Net Zero by 2050

A Roadmap for the Global Energy Sector

International Energy Agency

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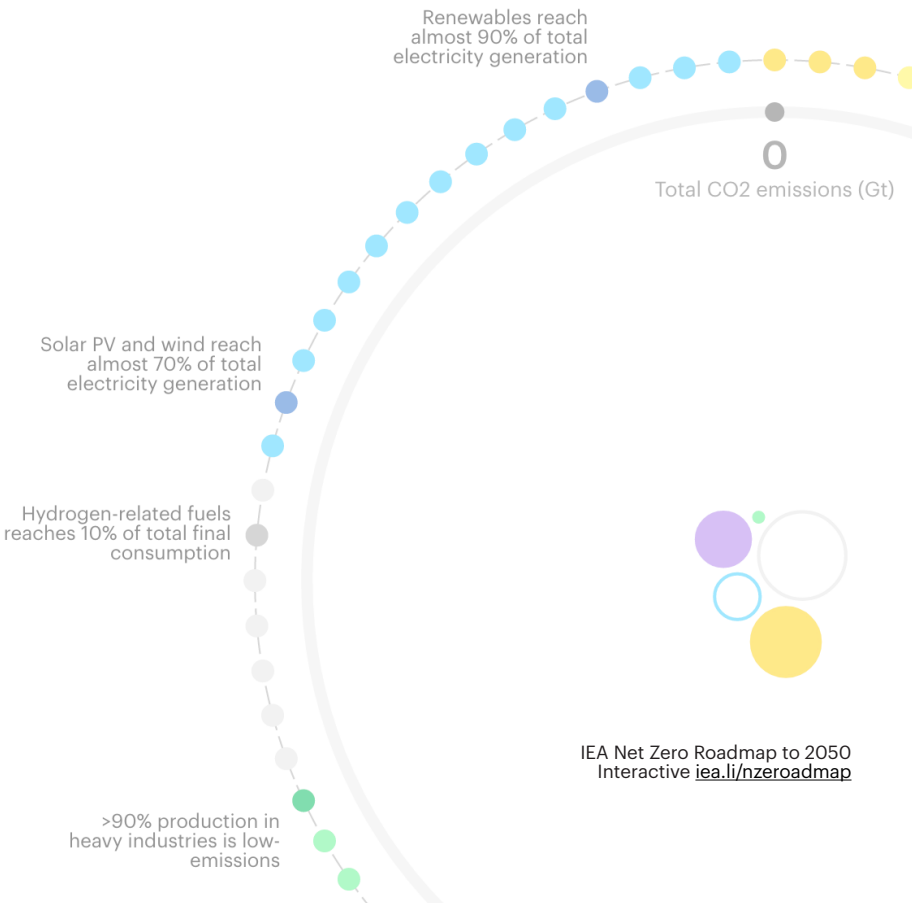
Reaching net-zero emissions globally by 2050

is a critical and formidable goal



IEA Net Zero Roadmap to 2050
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The energy sector is the source of around three-quarters of greenhouse gas emissions today and holds the key to averting the worst effects of climate change, perhaps the greatest challenge humankind has faced. Reducing global carbon dioxide (CO_2) emissions to net zero by 2050 is consistent with efforts to limit the long-term increase in average global temperatures to 1.5˚C. This calls for nothing less than a complete transformation of how we produce, transport and consume energy. The growing political consensus on reaching net zero is cause for considerable optimism about the progress the world can make, but the changes required to reach net-zero emissions globally by 2050 are poorly understood. A huge amount of work is needed to turn today's impressive ambitions into reality, especially given the range of different situations among countries and their differing capacities to make the necessary changes. This special IEA report sets out a pathway for achieving this goal, resulting in a clean and resilient energy system that would bring major benefits for human prosperity and well-being.

The global pathway to net-zero emissions by 2050 detailed in this report requires all governments to significantly strengthen and then successfully implement their energy and climate policies. Commitments made to date fall far short of what is required by that pathway. The number of countries that have pledged to achieve net-zero emissions has grown rapidly over the last year and now covers around 70% of global emissions of CO_2. This is a huge step forward. However, most pledges are not yet underpinned by near-term policies and measures. Moreover, even if successfully fulfilled, the pledges to date would still leave around 22 billion tonnes of CO_2 emissions worldwide in 2050. The continuation of that trend would be consistent with a temperature rise in 2100 of around 2.1 °C. Global emissions fell in 2020 because of the Covid-19 crisis but are already rebounding strongly as economies recover. Further delay in acting to reverse that trend will put net zero by 2050 out of reach.

In this Summary for Policy Makers, we outline the essential conditions for the global energy sector to reach net-zero CO_2 emissions by 2050. The pathway described in depth in this report achieves this objective with no offsets from outside the energy sector, and with low reliance on negative emissions technologies. It is designed to maximise technical feasibility, cost-effectiveness and social acceptance while ensuring continued economic growth and secure energy supplies. We highlight the priority actions that are needed today to ensure the opportunity of net zero by 2050 – narrow but still achievable – is not lost. The report provides a global view, but countries do not start in the same place or finish at the same time: advanced economies have to reach net zero before emerging markets and developing economies, and assist others in getting there. We also recognise that the route mapped out here is a path, not necessarily the path, and so we examine some key uncertainties, notably concerning the roles played by bioenergy, carbon capture and behavioural changes. Getting to net zero will involve countless decisions by people across the world, but our primary aim is to inform the decisions made by policy makers, who have the greatest scope to move the world closer to its climate goals.

