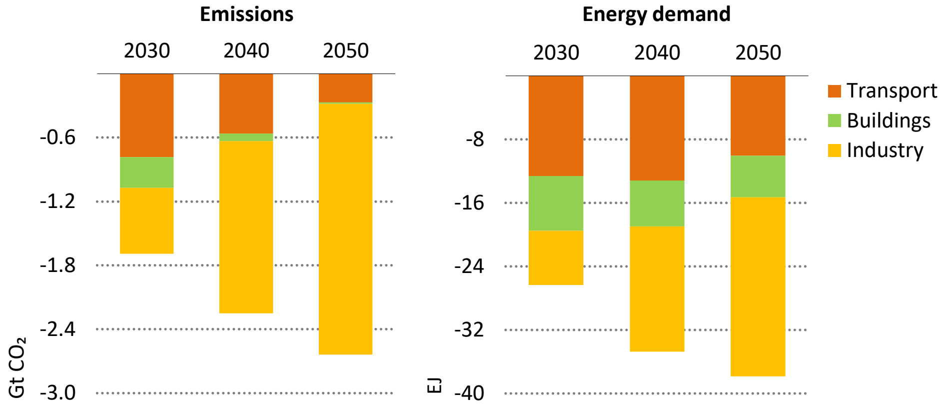
40% of emissions savings in 2030 occur in industry because of improvements in materials efficiency and increased recycling, with the biggest impacts coming from reducing waste and improving the design and construction of buildings. The remainder of emissions savings in 2030 are from behavioural changes in buildings, for example adjusting space heating and cooling temperatures.

Figure 2.15 ▷ CO_2 emissions and energy demand reductions from behavioural changes and materials efficiency in the NZE



By 2030, behaviour changes and materials efficiency gains reduce emissions by 1.7 Gt CO_2, and energy demand by 27 EJ; reductions increase further through to 2050

In 2050, the growing importance of low-emissions electricity and fuels in transport and buildings means that 90% of emissions reductions are in industry, predominantly in those sectors where it is most challenging to tackle emissions directly. Material efficiency alone reduces demand for cement and steel by 20%, saving around 1 700 Mt CO_2. Of the emissions reductions in transport in 2050, nearly 80% come from measures to reduce passenger aviation demand, with the remainder from road transport.

The scope, scale and speed of adoption of the behavioural changes in the NZE varies widely between regions, depending on several factors including the ability of existing infrastructure to support such changes and differences in geography, climate, urbanisation, social norms and cultural values. For example, regions with high levels of private car use today see a more gradual shift than others towards public transport, shared car use, walking and cycling; air travel is assumed to switch to high-speed rail on existing or potential routes only where trains could offer a similar journey time; and the potential for moderating air conditioning in buildings and vehicles takes into account seasonal effects and humidity. Wealthier regions generally have higher levels of per capita energy-related activity, and behavioural changes play an especially important role in these regions in reducing excessive or wasteful energy consumption.

Most of the behavioural changes in the NZE would have some effect on nearly everyone's daily life, but none represents a radical departure from energy-reducing practices already experienced in many parts of the world today. For example, in Japan an awareness campaign has successfully reduced cooling demand in line with the reductions assumed in many regions in the NZE by 2040; legislation to limit urban car use has been introduced in many large cities; and speed limit reductions to around 100 km/h (the level adopted globally in the NZE by 2030) have been tested in the United Kingdom and Spain to reduce air pollution and improve safety.

Table 2.4 ▷ Key global milestones for behavioural change in the NZE

Sector	Year	Milestone
Industry	2020	• Global average plastics collection rate = 17%.
	2030	• Global average plastics collection rate = 27%. • Lightweighting reduces the weight of an average passenger car by 10%.
	2050	• Global average plastics collection rate = 54%. • Efficiency of fertiliser use improved by 10%.
Transport	2030	• Eco-driving and motorway speed limits of 100 km/h introduced. • Use of ICE cars phased out in large cities.
	2050	• Regional flights are shifted to high-speed rail where feasible. • Business and long-haul leisure air travel does not exceed 2019 levels.
Buildings	2030	• Space heating temperatures moderated to 19-20 °C on average. • Space cooling temperatures moderated to 24-25°C on average. • Excessive hot-water temperatures reduced.
	2050	• Use of energy-intensive materials per unit of floor area decreases by 30%. • Building lifetime extended by 20% on average.

