risk or localise supply chains risk undermines the benefits of global supply chains, raises costs and hinders the clean energy transition.

At their summit in May 2023, G7 countries expressed the importance of building resilient, secure and sustainable supply chains to accelerate the clean energy transition and to reduce vulnerabilities associated with undue dependencies (G7 Ministers of Climate, 2023). Countries can address risks at the domestic level by developing dedicated industrial strategies and making the most of their competitive advantages. International co-operation will remain crucial to share lessons learned and to build partnerships as well as efforts to ensure the smooth operation of regional and global supply chains.

Recommended policy actions to enhance supply chain diversity include:

- **Identify the major clean energy technology supply chain risks** that could delay or disrupt deployment and hinder resilience in case of disruption. While much attention currently focuses on the security of supply of critical minerals, other elements could be problematic as well.
- **Build strategic partnerships** where it is not realistic or efficient to compete in a supply chain or supply chain segment. Identifying relative strengths and seeking complementary partnerships should be central to industrial strategies for clean technology manufacturing.
- **Facilitate investment in emerging market and developing economies** through pooled investments, knowledge-sharing and other strategies designed to reduce risks for capital-intensive components of supply chains and spread the benefits of the new clean energy economy. Funding provisions for specific projects in appropriate cases should be dependent on adequate environmental, social and governance regulations being in place.

- **Promote technologies and strategies to enhance resource efficiency**, thereby increasing the resilience of clean technology supply chains. Among others, manufacturing processes that minimise material use, technology designs that allow for the use of substitute materials when security of supply is in question, and product designs that facilitate reuse, repairability and recyclability should be promoted through innovation policy.

Step up clean energy technology demonstration projects

Accelerating innovation cycles for early stage clean energy technologies is vital to meet net zero emissions goals. Bringing clean energy technologies under development today to market by 2030 requires advancing from prototype to market significantly faster on average than some of the quickest energy technology developments in the past. Such an acceleration would require demonstrating technologies not yet available on the market quickly, at scale, in multiple technical configurations and in various locations and situations. In most cases in the NZE Scenario, these demonstrations run in parallel, in contrast with usual practice whereby learning is transferred across consecutive projects in different contexts to build confidence before widespread deployment begins.

Government support for clean energy demonstrations is crucial, particularly in sectors where economies of scale favour large installations. Private financing is often hard to put in place when large installations are necessary because of the very significant sums of money involved (sometimes over USD 1 billion). This is much less of an issue with mass-manufactured equipment or digital consumer goods, where experimentation at commercial scale can usually be carried out at much lower cost. In 2022, 16 governments together committed USD 94 billion by 2026 for clean energy demonstration projects (US Department of Energy, 2022). The size of this commitment is broadly in line with the amount that the IEA calculated was needed two years ago (IEA, 2021a). If all this funding is forthcoming, it will give a tremendous boost to the commercialisation of emerging technologies.

While it is too early to match recent government pledges with new projects, IEA tracking suggests that progress is underway in several critical areas (IEA, 2023g). These include large-scale solid oxide electrolysers for hydrogen production, industrial-scale hydrogen-based steelmaking through direct reduced iron, carbon capture demonstrations in cement production, first-of-a-kind direct air capture, small electric planes, low-emissions jet fuels production, novel foundations for floating offshore wind turbines and small modular nuclear reactors. Nearly 80% of around 200 recent demonstration programmes are in advanced economies, primarily in Europe (55%) and North America (15%), with about 10% in China and 10% in other emerging market and developing economies.

When assessing the need for clean energy demonstrations, we assume a high level of international co-operation. The sharing of knowledge and learning among stakeholders and projects is critical to the process of making technological advances, and that remains true even when projects fail. Information sharing among governments promotes more informed policy making and helps ensure that new projects complement others taking place elsewhere. Without such co-operation, the number of projects would certainly be unnecessarily larger and the portfolio more costly. International co-operation also increases the chances that demonstration projects will take place in the best locations for those projects, and that supply chains will operate smoothly to the benefit of those demonstration projects.

Recommended policy actions to boost clean energy demonstration include:

- **Increase engagement with emerging market and developing economies on clean energy demonstrations.** Technologies will generally be more commercially successful in emerging market and developing economies if they are tested in the relevant climatic, regulatory and market conditions.
- **Set up international tracking mechanisms to measure progress and adjust priorities over time**. Such mechanisms can help to ensure that investments are focussed in critical areas, to share learnings with international partners and to build evidence-based support for clean energy projects.
- **Tap into existing multilateral initiatives**. Existing fora such as the IEA Technology Collaboration Programmes and Mission Innovation can help share technology and policy best practice across borders, while multilateral financial institutions and development banks have expert knowledge of how to share investment risks for large-scale projects.
- **Share financing risks during the early stages of new technology deployment and send clear demand signals thereafter.** Even after they have been demonstrated successfully, new technologies often face more risks than incumbent technologies. Instruments like grants, public debt guarantees and concessional finance can help to mitigate these risks, thereby increasing the likelihood of these technologies being able to secure private sector investment. Early signals that there will be a broader market in which to participate can also increase the incentives to invest in demonstration projects and initial deployment.

ANNEXES

Tables for scenario projections

General note to the tables

This annex includes global historical and projected data for the Net Zero Emissions by 2050 (NZE) Scenario for the following datasets:

- A.1: Energy supply
- A.2: Total final energy consumption
- A.3: Electricity sector: gross electricity generation and electrical capacity
- A.4: CO_2 emissions: carbon dioxide (CO_2) emissions from fossil fuel combustion and industrial processes
- A.5: Indicators and activity: selected economic and activity indicators

Definitions for regions, fuels and sectors are outlined in Annex B.

Abbreviations/acronyms used in the tables include: CAAGR = compound average annual growth rate; CCUS = carbon capture, utilisation and storage; EJ = exajoule; GJ = gigajoule; GW = gigawatt; Mt CO_2 = million tonnes of carbon dioxide; TWh = terawatt-hour. Use of fossil fuels in facilities without CCUS is classified as "unabated".

Both in the text of this report and in these annex tables, rounding may lead to minor differences between totals and the sum of their individual components. Growth rates are calculated on a compound average annual basis and are marked "n.a." when the base year is zero or the value exceeds 200%. Nil values are marked "-".

The tables for scenario projections will be available for download as part of the *World Energy Outlook 2023* free dataset to be released at the end of October 2023: https://iea.li/weo-data

Data sources

The Global Energy and Climate (GEC) Model is a very data-intensive model covering the whole global energy system. Detailed references on databases and publications used in the modelling and analysis may be found in Annex E of the World Energy Outlook 2023[1].

The formal base year for this year's projections is 2021, as this is the last year for which a complete picture of energy demand and production is in place. However, we have used more recent data wherever available, and we include our 2022 estimates for energy production and demand in this annex (Tables A.1 to A.3). Estimates for the year 2022 are based on the IEA *CO_2 Emissions in 2022* report which are derived from a number of sources, including the latest monthly data submissions to the IEA Energy Data Centre, other statistical releases from national administrations, and recent market data from the IEA *Market Report Series* that cover coal, oil, natural gas, renewables and power. Investment estimates include the year 2022, based on the IEA *World Energy Investment 2023* report.

[1] The World Energy Outlook 2023 will be released at the end of October 2023.

Historical data for gross power generation capacity (Table A.3) are drawn from the S&P Global Market Intelligence World Electric Power Plants Database (March 2023 version) and the International Atomic Energy Agency PRIS database.

Definitional note: A.1 Table: Energy supply and transformation

Total energy supply (TES) is equivalent to electricity and heat generation plus the *other energy sector*, excluding electricity, heat and hydrogen, plus total final consumption, excluding electricity, heat and hydrogen. TES does not include ambient heat from heat pumps or electricity trade. Solar in TES includes solar photovoltaic (PV) generation, concentrating solar power (CSP) and final consumption of solar thermal. *Biofuels conversion losses* are the conversion losses to produce biofuels (mainly from modern solid bioenergy) used in the energy sector. *Low-emissions hydrogen production* is merchant low-emissions hydrogen production (excluding onsite production at industrial facilities and refineries), with inputs referring to total fuel inputs and outputs to produced hydrogen. While not itemised separately, *geothermal* and *marine* (tidal and wave) energy are included in the *renewables* item *of* TES and *electricity and heat sectors*. While not itemised separately, *non-renewable waste* and *other sources* are included in TES.