Net zero by 2050 hinges on an unprecedented clean technology push to 2030

The path to net-zero emissions is narrow: staying on it requires immediate and massive deployment of all available clean and efficient energy technologies. In the net-zero emissions pathway presented in this report, the world economy in 2030 is some 40% larger than today but uses 7% less energy. A major worldwide push to increase energy efficiency is an essential part of these efforts, resulting in the annual rate of energy intensity improvements averaging 4% to 2030 – about three-times the average rate achieved over the last two decades. Emissions reductions from the energy sector are not limited to CO_2: in our pathway, methane emissions from fossil fuel supply fall by 75% over the next ten years as a result of a global, concerted effort to deploy all available abatement measures and technologies.

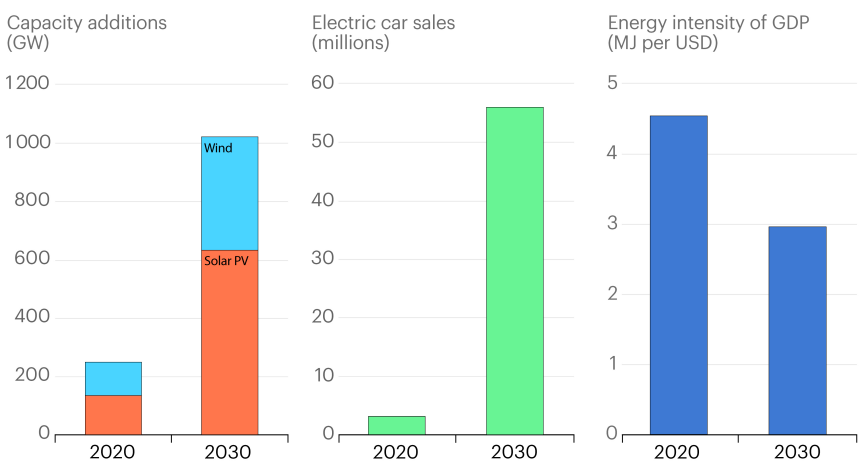
Ever-cheaper renewable energy technologies give electricity the edge in the race to zero. Our pathway calls for scaling up solar and wind rapidly this decade, reaching annual additions of 630 gigawatts (GW) of solar photovoltaics (PV) and 390 GW of wind by 2030, four-times the record levels set in 2020. For solar PV, this is equivalent to installing the world's current largest solar park roughly every day. Hydropower and nuclear, the two largest sources of low-carbon electricity today, provide an essential foundation for transitions. As the electricity sector becomes cleaner, electrification emerges as a crucial economy-wide tool for reducing emissions. Electric vehicles (EVs) go from around 5% of global car sales to more than 60% by 2030.

Priority action: Make the 2020s the decade of massive clean energy expansion

All the technologies needed to achieve the necessary deep cuts in global emissions by 2030 already exist, and the policies that can drive their deployment are already proven.

As the world continues to grapple with the impacts of the Covid-19 pandemic, it is essential that the resulting wave of investment and spending to support economic recovery is aligned with the net zero pathway. Policies should be strengthened to speed the deployment of clean and efficient energy technologies. Mandates and standards are vital to drive consumer spending and industry investment into the most efficient technologies. Targets and competitive auctions can enable wind and solar to accelerate the electricity sector transition. Fossil fuel subsidy phase-outs, carbon pricing and other market reforms can ensure appropriate price signals. Policies should limit or provide disincentives for the use of certain fuels and technologies, such as unabated coal-fired power stations, gas boilers and conventional internal combustion engine vehicles. Governments must lead the planning and incentivising of the massive infrastructure investment, including in smart transmission and distribution grids.

Key clean technologies ramp up by 2030 in the net zero pathway



Note: MJ = megajoule; GDP = gross domestic product in purchasing power parity.

Net zero by 2050 requires huge leaps in clean energy innovation

Reaching net zero by 2050 requires further rapid deployment of available technologies as well as widespread use of technologies that are not on the market yet. Major innovation efforts must occur over this decade in order to bring these new technologies to market in time. Most of the global reductions in CO_2 emissions through 2030 in our pathway come from technologies readily available today. But in 2050, almost half the reductions come from technologies that are currently at the demonstration or prototype phase. In heavy industry and long-distance transport, the share of emissions reductions from technologies that are still under development today is even higher.