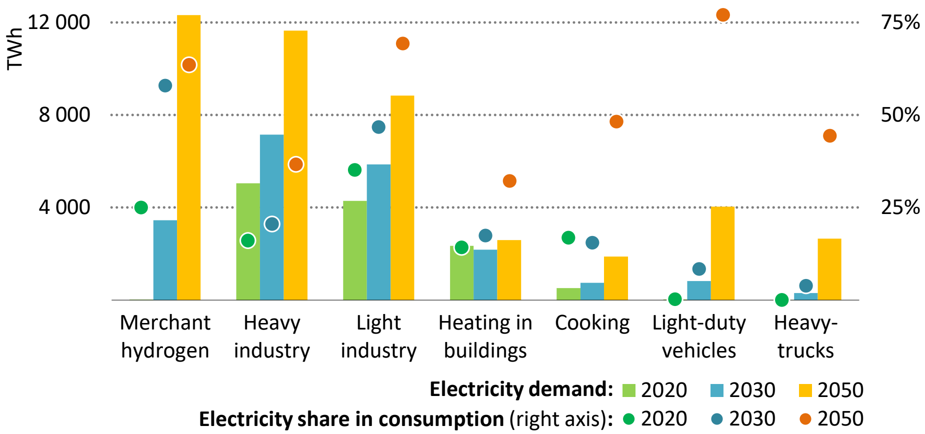
Note: Eco-driving involves pre-emptive stopping and starting; ICE = internal combustion engine.

2.5.3 Electrification

The direct use of low-emissions electricity in place of fossil fuels is one of the most important drivers of emissions reductions in the NZE, accounting for around 20% of the total reduction achieved by 2050. Global electricity demand more than doubles between 2020 and 2050, with the largest absolute rise in electricity use in end-use sectors taking place in industry, which registers an increase of more than 11 000 TWh between 2020 and 2050. Much of this is due to the increasing use of electricity for low- and medium-temperature heat and in secondary scrap-based steel production (Figure 2.16).

In transport, the share of electricity increases from less than 2% in 2020 to around 45% in 2050 in the NZE. More than 60% of total passenger car sales globally are EVs by 2030 (compared with 5% of sales in 2020), and the car fleet is almost fully electrified worldwide by 2050 (the remainder are hydrogen-powered cars). The increase in electric passenger car sales globally over the next ten years is over twenty-times higher than the increase in ICE car sales over the last decade. Electrification is slower for trucks because it depends on higher density batteries than those currently available on the market, especially for long-haul trucking, and on new high-power charging infrastructure: electric trucks nevertheless account for around 25% of total heavy truck sales globally by 2030 and around two-thirds in 2050. The electrification of shipping and aviation is much more limited and only gets under way after large improvements in battery energy density (see section 3.6) (Figure 2.17). In the NZE, demand for batteries for transport reaches around 14 TWh in 2050, 90-times more than in 2020. Growth in battery demand translates into an increasing demand for critical minerals. For example, demand for lithium for use in batteries grows 30-fold to 2030 and is more than 100-times higher in 2050 than in 2020 (IEA, 2021).

Figure 2.16 ▷ Global electricity demand and share of electricity in energy consumption in selected applications in the NZE



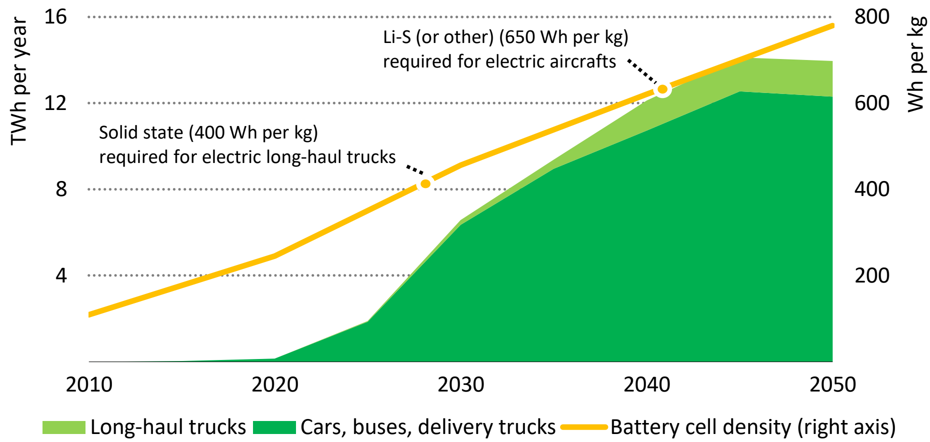
Global electricity demand more than doubles in the period to 2050, with the largest rises to produce hydrogen and in industry