Definitional note: A.2 Table: Energy demand

Sectors comprising **total final consumption** (TFC) include *industry* (energy use and feedstock), *transport* and *buildings* (residential, services and non-specified other). While not itemised separately, *agriculture* and *other non-energy use* are included in TFC. While not itemised separately, non-renewable waste, *solar thermal* and *geothermal* energy are included in *buildings*, *industry* and *TFC*. Aviation and navigation include both domestic and international energy demand. Energy demand from international marine and aviation bunkers are included in global transport totals, and TFC.

Definitional note: A.3 Table: Electricity

Electricity generation expressed in terawatt-hours (TWh) and installed electrical capacity data expressed in gigawatts (GW) are both provided on a gross basis, i.e. includes own use by the generator. Projected gross electrical capacity is the sum of existing capacity and additions, less retirements. While not itemised separately, *other sources* are included in total electricity generation. Installed capacity for hydrogen and ammonia refers to full conversion only, not including co-firing with natural gas or coal.

Definitional note: A.4 Table: CO_2 emissions

Total CO_2 includes carbon dioxide emissions: from the combustion of fossil fuels and non-renewable wastes; from industrial and fuel transformation processes (process emissions); and CO_2 emissions from flaring and CO_2 removal. CO_2 removal includes: captured and stored emissions from the combustion of bioenergy and renewable wastes; from biofuels production; and from direct air capture (DAC).

The first two entries are often reported as bioenergy with carbon capture and storage (BECCS). Note that some of the CO_2 captured from biofuels production and direct air capture is used to produce synthetic fuels, which is not included as CO_2 removal.

Total CO_2 captured includes the carbon dioxide captured from CCUS facilities, such as electricity generation or industry, and atmospheric CO_2 captured through direct air capture, but excludes that captured and used for urea production. *Aviation and navigation* include both domestic and international emissions.

Definitional note: A.5 Table: Economic and activity indicators

The emission intensity expressed in kilogrammes of carbon dioxide per kilowatt-hour (kg CO_2 per kWh) is calculated based on electricity-only plants and the electricity component of combined heat and power (CHP) plants[2]. *Primary chemicals* include ethylene, propylene, aromatics, methanol and ammonia. Industrial production data for *aluminium* excludes production based on internally generated scrap. Heavy-duty trucks activity includes freight activity of medium freight trucks and heavy freight trucks. *Aviation* activity includes both domestic and international flight activity. *Shipping* activity refers to international shipping activity.

Abbreviations used include: GDP = gross domestic product; GJ = gigajoules; m^2 = square metres Mt = million tonnes; pkm = passenger-kilometres; PPP = purchasing power parity; tkm = tonnes-kilometres.

Annex A licencing

[2] To derive the associated electricity-only emissions from CHP plants, we assume that the heat production of a CHP plant is 90% efficient and the remainder of the fuel input is allocated to electricity generation.

Table A.1: World energy supply

	Net Zero Emissions by 2050 Scenario (EJ)							Shares (%)			CAAGR (%) 2022 to:	
	2010	2021	2022	2030	2035	2040	2050	2022	2030	2050	2030	2050
Total energy supply	**541**	**624**	**632**	**573**	**535**	**528**	**541**	**100**	**100**	**100**	**-1.2**	**-0.6**
Renewables	43	71	75	166	241	306	385	12	29	71	10	6.0
Solar	1	5	7	35	66	97	138	1	6	26	23	11
Wind	1	7	8	25	43	61	84	1	4	16	16	9.0
Hydro	12	15	16	20	24	27	30	2	3	5	2.9	2.3
Modern solid bioenergy	23	33	35	55	65	71	73	6	10	13	5.8	2.6
Modern liquid bioenergy	2	4	4	11	13	13	11	1	2	2	13	3.3
Modern gaseous bioenergy	1	1	1	7	9	11	15	0	1	3	22	9.0
Traditional use of biomass	25	24	24	-	-	-	-	4	-	-	n.a.	n.a.
Nuclear	30	31	29	43	55	63	67	5	8	12	5.0	3.0
Unabated natural gas	115	146	144	112	68	40	14	23	20	3	-3.0	-8.1
Natural gas with CCUS	0	1	1	6	9	13	18	0	1	3	35	13
Oil	173	182	187	148	110	79	42	30	26	8	-2.8	-5.2
Non-energy use	25	31	32	35	34	33	30	5	6	6	1.3	-0.1
Unabated coal	153	167	170	93	43	16	3	27	16	1	-7.3	-14
Coal with CCUS	-	0	0	2	7	10	12	0	0	2	87	27
Electricity and heat sectors	**200**	**244**	**247**	**256**	**277**	**319**	**393**	**100**	**100**	**100**	**0.4**	**1.7**
Renewables	20	39	41	103	167	228	306	17	40	78	12	7.4
Solar PV	0	4	5	29	56	80	112	2	11	29	26	12
Wind	1	7	8	25	43	61	84	3	10	21	16	9.0
Hydro	12	15	16	20	24	27	30	6	8	8	2.9	2.3
Bioenergy	4	9	9	17	24	30	36	4	6	9	7.3	4.9
Hydrogen	-	-	-	2	4	5	6	-	1	2	n.a.	n.a.
Ammonia	-	-	-	1	2	2	2	-	0	1	n.a.	n.a.
Nuclear	30	31	29	43	55	63	67	12	17	17	5.0	3.0
Unabated natural gas	47	57	57	49	25	11	1	23	19	0	-1.7	-13
Natural gas with CCUS	-	-	-	0	2	2	3	-	0	1	n.a.	n.a.
Oil	11	8	8	2	1	0	0	3	1	0	-17	-23
Unabated coal	91	108	110	53	16	0	-	45	21	-	-8.9	n.a.
Coal with CCUS	-	0	0	2	5	6	7	0	1	2	102	29
Other energy sector	**50**	**64**	**65**	**64**	**64**	**70**	**78**	**100**	**100**	**100**	**-0.2**	**0.7**
Biofuels conversion losses	-	5	6	14	16	16	12	100	100	100	11	2.6
Low-emissions hydrogen (offsite)												
Production inputs	-	0	0	9	20	33	54	100	100	100	n.a.	n.a.
Production outputs	-	0	0	6	14	23	39	100	100	100	144	38
For hydrogen-based fuels	-	-	-	2	5	10	17	-	31	43	n.a.	n.a.

Table A.2: World final energy consumption

	Net Zero Emissions by 2050 Scenario (EJ)							Shares (%)			CAAGR (%) 2022 to:	
	2010	2021	2022	2030	2035	2040	2050	2022	2030	2050	2030	2050
Total final consumption	**383**	**436**	**442**	**406**	**379**	**360**	**343**	**100**	**100**	**100**	**-1.1**	**-0.9**
Electricity	64	87	89	113	133	154	183	20	28	53	3.0	2.6
Liquid fuels	154	168	172	150	120	94	62	39	37	18	-1.7	-3.6
Biofuels	2	4	4	11	13	13	11	1	3	3	13	3.3
Ammonia	-	-	-	1	2	2	4	-	0	1	n.a.	n.a.
Synthetic oil	-	-	-	0	1	2	6	-	0	2	n.a.	n.a.
Oil	151	164	168	138	104	76	41	38	34	12	-2.4	-4.9
Gaseous fuels	58	72	71	61	52	45	41	16	15	12	-1.8	-2.0
Biomethane	0	0	0	4	6	6	8	0	1	2	42	13
Hydrogen	-	0	0	2	5	8	16	0	1	5	113	33
Synthetic methane	-	-	-	-	-	-	-	-	-	-	n.a.	n.a.
Natural gas	57	72	70	54	41	29	15	16	13	4	-3.2	-5.3
Solid fuels	95	92	93	63	54	45	35	21	15	10	-4.8	-3.4
Solid bioenergy	38	39	40	24	26	26	28	9	6	8	-6.1	-1.2
Coal	56	52	52	38	27	18	7	12	9	2	-3.9	-6.9
Heat	12	15	15	12	11	9	6	3	3	2	-2.1	-3.2
Industry	**143**	**167**	**167**	**175**	**173**	**169**	**159**	**100**	**100**	**100**	**0.6**	**-0.2**
Electricity	27	37	38	52	62	70	79	23	30	49	4.2	2.7
Liquid fuels	29	33	32	34	32	29	24	19	19	15	0.7	-1.0
Oil	29	33	32	34	31	28	23	19	19	14	0.5	-1.2
Gaseous fuels	24	31	30	30	28	25	21	18	17	13	-0.1	-1.3
Biomethane	0	0	0	1	2	3	4	0	1	3	43	15
Hydrogen	-	0	0	1	2	4	5	0	1	3	137	36
Unabated natural gas	24	31	30	27	21	16	6	18	15	4	-1.5	-5.3
Natural gas with CCUS	-	0	0	1	2	3	5	0	1	3	46	18
Solid fuels	58	58	59	52	45	38	29	35	30	18	-1.5	-2.5
Modern solid bioenergy	8	10	11	15	18	20	22	7	9	14	4.2	2.5
Unabated coal	49	47	47	36	24	15	2	28	20	1	-3.5	-10
Coal with CCUS	-	0	0	1	2	4	5	0	0	3	71	25
Heat	5	7	7	5	4	3	1	4	3	1	-3.9	-6.1
Chemicals	38	48	48	54	55	55	51	29	31	32	1.6	0.2
Iron and steel	31	37	35	34	32	30	26	21	19	17	-0.6	-1.0
Cement	9	12	12	12	11	11	10	7	7	6	-0.4	-0.7
Aluminium	5	7	7	7	6	6	5	4	4	3	-0.4	-1.1