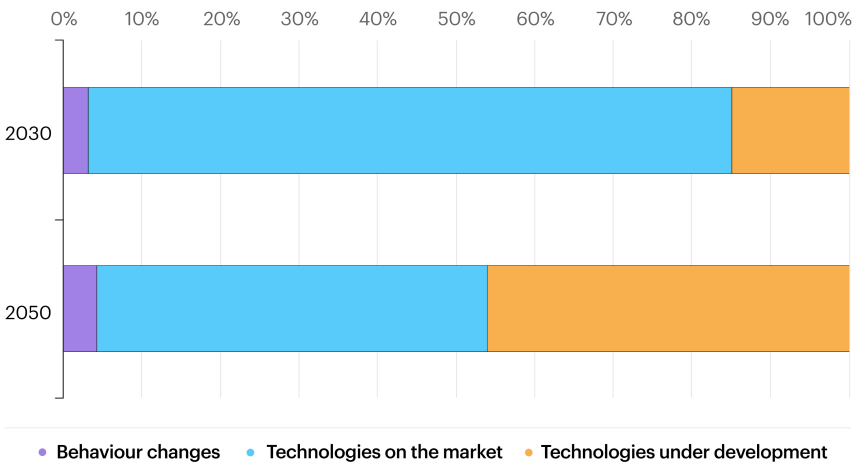
The biggest innovation opportunities concern advanced batteries, hydrogen electrolysers, and direct air capture and storage. Together, these three technology areas make vital contributions the reductions in CO_2 emissions between 2030 and 2050 in our pathway. Innovation over the next ten years – not only through research and development (R&D) and demonstration but also through deployment – needs to be accompanied by the large-scale construction of the infrastructure the technologies will need. This includes new pipelines to transport captured CO_2 emissions and systems to move hydrogen around and between ports and industrial zones.

Priority action: Prepare for the next phase of the transition by boosting innovation

Clean energy innovation must accelerate rapidly, with governments putting R&D, demonstration and deployment at the core of energy and climate policy.

Government R&D spending needs to be increased and reprioritised. Critical areas such as electrification, hydrogen, bioenergy and carbon capture, utilisation and storage (CCUS) today receive only around one-third of the level of public R&D funding of the more established low-carbon electricity generation and energy efficiency technologies. Support is also needed to accelerate the roll-out of demonstration projects, to leverage private investment in R&D, and to boost overall deployment levels to help reduce costs. Around USD 90 billion of public money needs to be mobilised globally as soon as possible to complete a portfolio of demonstration projects before 2030. Currently, only roughly USD 25 billion is budgeted for that period. Developing and deploying these technologies would create major new industries, as well as commercial and employment opportunities.

Annual CO_2 emissions savings in the net zero pathway, relative to 2020



The transition to net zero is for and about people

A transition of the scale and speed described by the net zero pathway cannot be achieved without sustained support and participation from citizens. The changes will affect multiple aspects of people's lives – from transport, heating and cooking to urban planning and jobs. We estimate that around 55% of the cumulative emissions reductions in the pathway are linked to consumer choices such as purchasing an EV, retrofitting a house with energy-efficient technologies or installing a heat pump. Behavioural changes, particularly in advanced economies – such as replacing car trips with walking, cycling or public transport, or foregoing a long-haul flight – also provide around 4% of the cumulative emissions reductions.

Providing electricity to around 785 million people that have no access and clean cooking solutions to 2.6 billion people that lack those options is an integral part of our pathway. Emissions reductions have to go hand-in-hand with efforts to ensure energy access for all by 2030. This costs around USD 40 billion a year, equal to around 1% of average annual energy sector investment, while also bringing major co-benefits from reduced indoor air pollution.

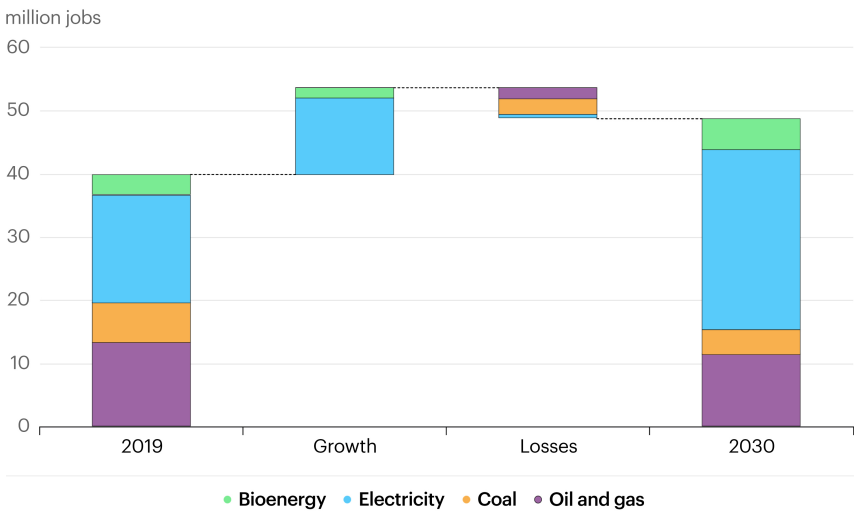
Some of the changes brought by the clean energy transformation may be challenging to implement, so decisions must be transparent, just and cost-effective. Governments need to ensure that clean energy transitions are people-centred and inclusive. Household energy expenditure as a share of disposable income – including purchases of efficient appliances and fuel bills – rises modestly in emerging market and developing economies in our net zero pathway as more people gain access to energy and demand for modern energy services increases rapidly. Ensuring the affordability of energy for households demands close attention: policy tools that can direct support to the poorest include tax credits, loans and targeted subsidies.

Priority action: Clean energy jobs will grow strongly but must be spread widely

Energy transitions have to take account of the social and economic impacts on individuals and communities, and treat people as active participants.