Notes: Merchant hydrogen = hydrogen produced by one company to sell to others. Light-duty vehicles = passenger cars and vans. Heavy trucks = medium-freight trucks and heavy-freight trucks.

In buildings, electricity demand is moderated in the NZE by a huge push to improve the efficiency of appliances, cooling, lighting and building envelopes. But a large increase in activity, along with the widespread electrification of heating through the use of heat pumps, means that electricity demand in buildings still rises steadily over the period reaching 66% of total energy consumption in buildings in 2050.

Alongside the growth in the direct use of electricity in end-use sectors, there is also a huge increase in the use of electricity for hydrogen production. Merchant hydrogen produced using electrolysis requires around 12 000 TWh in 2050 in the NZE, which is greater than current total annual electricity demand of China and the United States combined.

Figure 2.17 ▷ Battery demand growth in transport and battery energy density in the NZE



Nearly 20 battery giga-factories open every year to 2030 to satisfy battery demand for electric cars in the NZE; higher density batteries are needed to electrify long-haul trucks

Notes: Li-S = lithium-sulphur battery; Wh per kg = Watt hours per kilogramme.

The acceleration of electricity demand growth from 2% per year over the past decade to 3% per year through to 2050, together with a significantly increased share of variable renewable electricity generation, means that annual electricity sector investment in the NZE is three-times higher on average than in recent years. The rise in electricity demand also calls for extensive efforts to ensure the stability and flexibility of electricity supply through demand-side management, the operation of flexible low-emissions sources of generation including hydropower and bioenergy, and battery storage.

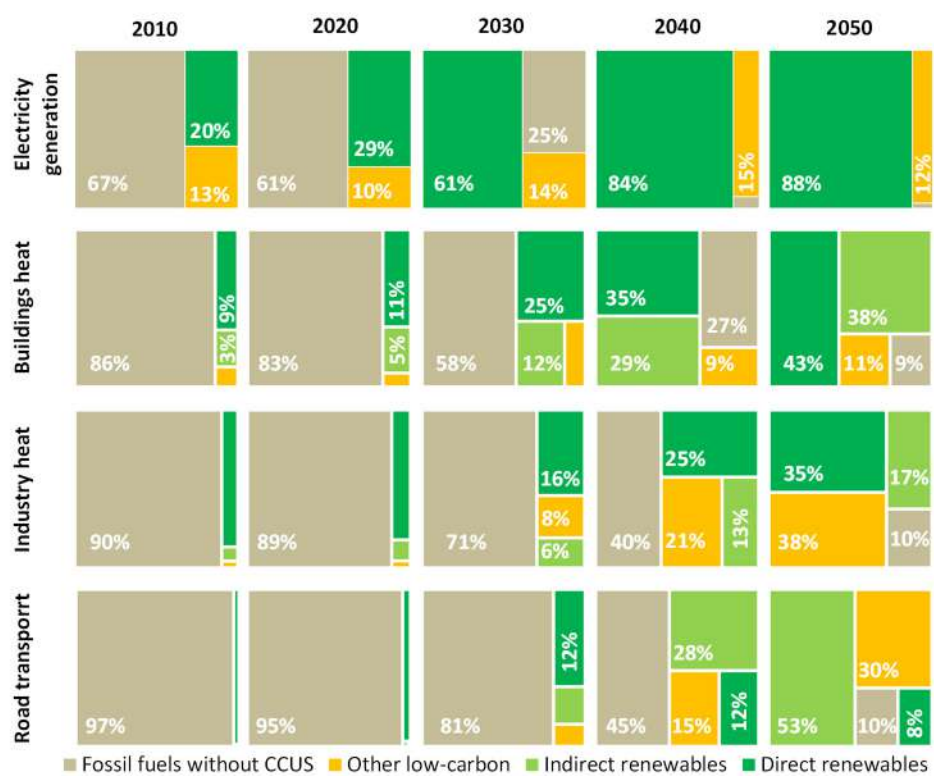
Table 2.5 ▷ Key global milestones for electrification in the NZE