Table A.2: World final energy consumption (continued)

	Net Zero Emissions by 2050 Scenario (EJ)							Shares (%)			CAAGR (%) 2022 to:	
	2010	2021	2022	2030	2035	2040	2050	2022	2030	2050	2030	2050
Transport	**102**	**112**	**116**	**105**	**89**	**79**	**76**	**100**	**100**	**100**	**-1.3**	**-1.5**
Electricity	1	1	2	8	15	25	38	1	8	51	23	12
Liquid fuels	97	106	110	92	69	49	26	94	88	35	-2.2	-5.0
Biofuels	2	4	4	10	12	11	8	4	10	11	12	2.6
Oil	95	102	105	81	55	33	8	91	77	10	-3.3	-8.9
Gaseous fuels	4	5	5	5	4	5	11	5	4	15	-1.9	2.7
Biomethane	0	0	0	0	0	0	0	0	0	0	18	5.1
Hydrogen	-	0	0	1	2	4	10	0	1	14	98	32
Natural gas	4	5	5	3	2	1	0	4	3	0	-5.6	-11
Road	76	87	89	74	60	52	47	76	71	62	-2.2	-2.2
Passenger cars	38	44	45	32	22	17	15	38	30	20	-4.1	-3.7
Heavy-duty trucks	21	26	27	27	26	24	22	23	26	29	0.2	-0.8
Aviation	11	9	11	15	14	14	15	10	14	20	3.5	1.2
Shipping	10	11	11	11	10	10	10	10	11	13	0.1	-0.4
Buildings	**117**	**131**	**133**	**100**	**92**	**89**	**89**	**100**	**100**	**100**	**-3.4**	**-1.4**
Electricity	35	45	46	48	51	55	62	35	48	70	0.5	1.1
Liquid fuels	13	13	13	9	5	3	1	10	9	1	-5.1	-8.5
Biofuels	-	-	-	0	0	0	0	-	0	0	n.a.	n.a.
Oil	13	13	13	9	5	3	1	10	9	1	-5.2	-9.5
Gaseous fuels	27	31	31	22	15	10	5	23	22	5	-4.1	-6.5
Biomethane	0	0	0	2	3	3	3	0	2	3	53	14
Hydrogen	-	-	-	0	0	0	0	-	0	0	n.a.	n.a.
Natural gas	26	31	30	19	11	5	0	23	19	0	-5.8	-22
Solid fuels	35	32	32	9	8	6	6	24	9	6	-14	-6.0
Modern solid bioenergy	4	4	4	8	8	6	6	3	8	6	8.4	1.0
Traditional use of biomass	25	24	24	-	-	-	-	18	-	-	n.a.	n.a.
Coal	6	4	4	1	0	0	0	3	1	0	-14	-26
Heat	6	7	7	7	6	6	5	5	7	5	-0.5	-1.7
Residential	83	93	93	65	59	57	58	71	65	65	-4.4	-1.7
Services	34	38	39	35	33	31	31	29	35	35	-1.3	-0.8

Table A.3: World electricity sector

	Net Zero Emissions by 2050 Scenario (TWh)							Shares (%)			CAAGR (%) 2022 to:	
	2010	2021	2022	2030	2035	2040	2050	2022	2030	2050	2030	2050
Total generation	**21 533**	**28 346**	**29 033**	**38 207**	**47 427**	**59 111**	**76 838**	**100**	**100**	**100**	**3.5**	**3.5**
Renewables	4 209	7 964	8 599	22 532	36 739	50 459	68 430	30	59	89	13	7.7
Solar PV	32	1 023	1 291	8 177	15 439	22 241	31 237	4	21	41	26	12
Wind	342	1 865	2 125	7 070	11 923	16 826	23 442	7	19	31	16	9.0
Hydro	3 456	4 299	4 378	5 507	6 530	7 435	8 225	15	14	11	2.9	2.3
Bioenergy	309	666	687	1 313	1 885	2 396	3 056	2	3	4	8.4	5.5
of which BECCS	-	-	-	65	300	471	644	-	0	1	n.a.	n.a.
CSP	2	15	16	139	414	831	1 486	0	0	2	31	18
Geothermal	68	96	101	306	508	662	862	0	1	1	15	7.9
Marine	1	1	1	19	39	67	123	0	0	0	44	19
Nuclear	2 756	2 810	2 682	3 936	4 952	5 583	6 015	9	10	8	4.9	2.9
Hydrogen and ammonia	-	-	-	373	745	1 028	1 161	-	1	2	n.a.	n.a.
Fossil fuels with CCUS	-	1	1	220	681	847	996	0	1	1	105	30
Coal with CCUS	-	1	1	156	455	547	644	0	0	1	97	28
Natural gas with CCUS	-	-	-	64	226	301	353	-	0	0	n.a.	n.a.
Unabated fossil fuels	14 479	17 456	17 636	11 066	4 241	1 121	158	61	29	0	-5.7	-15
Coal	8 669	10 247	10 427	4 988	1 379	-	-	36	13	-	-8.8	n.a.
Natural gas	4 847	6 526	6 500	5 943	2 834	1 119	158	22	16	0	-1.1	-12
Oil	963	683	709	135	28	2	1	2	0	0	-19	-23

	Net Zero Emissions by 2050 Scenario (GW)							Shares (%)			CAAGR (%) 2022 to:	
	2010	2021	2022	2030	2035	2040	2050	2022	2030	2050	2030	2050
Total capacity	**5 187**	**8 230**	**8 643**	**16 180**	**23 067**	**29 354**	**36 956**	**100**	**100**	**100**	**8.2**	**5.3**
Renewables	1 333	3 292	3 629	11 008	17 460	23 331	30 275	42	68	82	15	7.9
Solar PV	39	925	1 145	6 101	10 430	14 303	18 753	13	38	51	23	11
Wind	181	827	902	2 742	4 322	5 797	7 616	10	17	21	15	7.9
Hydro	1 027	1 360	1 392	1 765	2 054	2 313	2 612	16	11	7	3.0	2.3
Bioenergy	74	159	168	296	426	541	688	2	2	2	7.3	5.2
of which BECCS	-	-	-	15	59	87	114	-	0	0	n.a.	n.a.
CSP	1	6	7	48	134	251	427	0	0	1	27	16
Geothermal	10	15	15	48	78	99	129	0	0	0	16	8.0
Marine	0	1	1	8	16	27	48	0	0	0	34	16
Nuclear	403	413	417	541	688	813	916	5	3	2	3.3	2.9
Hydrogen and ammonia	-	-	-	129	367	447	427	-	1	1	n.a.	n.a.
Fossil fuels with CCUS	-	0	0	50	141	203	241	0	0	1	113	31
Coal with CCUS	-	0	0	36	95	131	153	0	0	0	104	29
Natural gas with CCUS	-	-	-	14	46	72	89	-	0	0	n.a.	n.a.
Unabated fossil fuels	3 439	4 480	4 535	3 423	2 453	1 710	892	52	21	2	-3.5	-5.6
Coal	1 614	2 200	2 236	1 457	910	548	242	26	9	1	-5.2	-7.6
Natural gas	1 389	1 854	1 875	1 746	1 402	1 088	611	22	11	2	-0.9	-3.9
Oil	436	426	423	220	141	75	39	5	1	0	-7.8	-8.2
Battery storage	1	27	45	1 018	1 949	2 841	4 199	1	6	11	48	18