The transition to net zero brings substantial new opportunities for employment, with 14 million jobs created by 2030 in our pathway thanks to new activities and investment in clean energy. Spending on more efficient appliances, electric and fuel cell vehicles, and building retrofits and energy-efficient construction would require a further 16 million workers. But these opportunities are often in different locations, skill sets and sectors than the jobs that will be lost as fossil fuels decline. In our pathway, around 5 million jobs are lost. Most of those jobs are located close to fossil fuel resources, and many are well paid, meaning structural changes can cause shocks for communities with impacts that persist over time. This requires careful policy attention to address the employment losses. It will be vital to minimise hardships associated with these disruptions, such as by retraining workers, locating new clean energy facilities in heavily affected areas wherever possible, and providing regional aid.

Global employment in energy supply in the net zero pathway, 2019-2030



An energy sector dominated by renewables

In the net zero pathway, global energy demand in 2050 is around 8% smaller than today, but it serves an economy more than twice as big and a population with 2 billion more people. More efficient use of energy, resource efficiency and behavioural changes combine to offset increases in demand for energy services as the world economy grows and access to energy is extended to all.

Instead of fossil fuels, the energy sector is based largely on renewable energy. Two-thirds of total energy supply in 2050 is from wind, solar, bioenergy, geothermal and hydro energy. Solar becomes the largest source, accounting for one-fifth of energy supplies. Solar PV capacity increases 20-fold between now and 2050, and wind power 11-fold.

Net zero means a huge decline in the use of fossil fuels. They fall from almost four-fifths of total energy supply today to slightly over one-fifth by 2050. Fossil fuels that remain in 2050 are used in goods where the carbon is embodied in the product such as plastics, in facilities fitted with CCUS, and in sectors where low-emissions technology options are scarce.

Electricity accounts for almost 50% of total energy consumption in 2050. It plays a key role across all sectors – from transport and buildings to industry – and is essential to produce low-emissions fuels such as hydrogen. To achieve this, total electricity generation increases over two-and-a-half-times between today and 2050. At the same time, no additional new final investment decisions should be taken for new unabated coal plants, the least efficient coal plants are phased out by 2030, and the remaining coal plants still in use by 2040 are retrofitted. By 2050, almost 90% of electricity generation comes from renewable sources, with wind and solar PV together accounting for nearly 70%. Most of the remainder comes from nuclear.

Emissions from industry, transport and buildings take longer to reduce. Cutting industry emissions by 95% by 2050 involves major efforts to build new infrastructure. After rapid innovation progress through R&D, demonstration and initial deployment between now and 2030 to bring new clean technologies to market, the world then has to put them into action. Every month from 2030 onwards, ten heavy industrial plants are equipped with CCUS, three new hydrogen-based industrial plants are built, and 2 GW of electrolyser capacity are added at industrial sites. Policies that end sales of new internal combustion engine cars by 2035 and boost electrification underpin the massive reduction in transport emissions. In 2050, cars on the road worldwide run on electricity or fuel cells. Low-emissions fuels are essential where energy needs cannot easily or economically be met by electricity. For example, aviation relies largely on biofuels and synthetic fuels, and ammonia is vital for shipping. In buildings, bans on new fossil fuel boilers need to start being introduced globally in 2025, driving up sales of electric heat pumps. Most old buildings and all new ones comply with zero-carbon-ready building energy codes.[1]

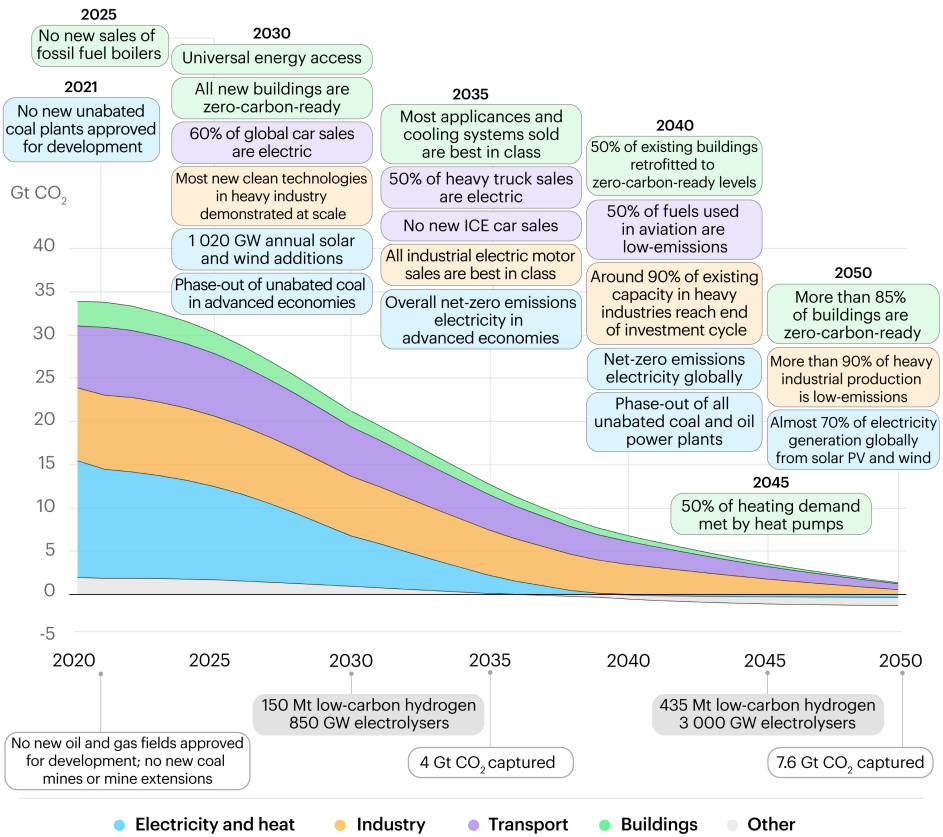
[1] A zero-carbon-ready building is highly energy efficient and either uses renewable energy directly or uses an energy supply that will be fully decarbonised by 2050, such as electricity or district heat.