Sector		2020	2030	2050
Share of electricity in total final consumption		20%	26%	49%
Industry				
Share of steel production using electric arc furnace		24%	37%	53%
Electricity share of light industry		43%	53%	76%
Transport				
Share of electric vehicles in stock:	cars	1%	20%	86%
	two/three-wheelers	26%	54%	100%
	bus	2%	23%	79%
	vans	0%	22%	84%
	heavy trucks	0%	8%	59%
Annual battery demand for electric vehicles (TWh)		0.16	6.6	14
Buildings				
Heat pumps installed (millions)		180	600	1 800
Share of heat pumps in energy demand for heating		7%	20%	55%
Million people without access to electricity		786	0	0

2.5.4 Renewables

At a global level, renewable energy technologies are the key to reducing emissions from electricity supply. Hydropower has been a leading low-emission source for many decades, but it is mainly the expansion of wind and solar that triples renewables generation by 2030 and increases it more than eightfold by 2050 in the NZE. The share of renewables in total electricity generation globally increases from 29% in 2020 to over 60% in 2030 and to nearly 90% in 2050 (Figure 2.18). To achieve this, annual capacity additions of wind and solar between 2020 and 2050 are five-times higher than the average over the last three years. Dispatchable renewables are critical to maintain electricity security, together with other low-carbon generation, energy storage and robust electricity networks. In the NZE, the main dispatchable renewables globally in 2050 are hydropower (12% of generation), bioenergy (5%), concentrating solar power (2%) and geothermal (1%).

Figure 2.18 ▻ Fuel shares in total energy use in selected applications in the NZE



Renewables are central to emissions reductions in electricity, and they make major contributions to cut emissions in buildings, industry and transport both directly and indirectly

Notes: Indirect renewables = use of electricity and district heat produced by renewables. Other low-carbon = nuclear power, facilities equipped with CCUS, and low-carbon hydrogen and hydrogen-based fuels.

Renewables also play an important role in reducing emissions in buildings, industry and transport. Renewables can be used either indirectly, via the consumption of electricity or district heating that was produced by renewables, or directly, mainly to produce heat.

In transport, renewables play an important indirect role in reducing emissions by generating the electricity to power electric vehicles. They also contribute to direct emissions reductions through the use of liquid biofuels and biomethane.

In buildings, renewable energy is mainly used for water and space heating. The direct use of renewable energy rises from about 10% of heating demand globally in 2020 to 40% in 2050, about three-quarters of the increase is in the form of solar thermal and geothermal. Deep retrofits and energy-related building codes are paired with renewables whenever possible: almost all buildings with available roof space and sufficient solar insolation are equipped with solar thermal water heaters by 2050, as they are more productive per square metre than solar PV and as heat storage in water tanks is generally more cost-effective than storage of electricity. Rooftop solar PV, which produces renewable electricity onsite, is currently installed on around 25 million rooftops worldwide; the number increases to 100 million rooftops by 2030 and 240 million by 2050. A further 15% of heating in buildings in 2030 comes indirectly from renewables in the form of electricity, and this rises to almost 40% in 2050.

In industry, bioenergy is the most important direct renewable energy source for low- and medium-temperature needs in the NZE. Solar thermal and geothermal also produce low temperature heat for use in non-energy-intensive industries and ancillary or downstream processes in heavy industries. Bioenergy, solar thermal and geothermal together provide about 15% of industry heat demand in 2030, roughly double their share in 2010, and this increases to 40% in 2050. The indirect use of renewable energy via electricity adds 15% to the contribution that renewables make to total industry energy use in 2050.