Table A.4: World CO_2 emissions

	Net Zero Emissions by 2050 Scenario (Mt CO_2)							CAAGR (%) 2022 to:	
	2010	2021	2022	2030	2035	2040	2050	2030	2050
Total CO_2*	**32 877**	**36 589**	**36 930**	**24 030**	**13 375**	**6 471**	**-**	**-5.2**	**n.a.**
Combustion activities (+)	**30 624**	**33 634**	**34 042**	**21 958**	**12 017**	**5 820**	**655**	**-5.3**	**-13**
Coal	13 846	15 104	15 330	8 173	3 541	1 200	171	-7.6	-15
Oil	10 545	10 683	10 963	7 910	5 325	3 219	824	-4.0	-8.8
Natural gas	6 052	7 577	7 499	5 795	3 327	1 780	358	-3.2	-10
Bioenergy and waste	181	269	251	80	- 176	- 379	- 698	-13	n.a.
Other removals (-)**	**-**	**1**	**2**	**167**	**348**	**523**	**933**	**78**	**25**
Biofuels production	-	1	2	98	186	227	312	67	21
Direct air capture	-	-	-	69	162	295	621	n.a.	n.a.
Electricity and heat sectors	**12 511**	**14 598**	**14 822**	**8 113**	**2 854**	**411**	**- 275**	**-7.3**	**n.a.**
Coal	8 946	10 646	10 876	5 156	1 545	42	21	-8.9	-20
Oil	828	574	596	135	45	23	0	-17	-23
Natural gas	2 623	3 227	3 201	2 781	1 401	604	78	-1.7	-12
Bioenergy and waste	114	151	149	41	- 138	- 257	- 374	-15	n.a.
Other energy sector**	**1 438**	**1 530**	**1 554**	**782**	**322**	**108**	**- 198**	**-8.2**	**n.a.**
Final consumption**	**18 668**	**20 191**	**20 293**	**15 187**	**10 350**	**6 241**	**1 088**	**-3.6**	**-9.9**
Coal	4 699	4 355	4 352	2 983	1 971	1 142	138	-4.6	-12
Oil	9 087	9 552	9 815	7 398	4 993	2 989	711	-3.5	-9.0
Natural gas	2 842	3 566	3 500	2 543	1 718	1 036	173	-3.9	-10
Bioenergy and waste	66	118	102	43	- 26	- 93	- 205	-10	n.a.
Industry**	8 324	9 185	8 998	7 158	5 111	3 222	440	-2.8	-10
Chemicals**	1 201	1 329	1 330	1 150	850	521	45	-1.8	-11
Iron and steel**	2 083	2 733	2 623	2 118	1 584	1 032	233	-2.6	-8.3
Cement**	1 916	2 514	2 418	1 911	1 343	875	79	-2.9	-12
Aluminium**	185	261	265	218	172	107	8	-2.4	-12
Transport	7 014	7 599	7 874	5 992	4 062	2 430	578	-3.4	-8.9
Road	5 216	5 847	5 964	4 213	2 718	1 491	236	-4.2	-11
Passenger cars	2 609	2 930	2 975	1 752	916	403	37	-6.4	-14
Heavy-duty trucks	1 489	1 766	1 812	1 610	1 284	856	178	-1.5	-8.0
Aviation	754	661	792	932	744	554	208	2.0	-4.7
Shipping	797	827	855	695	495	313	112	-2.6	-7.0
Buildings	2 891	2 973	2 979	1 741	971	463	54	-6.5	-13
Residential	1 961	2 013	1 997	1 189	675	326	48	-6.3	-12
Services	929	959	983	552	296	137	6	-7.0	-16
Total CO_2 removals**	**-**	**2**	**2**	**234**	**632**	**995**	**1 710**	**85**	**28**
Total CO_2 captured**	**15**	**41**	**42**	**1 024**	**2 421**	**3 724**	**6 040**	**49**	**19**

*Includes industrial process and flaring emissions.

**Includes industrial process emissions.

Table A.5: Economic and activity indicators

	Net Zero Emissions by 2050 Scenario							CAAGR (%) 2022 to:	
	2010	2021	2022	2030	2035	2040	2050	2030	2050
Indicators									
Population (million)	6 967	7 884	7 950	8 520	8 853	9 161	9 681	0.9	0.7
GDP (USD 2022 billion, PPP)	114 463	158 505	163 734	207 282	238 066	270 050	339 273	3.0	2.6
GDP per capita (USD 2022, PPP)	16 429	20 104	20 596	24 329	26 892	29 479	35 044	2.1	1.9
TES/GDP (GJ per USD 1 000, PPP)	4.7	3.9	3.9	2.8	2.3	2.0	1.6	-4.1	-3.1
TFC/GDP (GJ per USD 1 000, PPP)	3.2	2.6	2.6	1.9	1.5	1.3	1.0	-3.9	-3.3
CO_2 intensity of electricity generation (kg CO_2 per kWh)	528	464	460	186	48	3	- 4	-11	n.a.
Industrial production (Mt)									
Primary chemicals	513	689	695	831	872	884	856	2.3	0.7
Steel	1 435	1 960	1 878	1 973	1 966	1 958	1 957	0.6	0.1
Cement	3 280	4 374	4 158	4 264	4 140	4 022	3 934	0.3	-0.2
Aluminium	62	105	108	120	128	136	146	1.4	1.1
Transport									
Passenger cars (billion pkm)	18 984	25 679	26 535	28 608	30 355	33 841	41 638	0.9	1.6
Heavy-duty trucks (billion tkm)	23 364	29 482	30 479	38 037	43 341	49 036	60 335	2.8	2.5
Aviation (billion pkm)	4 923	3 673	6 025	10 969	11 417	12 843	16 545	7.8	3.7
Shipping (billion tkm)	77 101	115 830	124 272	145 087	165 073	188 756	265 253	2.0	2.7
Buildings									
Households (million)	1 798	2 175	2 208	2 439	2 579	2 715	2 963	1.2	1.1
Residential floor area (million m²)	153 219	194 691	198 090	227 039	247 262	268 130	310 109	1.7	1.6
Services floor area (million m²)	39 262	53 415	54 624	51 956	50 141	48 180	44 226	-0.6	-0.8

Definitions

This annex provides general information on terminology used throughout this report including: units and general conversion factors; definitions of fuels, processes and sectors; regional and country groupings; and abbreviations and acronyms.

Units

Area	km^2	square kilometre
	Mha	million hectares
Batteries	Wh/kg	watt hours per kilogramme
Coal	Mtce	million tonnes of coal equivalent (equals 0.7 Mtoe)
Distance	km	kilometre
Emissions	ppm	parts per million (by volume)
	t CO_2	tonnes of carbon dioxide
	Gt CO_2-eq	gigatonnes of carbon-dioxide equivalent (using 100-year global warming potentials for different greenhouse gases)
	kg CO_2-eq	kilogrammes of carbon-dioxide equivalent
	g CO_2/km	grammes of carbon dioxide per kilometre
	g CO_2/kWh	grammes of carbon dioxide per kilowatt-hour
	kg CO_2/kWh	kilogrammes of carbon dioxide per kilowatt-hour
Energy	EJ	exajoule (1 joule x 10^{18})
	PJ	petajoule (1 joule x 10^{15})
	TJ	terajoule (1 joule x 10^{12})
	GJ	gigajoule (1 joule x 10^{9})
	MJ	megajoule (1 joule x 10^{6})
	boe	barrel of oil equivalent
	toe	tonne of oil equivalent
	ktoe	thousand tonnes of oil equivalent
	Mtoe	million tonnes of oil equivalent
	bcme	billion cubic metres of natural gas equivalent
	MBtu	million British thermal units
	kWh	kilowatt-hour
	MWh	megawatt-hour
	GWh	gigawatt-hour
	TWh	terawatt-hour
	Gcal	gigacalorie
Gas	bcm	billion cubic metres
	tcm	trillion cubic metres
Mass	kg	kilogramme
	t	tonne (1 tonne = 1 000 kg)
	kt	kilotonnes (1 tonne x 10^3)
	Mt	million tonnes (1 tonne x 10^6)
	Gt	gigatonnes (1 tonne x 10^9)