Priority action: Set near-term milestones to get on track for long-term targets

Governments need to provide credible step-by-step plans to reach their net zero goals, building confidence among investors, industry, citizens and other countries.

Governments must put in place long-term policy frameworks to allow all branches of government and stakeholders to plan for change and facilitate an orderly transition. Long-term national low-emissions strategies, called for by the Paris Agreement, can set out a vision for national transitions, as this report has done on a global level. These long-term objectives need to be linked to measurable short-term targets and policies. Our pathway details more than 400 sectoral and technology milestones to guide the global journey to net zero by 2050.

Key milestones in the pathway to net zero



There is no need for investment in new fossil fuel supply in our net zero pathway

Beyond projects already committed as of 2021, there are no new oil and gas fields approved for development in our pathway, and no new coal mines or mine extensions are required. The unwavering policy focus on climate change in the net zero pathway results in a sharp decline in fossil fuel demand, meaning that the focus for oil and gas producers switches entirely to output – and emissions reductions – from the operation of existing assets. Unabated coal demand declines by 98% to just less than 1% of total energy use in 2050. Gas demand declines by 55% to 1 750 billion cubic metres and oil declines by 75% to 24 million barrels per day (mb/d), from around 90 mb/d in 2020.

Clean electricity generation, network infrastructure and end-use sectors are key areas for increased investment. Enabling infrastructure and technologies are vital for transforming the energy system. Annual investment in transmission and distribution grids expands from USD 260 billion today to USD 820 billion in 2030. The number of public charging points for EVs rises from around 1 million today to 40 million in 2030, requiring annual investment of almost USD 90 billion in 2030. Annual battery production for EVs leaps from 160 gigawatt-hours (GWh) today to 6 600 GWh in 2030 – the equivalent of adding almost 20 gigafactories[2] each year for the next ten years. And the required roll-out of hydrogen and CCUS after 2030 means laying the groundwork now: annual investment in CO_2 pipelines and hydrogen-enabling infrastructure increases from USD 1 billion today to around USD 40 billion in 2030.

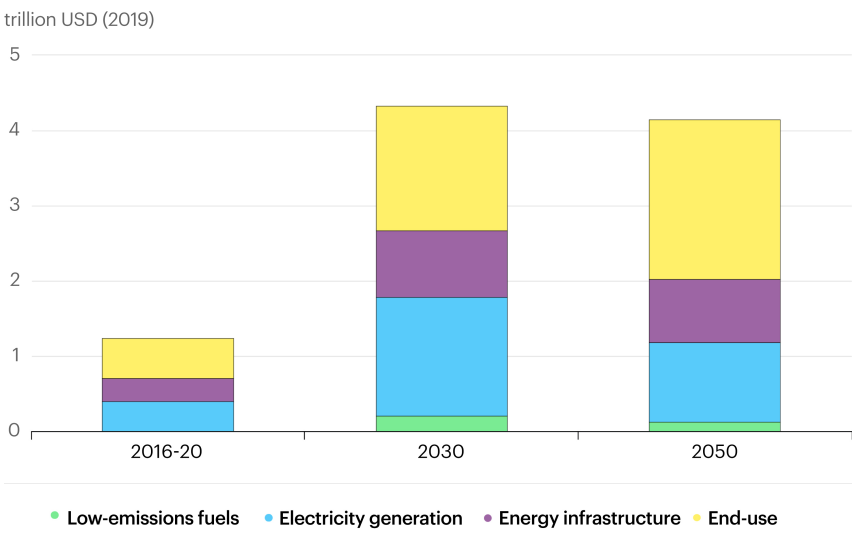
[2] Battery gigafactory capacity assumption = 35 gigawatt-hours per year.

Priority action: Drive a historic surge in clean energy investment

Policies need to be designed to send market signals that unlock new business models and mobilise private spending, especially in emerging economies.

Accelerated delivery of international public finance will be critical to energy transitions, especially in developing economies, but ultimately the private sector will need to finance most of the extra investment required. Mobilising the capital for large-scale infrastructure calls for closer co operation between developers, investors, public financial institutions and governments. Reducing risks for investors will be essential to ensure successful and affordable clean energy transitions. Many emerging market and developing economies, which rely mainly on public funding for new energy projects and industrial facilities, will need to reform their policy and regulatory frameworks to attract more private finance. International flows of long-term capital to these economies will be needed to support the development of both existing and emerging clean energy technologies.

Clean energy investment in the net zero pathway



An unparalleled clean energy investment boom lifts global economic growth

Total annual energy investment surges to USD 5 trillion by 2030, adding an extra 0.4 percentage point a year to annual global GDP growth, based on our joint analysis with the International Monetary Fund. This unparalleled increase – with investment in clean energy and energy infrastructure more than tripling already by 2030 – brings significant economic benefits as the world emerges from the Covid-19 crisis. The jump in private and government spending creates millions of jobs in clean energy, including energy efficiency, as well as in the engineering, manufacturing and construction industries. All of this puts global GDP 4% higher in 2030 than it would be based on current trends.