Table 2.6 ▷ Key deployment milestones for renewables

Sector		2020	2030	2050
Electricity sector				
Renewables share in generation		29%	61%	88%
Annual capacity additions (GW):	Total solar PV	134	630	630
	Total wind	114	390	350
	– of which: Offshore wind	5	80	70
	Dispatchable renewables	31	120	90
End-uses sectors				
Renewable share in TFC		5%	12%	19%
Households with rooftop solar PV (million)		25	100	240
Share of solar thermal and geothermal in buildings		2%	5%	12%
Share of solar thermal and geothermal in industry final consumption		0%	1%	2%

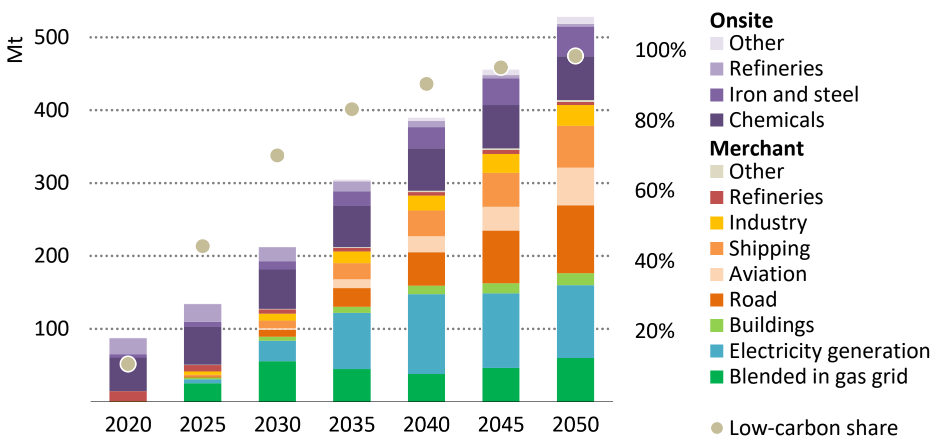
Note: TFC = total final consumption.

2.5.5 Hydrogen and hydrogen-based fuels

The initial focus for hydrogen use in the NZE is the conversion of existing uses of fossil energy to low-carbon hydrogen in ways that do not immediately require new transmission and distribution infrastructure. This includes hydrogen use in industry and in refineries and power plants, and the blending of hydrogen into natural gas for distribution to end-users.

Global hydrogen use expands from less than 90 Mt in 2020 to more than 200 Mt in 2030; the proportion of low-carbon hydrogen rises from 10% in 2020 to 70% in 2030 (Figure 2.19). Around half of low-carbon hydrogen produced globally in 2030 comes from electrolysis and the remainder from coal and natural gas with CCUS, although this ratio varies substantially between regions. Hydrogen is also blended with natural gas in gas networks: the global average blend in 2030 includes 15% of hydrogen in volumetric terms, reducing CO_2 emissions from gas consumption by around 6%.

Figure 2.19 ▷ Global hydrogen and hydrogen-based fuel use in the NZE



The initial focus for hydrogen is to convert existing uses to low-carbon hydrogen; hydrogen and hydrogen-based fuels then expand across all end-uses

Note: Includes hydrogen and hydrogen contained in ammonia and synthetic fuels.

These developments facilitate a rapid scaling up of electrolyser manufacturing capacity and the parallel development of new hydrogen transport infrastructure. This leads to rapid cost reductions for electrolysers and for hydrogen storage, notably in salt caverns. Stored hydrogen is used to help balance both seasonal fluctuations in electricity demand and imbalances that may arise between the demand for hydrogen and its supply by off-grid renewable systems. During the 2020s, there is also a large increase in the installation of end-use equipment for hydrogen, including more than 15 million hydrogen fuel cell vehicles on the road by 2030.

After 2030, low-carbon hydrogen use expands rapidly in all sectors in the NZE. In the electricity sector, hydrogen and hydrogen-based fuels provide an important low-carbon source of electricity system flexibility, mainly through retrofitting existing gas-fired capacity to co-fire with hydrogen, together with some retrofitting of coal-fired power plants to co-fire with ammonia. Although these fuels provide only around 2% of overall electricity generation in 2050, this translates into very large volumes of hydrogen and makes the electricity sector an important driver of hydrogen demand. In transport, hydrogen provides around one-third of fuel use in trucks in 2050 in the NZE: this is contingent on policy makers taking decisions that enable the development of the necessary infrastructure by 2030. By 2050, hydrogen-based fuels also provide more than 60% of total fuel consumption in shipping.