Monetary	USD million	1 US dollar x 10^6
	USD billion	1 US dollar x 10^9
	USD trillion	1 US dollar x 10^{12}
	USD/t CO_2	US dollars per tonne of carbon dioxide
Oil	kb/d	thousand barrels per day
	mb/d	million barrels per day
	mboe/d	million barrels of oil equivalent per day
Power	W	watt (1 joule per second)
	kW	kilowatt (1 watt x 10^3)
	MW	megawatt (1 watt x 10^6)
	GW	gigawatt (1 watt x 10^9)
	TW	terawatt (1 watt x 10^{12})

General conversion factors for energy

		Multiplier to convert to:					
		EJ	Gcal	Mtoe	MBtu	bcme	GWh
Convert from:	EJ	1	2.388 x 10^8	23.88	9.478 x 10^8	27.78	2.778 x 10^5
	Gcal	4.1868 x 10^{-9}	1	10^{-7}	3.968	1.163 x 10^{-7}	1.163 x 10^{-3}
	Mtoe	4.1868 x 10^{-2}	10^7	1	3.968 x 10^7	1.163	11 630
	MBtu	1.0551 x 10^{-9}	0.252	2.52 x 10^{-8}	1	2.932 x 10^{-8}	2.931 x 10^{-4}
	bcme	0.036	8.60 x 10^6	0.86	3.41 x 10^7	1	9 999
	GWh	3.6 x 10^{-6}	860	8.6 x 10^{-5}	3 412	1 x 10^{-4}	1

Note: There is no generally accepted definition of boe; typically, the conversion factors used vary from 7.15 to 7.40 boe per toe. Natural gas is attributed a low heating value of 1 MJ per 44.1 kg. Conversions to and from billion cubic metres of natural gas equivalent (bcme) are given as representative multipliers but may differ from the average values obtained by converting natural gas volumes between IEA balances due to the use of country-specific energy densities. Lower heating values (LHV) are used throughout.

Definitions

Advanced bioenergy: Sustainable fuels produced from non-food crop feedstocks, which are capable of delivering significant life cycle greenhouse gas emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts. This definition differs from the one used for "advanced biofuels" in US legislation, which is based on a minimum 50% life cycle greenhouse gas reduction and, therefore, includes sugar cane ethanol.

Agriculture: Includes all energy used on farms, in forestry and for fishing.

Agriculture, forestry and other land use (AFOLU) emissions: Includes greenhouse gas emissions from agriculture, forestry and other land use.

Ammonia (NH_3): Is a compound of nitrogen and hydrogen. It can be used as a feedstock in the chemical sector, as a fuel in direct combustion processes or in fuel cells, and as a hydrogen carrier. To be considered a low-emissions fuel, ammonia must be produced from low-emissions hydrogen. Produced in such a way, ammonia is considered a low-emissions hydrogen-based liquid fuel.

Aviation: This transport mode includes both domestic and international flights and their use of aviation fuels. Domestic aviation covers flights that depart and land in the same country; flights for military purposes are included. International aviation includes flights that land in a country other than the departure location.

Back-up generation capacity: Households and businesses connected to a main power grid may also have a source of back-up power generation capacity that, in the event of disruption, can provide electricity. Back-up generators are typically fuelled with diesel or gasoline or based on solar PV and battery technologies. Capacity can be as little as a few kilowatts. Such capacity is distinct from mini-grid and off- grid systems that are not connected to a main power grid.

Battery storage: Energy storage technology that uses reversible chemical reactions to absorb and release electricity on demand.

Biodiesel: Diesel-equivalent fuel made from the transesterification (a chemical process that converts triglycerides in oils) of vegetable oils and animal fats.

Bioenergy: Energy content in solid, liquid and gaseous products derived from biomass feedstocks and biogas. It includes solid bioenergy, liquid biofuels and biogases.

Biogas: A mixture of methane, CO_2 and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen-free environment.

Biogases: Includes biogas and biomethane.

Biomethane: Biomethane is a near-pure source of methane produced either by "upgrading" biogas (a process that removes any carbon dioxide and other contaminants present in the biogas) or through the gasification of solid biomass followed by methanation. It is also known as renewable natural gas.

Blended finance: A broad category of development finance arrangements that blend relatively small amounts of concessional donor funds into investments in order to mitigate specific investment risks. This can catalyse important investment that would otherwise be unable to proceed under conventional commercial terms. These arrangements can be structured as debt, equity, risk-sharing or guarantee products. Specific terms of these arrangements, such as interest rates, tenor, security or rank, can vary across scenarios.

Buildings: The buildings sector includes energy used in residential and services buildings. Services buildings include commercial and institutional buildings and other non-specified buildings. Building energy use includes space heating and cooling, water heating, lighting, appliances and cooking equipment.

Bunkers: Includes both international marine bunker fuels and international aviation bunker fuels.

Capacity credit: Proportion of the installed capacity that can be reliably expected to generate electricity during times of peak demand in the grid to which it is connected.

Capital costs: Costs to develop and construct a fixed asset such as a power plant and grid infrastructure or execute a project, excluding financing costs. For power generation assets, capital costs include refurbishment and decommissioning costs.

Carbon capture, utilisation and storage (CCUS)**:** The process of capturing carbon dioxide emissions from fuel combustion, industrial processes or directly from the atmosphere. Captured CO_2 emissions can be stored in underground geological formations, onshore or offshore, or used as an input or feedstock in manufacturing.

Cars: Include passenger cars, sport utility vehicles and light trucks.

Clean cooking systems, fuels, stoves and technologies: Cooking solutions that release less harmful pollutants, are more efficient and environmentally sustainable than traditional cooking options that make use of solid biomass (such as a three-stone fire), coal or kerosene. This refers to improved biomass cook stoves, biogas/biodigester systems, electric cooking devices and liquefied petroleum gas, natural gas or ethanol fuelled stoves.

Clean energy: In *power*, clean energy includes generation from renewable sources, nuclear, fossil fuels fitted with CCUS, battery storage, and electricity grids. In *efficiency*, clean energy includes energy efficiency in buildings, industry, and transport excluding aviation bunkers and domestic navigation. In *end-use applications*, clean energy includes direct use of renewables; electric vehicles; electrification in buildings, industry and international marine transport; CCUS in industry and direct air capture. In *fuel supply*, clean energy includes low-emissions fuels.

Coal: Includes both primary coal (including lignite, coking and steam coal) and derived fuels (including patent fuel, brown-coal briquettes, coke-oven coke, gas coke, gas-works gas, coke-oven gas, blast furnace gas and oxygen steel furnace gas). Peat is also included.

Coalbed methane: Category of unconventional natural gas that refers to methane found in coal seams.

Concentrating solar power (CSP)**:** Thermal power generation technology that collects and concentrates sunlight to produce high temperature heat to generate electricity.

Concessional financing: Resources extended at terms more favourable than those available on the market. This can be achieved through one or a combination of the following factors: interest rates below those available on the market; maturity, grace period, security, rank or back-weighted repayment profile that would not be accepted/extended by a commercial financial institution; and/or by providing financing to the recipient otherwise not served by commercial financing.

Conventional liquid biofuels: Fuels produced from food crop feedstocks. Commonly referred to as first generation biofuels and include sugar cane ethanol, starch-based ethanol, fatty acid methyl ester (FAME), straight vegetable oil (SVO) and hydrotreated vegetable oil (HVO) produced from palm, rapeseed or soybean oil.

Critical minerals: A wide range of minerals and metals that are essential in clean energy technologies and other modern technologies and have supply chains that are vulnerable to disruption. Although the exact definition and criteria differ among countries, critical minerals for clean energy technologies typically include chromium, cobalt, copper, graphite, lithium, manganese, molybdenum, nickel, platinum group metals, zinc, rare earth elements and other commodities, as listed in the Annex of the IEA special report on the Role of Critical Minerals in Clean Energy Transitions available at: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

Debt: Bonds or loans issued or taken out by a company to finance its growth and operations.

Decomposition analysis: Statistical approach that decomposes an aggregate indicator to quantify the relative contribution of a set of pre-defined factors leading to a change in the aggregate indicator. The *World Energy Outlook* uses an additive index decomposition of the type Logarithmic Mean Divisia Index (LMDI).

Demand-side integration (DSI)**:** Consists of two types of measures: actions that influence load shape such as energy efficiency and electrification; and actions that manage load such as demand-side response measures.

Demand-side response (DSR)**:** Describes actions which can influence the load profile such as shifting the load curve in time without affecting total electricity demand, or load shedding such as interrupting demand for a short duration or adjusting the intensity of demand for a certain amount of time.