Governments have a key role in enabling investment-led growth and ensuring that the benefits are shared by all. There are large differences in macroeconomic impacts between regions. But government investment and public policies are essential to attract large amounts of private capital and to help offset the declines in fossil fuel income that many countries will experience. The major innovation efforts needed to bring new clean energy technologies to market could boost productivity and create entirely new industries, providing opportunities to locate them in areas that see job losses in incumbent industries. Improvements in air quality provide major health benefits, with 2 million fewer premature deaths globally from air pollution in 2030 than today in our net zero pathway. Achieving universal energy access by 2030 would provide a major boost to well-being and productivity in developing economies.

New energy security concerns emerge, and old ones remain

The contraction of oil and natural gas production will have far-reaching implications for all the countries and companies that produce these fuels. No new oil and natural gas fields are needed in our pathway, and oil and natural gas supplies become increasingly concentrated in a small number of low-cost producers. For oil, the OPEC share of a much-reduced global oil supply increases from around 37% in recent years to 52% in 2050, a level higher than at any point in the history of oil markets. Yet annual per capita income from oil and natural gas in producer economies falls by about 75%, from USD 1 800 in recent years to USD 450 by the 2030s, which could have knock-on societal effects. Structural reforms and new sources of revenue are needed, even though these are unlikely to compensate fully for the drop in oil and gas income. While traditional supply activities decline, the expertise of the oil and natural gas industry fits well with

technologies such as hydrogen, CCUS and offshore wind that are needed to tackle emissions in sectors where reductions are likely to be most challenging.

The energy transition requires substantial quantities of critical minerals, and their supply emerges as a significant growth area. The total market size of critical minerals like copper, cobalt, manganese and various rare earth metals grows almost sevenfold between 2020 and 2030 in the net zero pathway. Revenues from those minerals are larger than revenues from coal well before 2030. This creates substantial new opportunities for mining companies. It also creates new energy security concerns, including price volatility and additional costs for transitions, if supply cannot keep up with burgeoning demand.

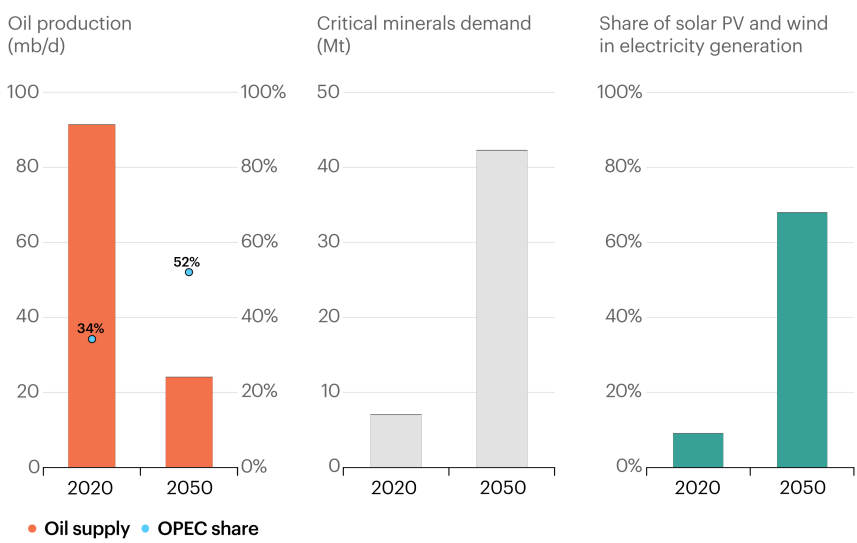
The rapid electrification of all sectors makes electricity even more central to energy security around the world than it is today. Electricity system flexibility – needed to balance wind and solar with evolving demand patterns – quadruples by 2050 even as retirements of fossil fuel capacity reduce conventional sources of flexibility. The transition calls for major increases in all sources of flexibility: batteries, demand response and low-carbon flexible power plants, supported by smarter and more digital electricity networks. The resilience of electricity systems to cyberattacks and other emerging threats needs to be enhanced.

Priority action: Address emerging energy security risks now

Ensuring uninterrupted and reliable supplies of energy and critical energy-related commodities at affordable prices will only rise in importance on the way to net zero.

The focus of energy security will evolve as reliance on renewable electricity grows and the role of oil and gas diminishes. Potential vulnerabilities from the increasing importance of electricity include the variability of supply and cybersecurity risks. Governments need to create markets for investment in batteries, digital solutions and electricity grids that reward flexibility and enable adequate and reliable supplies of electricity. The growing dependence on critical minerals required for key clean energy technologies calls for new international mechanisms to ensure both the timely availability of supplies and sustainable production. At the same time, traditional energy security concerns will not disappear, as oil production will become more concentrated.

Global energy security indicators in the net zero pathway



Note: mb/d = million barrels per day; Mt = million tonnes.

International co-operation is pivotal for achieving net-zero emissions by 2050

Making net-zero emissions a reality hinges on a singular, unwavering focus from all governments – working together with one another, and with businesses, investors and citizens. All stakeholders need to play their part. The wide-ranging measures adopted by governments at all levels in the net zero pathway help to frame, influence and incentivise the purchase by consumers and investment by businesses. This includes how energy companies invest in new ways of producing and supplying energy services, how businesses invest in equipment, and how consumers cool and heat their homes, power their devices and travel.