Direct air capture (DAC)**:** Technology to capture CO_2 directly from the atmosphere using liquid solvents or solid sorbents. It is generally coupled with permanent storage of the CO_2 in deep geological formations or its use in the production of fuels, chemicals, building materials or other products. When coupled with permanent geological CO_2 storage, DAC is a carbon removal technology.

Direct air capture and storage (DACS)**:** The process of capturing carbon dioxide emissions directly from the atmosphere. Emissions are then stored in underground geological formations, onshore or offshore, or used as an input or feedstock in manufacturing.

Dispatchable generation: Refers to technologies whose power output can be readily controlled, i.e. increased to maximum rated capacity or decreased to zero in order to match supply with demand at any time except in cases of technical malfunction.

Electricity demand: Defined as total gross electricity generation less own use generation, plus net trade (imports less exports), less transmissions and distribution losses.

Energy efficiency investment: Incremental spending on new energy-efficient equipment or the full cost of refurbishment that reduces energy use. The intention is to capture spending that leads to reduced energy consumption. Under conventional accounting, part of this is categorised as consumption rather than investment.

Electricity generation: Defined as the total amount of electricity generated by power only or combined heat and power plants including generation required for own use. This is also referred to as gross generation.

Electric vehicles: Includes battery electric vehicles and plug-in hybrid electric vehicles.

End-use investment: Includes investment in three categories on the demand side: energy efficiency, end-use renewables and other end-uses.

End-use sectors: Include industry, transport, buildings and others, i.e. agriculture and other non-energy use.

Energy sector CO_2 emissions: CO_2 emissions from fossil fuel combustion, industrial processes, and fugitive and flaring CO_2 from fossil fuel extraction.

Energy sector greenhouse gas emissions: Energy-related and industrial process CO_2 emissions plus fugitive and vented methane (CH_4) and nitrous oxide (N_2O) emissions from the energy and industry sectors.

Energy services: See useful energy.

Ethanol: Refers to bioethanol only. Ethanol is produced from fermenting any biomass high in carbohydrates. Currently, ethanol is made from starches and sugars, but second-generation technologies will allow it to be made from cellulose and hemicellulose, the fibrous material that makes up the bulk of most plant matter.

Fossil fuels: Include coal, natural gas and oil.

Gaseous fuels: Include natural gas, biogases, synthetic methane and hydrogen.

Geothermal: Geothermal energy is heat from the sub-surface of the earth. Water and/or steam carry the geothermal energy to the surface. Depending on its characteristics, geothermal energy can be used for heating and cooling purposes or be harnessed to generate clean electricity if the temperature is adequate.

Heat (end-use)**:** Can be obtained from the combustion of fossil or renewable fuels, direct geothermal or solar heat systems, exothermic chemical processes and electricity (through resistance heating or heat pumps which can extract it from ambient air and liquids). This category refers to the wide range of end-uses, including space and water heating, and cooking in buildings, desalination and process applications in industry. It does not include cooling applications.

Heat (supply)**:** Obtained from the combustion of fuels, nuclear reactors, geothermal resources or the capture of sunlight. It may be used for heating, cooling, or converted into mechanical energy for transport or electricity generation. Commercial heat sold is reported under total final consumption with the fuel inputs allocated under power generation.

Heavy trucks: Include commercial vehicles: medium freight trucks (gross vehicle weight between 3.5 and 15 tonnes); and heavy freight trucks (>15 tonnes).

Hydrogen: Hydrogen is used as a raw material in industry and refining, in the energy system as an energy carrier or is combined with other inputs to produce hydrogen-based fuels. Unless otherwise stated, hydrogen in this report refers to low-emissions hydrogen.

Hydrogen-based fuels: See low-emissions hydrogen-based fuels.

Hydropower: Energy content of the electricity produced in hydropower plants, assuming 100% efficiency. It excludes output from pumped storage and marine (tidal and wave) plants.

Improved cook stoves: Intermediate and advanced improved biomass cook stoves (ISO tier >2). It excludes basic improved cook stoves (ISO tier 0-2).

Industry: The sector includes fuel used within the manufacturing and construction industries. Key industry branches include iron and steel, chemical and petrochemical, cement, aluminium, and pulp and paper. Use by industries for the transformation of energy into another form or for the production of fuels is excluded and reported separately under other energy sector. There is an exception for fuel transformation in blast furnaces and coke ovens, which are reported within iron and steel. Consumption of fuels for the transport of goods is reported as part of the transport sector, while consumption by off-road vehicles is reported under industry.

International aviation bunkers: Includes the deliveries of aviation fuels to aircraft for international aviation. Fuels used by airlines for their road vehicles are excluded. The domestic/international split is determined on the basis of departure and landing locations and not by the nationality of the airline. For many countries this incorrectly excludes fuels used by domestically owned carriers for their international departures.

International marine bunkers: Includes the quantities delivered to ships of all flags that are engaged in international navigation. The international navigation may take place at sea, on inland lakes and waterways, and in coastal waters. Consumption by ships engaged in domestic navigation is excluded. The domestic/international split is determined on the basis of port of departure and port of arrival, and not by the flag or nationality of the ship. Consumption by fishing vessels and by military forces is excluded and instead included in the residential, services and agriculture category.

Investment: Investment is the capital expenditure in energy supply, infrastructure, end-use and efficiency. *Fuel supply investment* includes the production, transformation and transport of oil, gas, coal and low-emissions fuels. *Power sector investment* includes new construction and refurbishment of generation, electricity grids (transmission, distribution and public electric vehicle chargers) and battery storage. *Energy efficiency investment* includes efficiency improvements in buildings, industry and transport. *Other end-use investment* includes the purchase of equipment for the direct use of renewables, electric vehicles, electrification in buildings, industry and international marine transport, equipment for the use of low-emissions fuels, and CCUS in industry and direct air capture. Data and projections reflect spending over the lifetime of projects and are presented in real terms in year-2022 US dollars converted at market exchange rates unless otherwise stated. Total investment reported for a year reflects the amount spent in that year.

Light-duty vehicles (LDVs)**:** Include passenger cars and light commercial vehicles (gross vehicle weight <3.5 tonnes).

Liquid biofuels: Include liquid fuels derived from biomass or waste feedstock, e.g. ethanol, biodiesel and biojet fuels. They can be classified as conventional and advanced biofuels according to the combination of feedstock and technologies used to produce them and their respective maturity. Unless otherwise stated, biofuels are expressed in energy-equivalent volumes of gasoline, diesel and kerosene.

Liquid fuels: Include oil, liquid biofuels (expressed in energy-equivalent volumes of gasoline and diesel), synthetic oil and ammonia.

Low-emissions electricity: Includes renewable energy technologies, low-emissions hydrogen-based generation, low-emissions hydrogen-based fuel generation, nuclear power and fossil fuel power plants equipped with carbon capture, utilisation and storage.

Low-emissions fuels: Include modern bioenergy, low-emissions hydrogen and low-emissions hydrogen-based fuels.

Low-emissions hydrogen: Hydrogen which is produced through water electrolysis with electricity generated from a low-emissions source such as renewables or nuclear, or biomass or from fossil fuels equipped with CCUS technology. Production from fossil fuels with CCUS is included only if upstream emissions are sufficiently low, if capture, at high rates, is applied to all CO_2 streams associated with the production route, and if all CO_2 is permanently stored to prevent its release to the atmosphere.

Low-emissions hydrogen-based fuels: Include ammonia and synthetic hydrocarbons produced from low-emissions hydrogen. In the case of synthetic hydrocarbons, they are produced from low-emissions hydrogen and a sustainable carbon source (of biogenic origin or directly captured from the atmosphere).

Low-emissions material production: Production that achieves substantial emissions reductions but falls short of achieving near zero emissions. The IEA has proposed greenhouse gas emissions intensity thresholds and a continuous scale of evaluation for low-emissions production, with the quantity being proportional to the reduction in emissions intensity achieved for steel and cement in the *Achieving Net Zero Heavy Industry Sectors in G7 Members* (IEA, 2022). The thresholds depend on the scrap share of metallics input for steel and the clinker-to-cement ratio for cement. For other energy-intensive commodities such as aluminium, fertilisers and plastics, reductions in emissions intensity and the continuous scale evaluation would be equivalent to the considerations for low-emissions steel and cement.

Marine energy: Represents the mechanical energy derived from tidal movement, wave motion or ocean current and exploited for electricity generation.

Mini-grids: Small grid systems linking a number of households or other consumers.

Modern bioenergy and renewable waste: Refers to bioenergy excluding traditional use of biomass and renewable waste.

Modern energy access: Includes household access to a minimum level of electricity; household access to safer and more sustainable cooking and heating fuels, and clean cooking stoves; access that enables productive economic activity; and access for public services.

Modern liquid bioenergy: Includes biogasoline, biodiesel, biojet kerosene and other liquid biofuels.

Modern renewables: Includes all uses of renewable energy with the exception of traditional use of solid biomass.

Modern solid bioenergy: Includes all solid bioenergy products (see solid bioenergy definition) except the traditional use of biomass. It also includes the use of solid bioenergy in intermediate and advanced improved biomass cook stoves (ISO tier ≥ 3) requiring fuel to be cut in small pieces or often using processed biomass such as pellets.

Natural gas: Includes gas occurring in deposits, whether liquefied or gaseous, consisting mainly of methane. It includes both non-associated gases originating from fields producing hydrocarbons only in gaseous form, and associated gas produced in association with crude oil production as well as methane recovered from coal mines (colliery gas). Natural gas liquids, manufactured gas (produced from municipal or industrial waste, or sewage) and quantities vented or flared are not included. Gas data in cubic metres are expressed on a gross calorific value basis and are measured at 15 °C and at 760 mm Hg (Standard Conditions). Gas data expressed in tonnes of oil equivalent, mainly for comparison reasons with other fuels, are on a net calorific basis. The difference between the net and the gross calorific value is the latent heat of vaporisation of the water vapour produced during combustion of the fuel (for gas the net calorific value is 10% lower than the gross calorific value).

Near zero emission capable material production capacity: capacity that will achieve substantial emissions reductions from the start – but fall short of near zero emission material production (see following definition) initially – with plans to continue reducing emissions over time such that they could later achieve near zero emission production without additional capital investment.

Near zero emission material production: for steel and cement, production that achieves the near zero emission GHG emissions intensity thresholds defined in the IEA's 'Achieving Net Zero Heavy Industry Sectors in G7 Members' (2022); the thresholds depend on the scrap share of metallics input for steel and the clinker-to-cement ratio for cement. For other energy-intensive commodities like aluminium, fertilisers and plastics, production that achieves reductions in emissions intensity equivalent to the considerations for near zero emission steel and cement.

Near zero emission material production capacity: capacity that, once operational, will achieve near zero emission material production (see preceding definition) from the start.

Network gases: Includes natural gas, biomethane, synthetic methane and hydrogen blended in a gas network.

Non-energy use: The use of fuels as feedstocks for chemical products that are not used in energy applications. Examples of resulting products are lubricants, paraffin waxes, asphalt, bitumen, coal tars and timber preservative oils.

Nuclear: Refers to the primary energy equivalent of the electricity produced by a nuclear power plant, assuming an average conversion efficiency of 33%.

Off-grid systems: Mini-grids and stand-alone systems for individual households or groups of consumers not connected to a main grid.

Offshore wind: Refers to electricity produced by wind turbines that are installed in open water, usually in the ocean.

Oil: Oil production includes both conventional and unconventional oil. Petroleum products include refinery gas, ethane, liquid petroleum gas, aviation gasoline, motor gasoline, jet fuels, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirit, lubricants, bitumen, paraffin, waxes and petroleum coke.

Other energy sector: Covers the use of energy by transformation industries and the energy losses in converting primary energy into a form that can be used in the final consuming sectors. It includes losses in low-emissions hydrogen and hydrogen-based fuels production, bioenergy processing, gas works, petroleum refineries, coal and gas transformation and liquefaction. It also includes energy own use in coal mines, in oil and gas extraction and in electricity and heat production. Transfers and statistical differences are also included in this category. Fuel transformation in blast furnaces and coke ovens are not accounted for in the other energy sector category.

Power generation: Refers to fuel use in electricity generation plants, heat plants, and combined heat and power plants. Both main activity producer plants and small plants that produce fuel for their own use (auto-producers) are included.

Productive uses: Energy used towards an economic purpose: agriculture, industry, services and non-energy use. Some energy demand from the transport sector, for example freight, could be considered as productive, but is treated separately.

Renewables: Includes bioenergy, renewable waste, geothermal, hydropower, solar photovoltaics (PV), concentrating solar power (CSP), wind and marine (tide and wave) energy for electricity and heat generation.

Residential: Energy used by households including space heating and cooling, water heating, lighting, appliances, electronic devices and cooking.

Road transport: Includes all road vehicle types (passenger cars, two/three-wheelers. Light commercial vehicles, buses and medium and heavy trucks).

Services: Energy used in commercial facilities such as offices, shops, hotels, and restaurants, and in institutional buildings such as schools, hospitals and public offices. Energy use in services includes space heating and cooling, water heating, lighting, appliances, cooking and desalination.

Shipping/navigation: This transport sub-sector includes both domestic and international navigation and their use of marine fuels. Domestic navigation covers the transport of goods or persons on inland waterways and for national sea voyages (starts and ends in the same country without any intermediate foreign port). International navigation includes quantities of fuels delivered to merchant ships (including passenger ships) of any nationality for consumption during international voyages transporting goods or passengers.

Solar photovoltaics (PV)**:** Electricity produced from solar photovoltaic cells.

Solid bioenergy: Includes charcoal, fuelwood, dung, agricultural residues, wood waste and other solid biogenic wastes.

Steam coal: A type of coal that is mainly used for heat production or steam-raising in power plants and, to a lesser extent, in industry. Typically, steam coal is not of sufficient quality for steel making. Coal of this quality is also commonly known as thermal coal.

Synthetic fuel: Includes synthetic hydrocarbon fuels such as methane and oil products, e.g. diesel or kerosene.

Synthetic methane: Methane from sources other than natural gas, including coal-to-gas and low-emissions synthetic methane.

Total energy supply (TES)**:** Represents domestic demand only and is broken down into electricity and heat generation, other energy sector and total final consumption.

Total final consumption (TFC)**:** Is the sum of consumption by the various end-use sectors. TFC is broken down into energy demand in the following sectors: industry (including manufacturing, mining, chemicals production, blast furnaces and coke ovens), transport, buildings (including residential and services) and other (including agriculture and other non-energy use). It excludes international marine and aviation bunkers, except at world level where it is included in the transport sector.

Total final energy consumption (TFEC)**:** Is a variable defined primarily for tracking progress towards target 7.2 of the United Nations Sustainable Development Goals (SDG). It incorporates total final consumption by end-use sectors, but excludes non-energy use. It excludes international marine and aviation bunkers, except at world level. Typically, this is used in the context of calculating the renewable energy share in total final energy consumption (indicator SDG 7.2.1), where TFEC is the denominator.

Total primary energy demand (TPED)**:** See total energy supply.

Traditional use of biomass: Refers to the use of solid biomass with basic technologies, such as a three-stone fire or basic cook stoves (ISO tier 0-2), often with no or poorly operating chimneys. Forms of biomass used include wood, wood waste, charcoal agricultural residues and other bio-sourced fuels such as animal dung.

Transport: Fuels and electricity used in the transport of goods or people within the national territory irrespective of the economic sector within which the activity occurs. This includes fuel and electricity delivered to vehicles using public roads or for use in rail vehicles; fuel delivered to vessels for domestic navigation; fuel delivered to aircraft for domestic aviation; and energy consumed in the delivery of fuels through pipelines. Fuel delivered to international marine and aviation bunkers is presented only at the world level and is excluded from the transport sector at a domestic level.

Trucks: Includes all size categories of commercial vehicles: light trucks (gross vehicle weight less than 3.5 tonnes); medium freight trucks (gross vehicle weight 3.5-15 tonnes); and heavy freight trucks (>15 tonnes).

Unabated fossil fuel use: Combustion of fossil fuels in facilities without CCUS.

Useful energy: Refers to the energy that is available to end-users to satisfy their needs. This is also referred to as energy services demand. As result of transformation losses at the point of use, the amount of useful energy is lower than the corresponding final energy demand for most technologies. Equipment using electricity often has higher conversion efficiency than equipment using other fuels, meaning that for a unit of energy consumed, electricity can provide more energy services.

Wind: Electricity produced by wind turbines from the kinetic energy of wind.

Woody energy crops: Short-rotation plantings of woody biomass for bioenergy production, such as coppiced willow and miscanthus.

Vans: Includes commercial vehicles and light trucks (gross vehicle weight >3.5 tonnes).

Variable renewable energy (VRE): Refers to power generating technologies in which maximum output at any time depends on the availability of fluctuating renewable energy resources. VRE includes a broad array of technologies such as wind power, solar PV, run-of-river hydro, concentrating solar power (where no thermal storage is included) and marine (tidal and wave).