Underpinning all these changes are policy decisions made by governments. Devising cost-effective national and regional net zero roadmaps demands co-operation among all parts of government that breaks down silos and integrates energy into every country's policy making on finance, labour, taxation, transport and industry. Energy or environment ministries alone cannot carry out the policy actions needed to reach net zero by 2050.

Changes in energy consumption result in a significant decline in fossil fuel tax revenues. In many countries today, taxes on diesel, gasoline and other fossil fuel consumption are an important source of public revenues, providing as much as 10% in some cases. In the net zero pathway, tax revenue from oil and gas retail sales falls by about 40% between 2020 and 2030. Managing this decline will require long-term fiscal planning and budget reforms.

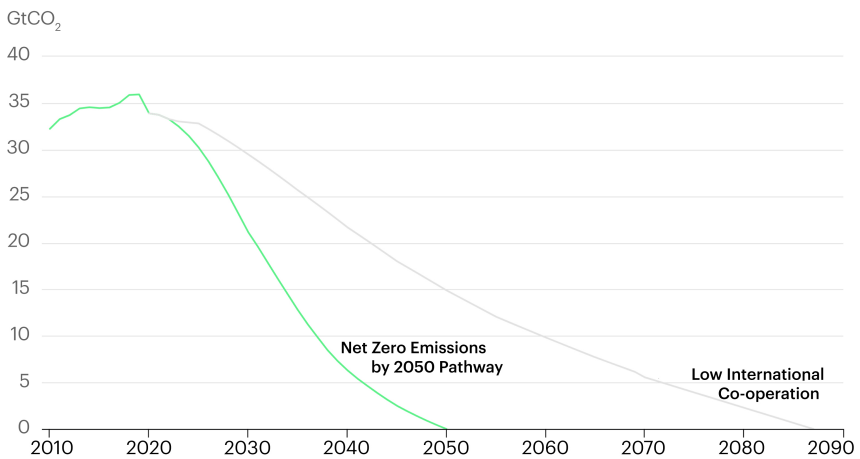
The net zero pathway relies on unprecedented international co-operation among governments, especially on innovation and investment. The IEA stands ready to support governments in preparing national and regional net zero roadmaps, to provide guidance and assistance in implementing them, and to promote international co-operation to accelerate the energy transition worldwide.

Priority action: Take international co-operation to new heights

This is not simply a matter of all governments seeking to bring their national emissions to net zero – it means tackling global challenges through co-ordinated actions.

Governments must work together in an effective and mutually beneficial manner to implement coherent measures that cross borders. This includes carefully managing domestic job creation and local commercial advantages with the collective global need for clean energy technology deployment. Accelerating innovation, developing international standards and co-ordinating to scale up clean technologies needs to be done in a way that links national markets. Co-operation must recognise differences in the stages of development of different countries and the varying situations of different parts of society. For many rich countries, achieving net-zero emissions will be more difficult and costly without international co-operation. For many developing countries, the pathway to net zero without international assistance is not clear. Technical and financial support is needed to ensure deployment of key technologies and infrastructure. Without greater international co-operation, global CO_2 emissions will not fall to net zero by 2050.

Global energy-related CO_2 emissions in the net zero pathway and Low International Co-operation Case



Note: Gt = billion tonnes.

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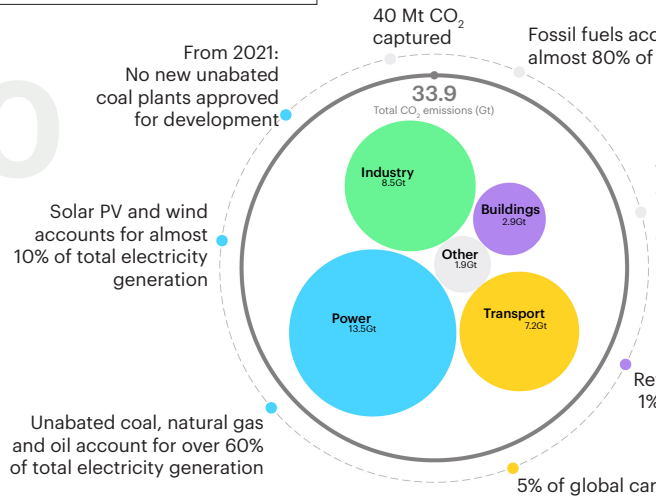
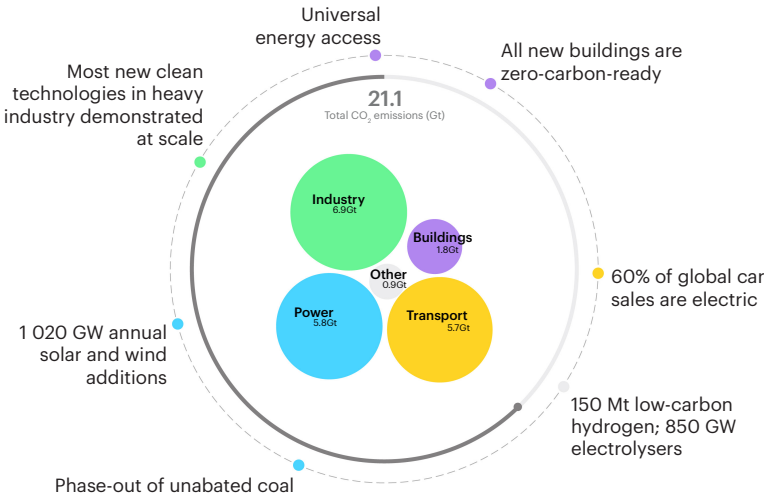
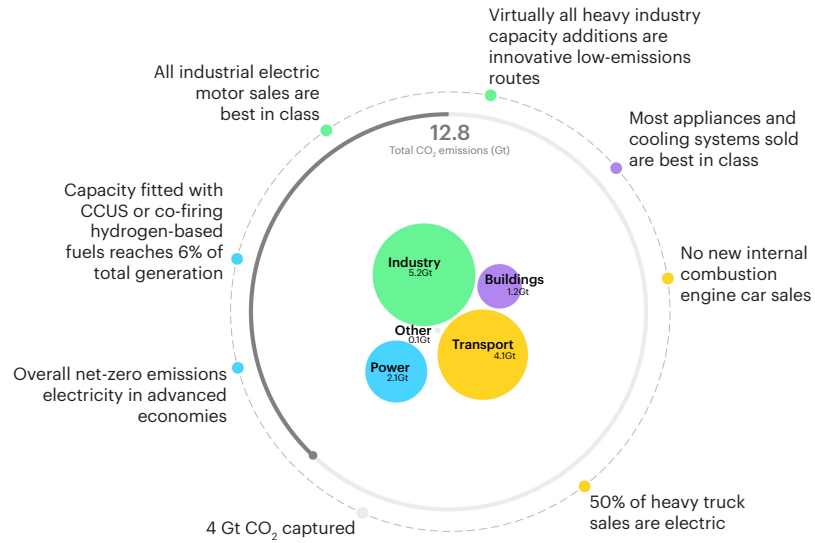
2020