Zero-carbon-ready buildings: A zero-carbon-ready building is highly energy efficient and either uses renewable energy directly, or an energy supply that can be fully decarbonised, such as electricity or district heat.

Regional and country groupings

Advanced economies: OECD regional grouping and Bulgaria, Croatia, Cyprus[1,2], Malta and Romania.

Africa: North Africa and sub-Saharan Africa regional groupings.

Asia Pacific: Southeast Asia regional grouping and Australia, Bangladesh, China, India, Japan, Korea, Democratic People's Republic of Korea, Mongolia, Nepal, New Zealand, Pakistan, Sri Lanka, Chinese Taipei, and other Asia Pacific countries and territories.[3]

Caspian: Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan.

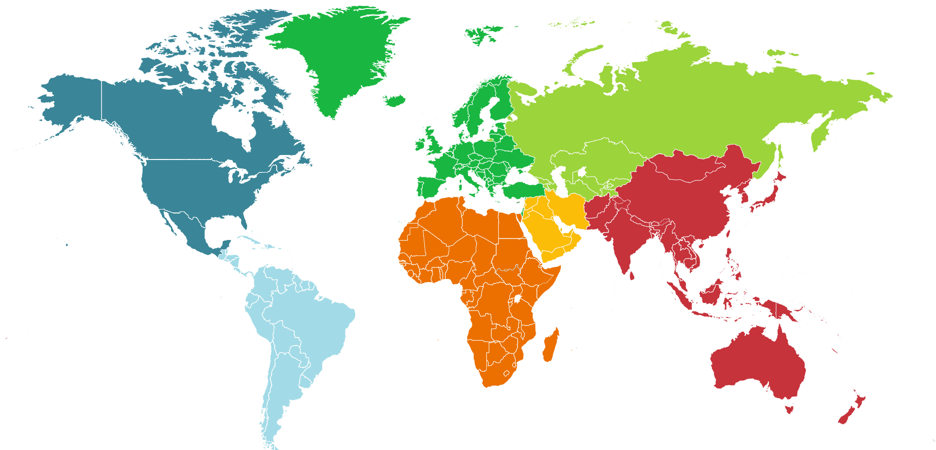
Central and South America: Argentina, Plurinational State of Bolivia (Bolivia), Brazil, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay, Bolivarian Republic of Venezuela (Venezuela), and other Central and South American countries and territories.[4]

China: Includes (the People's Republic of) China and Hong Kong, China.

Developing Asia: Asia Pacific regional grouping excluding Australia, Japan, Korea and New Zealand.

Emerging market and developing economies: All other countries not included in the advanced economies regional grouping.

Figure C.1 ▷ Main country groupings



Note: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Eurasia: Caspian regional grouping and the Russian Federation (Russia).

Europe: European Union regional grouping and Albania, Belarus, Bosnia and Herzegovina, North Macedonia, Gibraltar, Iceland, Israel[5], Kosovo, Montenegro, Norway, Republic of Moldova, Serbia, Switzerland, Türkiye, Ukraine and United Kingdom.

European Union: Austria, Belgium, Bulgaria, Croatia, Cyprus[1,2], Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain and Sweden.

IEA (International Energy Agency)**:** OECD regional grouping excluding Chile, Colombia, Iceland, Israel, Latvia, and Slovenia.

Latin America: Central and South America regional grouping and Mexico.

Middle East: Bahrain, Islamic Republic of Iran (Iran), Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic (Syria), United Arab Emirates and Yemen.

Non-OECD: All other countries not included in the OECD regional grouping.

Non-OPEC: All other countries not included in the OPEC regional grouping.

North Africa: Algeria, Egypt, Libya, Morocco and Tunisia.

North America: Canada, Mexico and United States.

OECD (Organisation for Economic Co-operation and Development)**:** Australia, Austria, Belgium, Canada, Chile, Colombia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Türkiye, United Kingdom and United States.

OPEC (Organisation of the Petroleum Exporting Countries)**:** Algeria, Angola, Republic of the Congo (Congo), Equatorial Guinea, Gabon, the Islamic Republic of Iran (Iran), Iraq, Kuwait, Libya, Nigeria, Saudi Arabia, United Arab Emirates and Bolivarian Republic of Venezuela (Venezuela).

Southeast Asia: Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic (Lao PDR), Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam. These countries are all members of the Association of Southeast Asian Nations (ASEAN).

Sub-Saharan Africa: Angola, Benin, Botswana, Cameroon, Republic of the Congo (Congo), Côte d'Ivoire, Democratic Republic of the Congo, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Mauritius, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania (Tanzania), Togo, Zambia, Zimbabwe and other African countries and territories.[6]

Country notes

[1] Note by Republic of Türkiye: The information in this document with reference to "Cyprus" relates to the southern part of the island. There is no single authority representing both Turkish and Greek Cypriot people on the island. Türkiye recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".

[2] Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Türkiye. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

[3] Individual data are not available and are estimated in aggregate for: Afghanistan, Bhutan, Cook Islands, Fiji, French Polynesia, Kiribati, Macau (China), Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste and Tonga and Vanuatu.

[4] Individual data are not available and are estimated in aggregate for: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Bonaire, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), French Guiana, Grenada, Guadeloupe, Guyana, Martinique, Montserrat, Saba, Saint Eustatius, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and Grenadines, Saint Maarten, Turks and Caicos Islands.

[5] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

[6] Individual data are not available and are estimated in aggregate for: Burkina Faso, Burundi, Cabo Verde, Central African Republic, Chad, Comoros, Djibouti, Kingdom of Eswatini, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Réunion, Rwanda, Sao Tome and Principe, Seychelles, Sierra Leone, Somalia and Uganda.

Abbreviations and acronyms

AC	alternating current
AFOLU	agriculture, forestry and other land use
APS	Announced Pledges Scenario
BECCS	bioenergy equipped with CCUS
CCUS	carbon capture, utilisation and storage
CDR	carbon dioxide removal
CH_4	methane
CO_2	carbon dioxide
CO_2-eq	carbon-dioxide equivalent
COP	Conference of Parties (UNFCCC)
CSP	concentrating solar power
DAC	direct air capture
DC	direct current
DER	distributed energy resources
DSI	demand-side integration
DSR	demand-side response
EAF	electric arc furnaces
EMDE	emerging market and developing economies
EU	European Union
EV	electric vehicle

FID	final investment decision
GDP	gross domestic product
GHG	greenhouse gases
ICE	internal combustion engine
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
LDVs	light-duty vehicles
LED	light-emitting diode
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MER	market exchange rate
NDCs	Nationally Determined Contributions
NO_X	nitrogen oxides
N_2O	nitrous oxide
NZE	Net Zero Emissions by 2050 Scenario
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PPP	purchasing power parity
PV	photovoltaics
R&D	research and development
RD&D	research, development and demonstration
SAF	sustainable aviation fuel
SDG	Sustainable Development Goals (United Nations)
SR1.5	IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels
STEPS	Stated Policies Scenario
T&D	transmission and distribution
TES	total energy supply
TFC	total final consumption
TFEC	total final energy consumption
TPED	total primary energy demand
UN	United Nations
UNDP	UN Development Programme
UNEP	UN Environment Programme
UNFCCC	UN Framework Convention on Climate Change
UK	United Kingdom
US	United States
VRE	variable renewable energy
WACC	weighted average cost of capital
WEO	*World Energy Outlook*
WHO	World Health Organization

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Annex B: Definitions

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Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach
2023 Update

In May 2021, the IEA published its landmark report *Net Zero Emissions by 2050: A Roadmap for the Global Energy Sector*. The report set out a narrow but feasible pathway for the global energy sector to contribute to the Paris Agreement's goal of limiting the rise in global temperatures to 1.5 °C above pre-industrial levels. The *Net Zero Roadmap* quickly became an important benchmark for policy makers, industry, the financial sector and civil society.

Since the report was released, many changes have taken place, notably amid the global energy crisis triggered by Russia's invasion of Ukraine in February 2022. And energy sector carbon dioxide emissions have continued to rise, reaching a new record in 2022. Yet there are also increasing grounds for optimism: the last two years have also seen remarkable progress in developing and deploying some key clean energy technologies.

This 2023 update to our *Net Zero Roadmap* surveys this complex and dynamic landscape and sets out an updated pathway to net zero by 2050, taking account of the key developments that have occurred since 2021.