2030



2035



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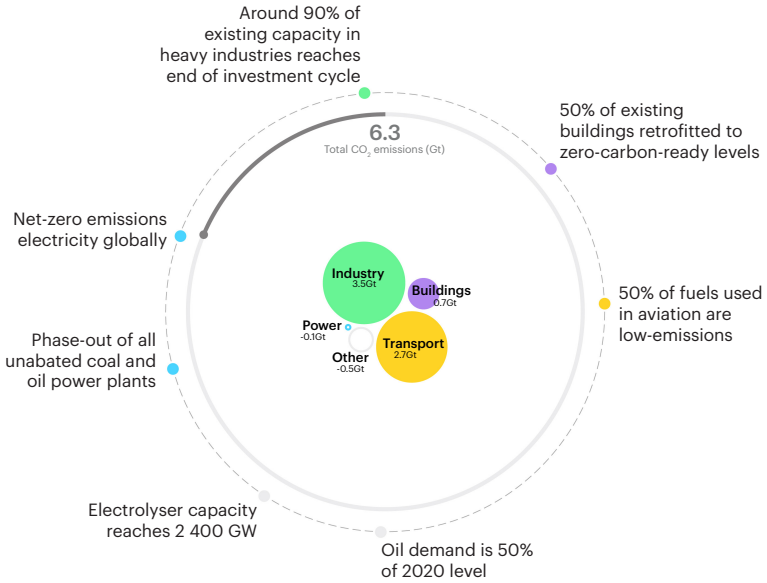

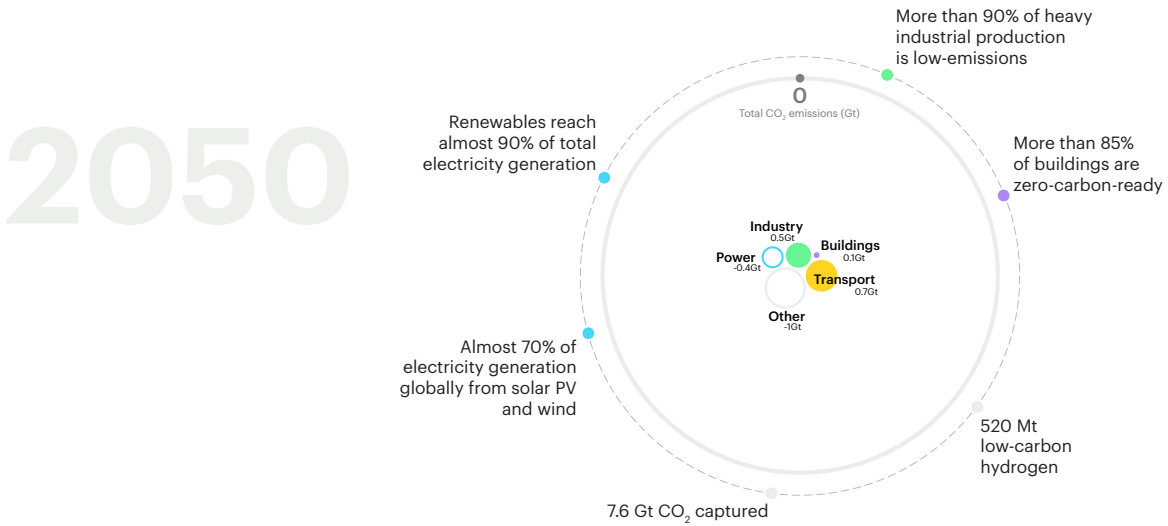

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