Of the 530 Mt of hydrogen produced in 2050, around 25% is produced within industrial facilities (including refineries), and the remainder is merchant hydrogen (hydrogen produced by one company to sell to others). Almost 30% of the low-carbon hydrogen used in 2050 takes the form of hydrogen-based fuels, which include ammonia and synthetic liquids and gases. An increasing share of hydrogen production comes from electrolysers, which account for 60% of total production in 2050. Electrolysers are powered by grid electricity, dedicated renewables in regions with excellent renewable resources and other low-carbon sources such as nuclear power. Rolling out electrolysers at the pace required in the NZE is a key challenge given the lack of manufacturing capacity today, as is ensuring the availability of sufficient electricity generation capacity. Global trade in hydrogen develops over time in the NZE, with large volumes exported from gas and renewables-rich areas in the Middle East, Central and South America and Australia to demand centres in Asia and Europe.

Table 2.7 ⊳ Key deployment milestones for hydrogen and hydrogen-based fuels

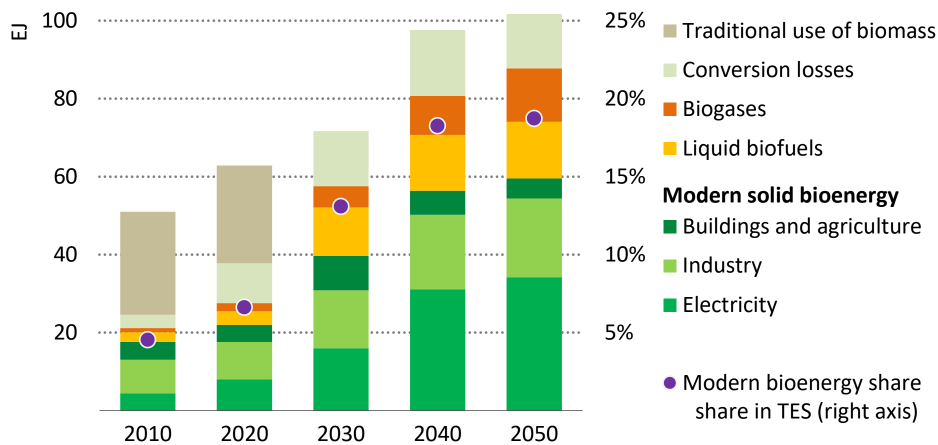
Sector	2020	2030	2050
Total production hydrogen-based fuels (Mt)	**87**	**212**	**528**
Low-carbon hydrogen production	9	150	520
share of fossil-based with CCUS	*95%*	*46%*	*38%*
share of electrolysis-based	*5%*	*54%*	*62%*
Merchant production	15	127	414
Onsite production	73	85	114
Total consumption hydrogen-based fuels (Mt)	**87**	**212**	**528**
Electricity	0	52	102
of which hydrogen	0	43	88
of which ammonia	0	8	13
Refineries	36	25	8
Buildings and agriculture	0	17	23
Transport	0	25	207
of which hydrogen	0	11	106
of which ammonia	0	5	56
of which synthetic fuels	0	8	44
Industry	51	93	187

Note: Hydrogen-based fuels are reported in million tonnes of hydrogen required to produce them.

2.5.6 Bioenergy

Global primary demand for bioenergy was almost 65 EJ in 2020, of which about 90% was solid biomass. Some 40% of the solid biomass was used in traditional cooking methods which is unsustainable, inefficient and polluting, and was linked to 2.5 million premature deaths in 2020. The use of solid biomass in this manner falls to zero by 2030 in the NZE, to achieve the UN Sustainable Development Goal 7. Increases in all forms of modern bioenergy more than offset this, with production rising from less than 40 EJ in 2020 to around 100 EJ in 2050 (Figure 2.20).[15] All bioenergy in 2050 comes from sustainable sources and the figures in the NZE for total bioenergy use are well below estimates of global sustainable bioenergy potential, thus avoiding the risk of negative impacts on biodiversity, fresh water systems, and food prices and availability (see section 2.7.2).

Figure 2.20 ▹ Total bioenergy supply in the NZE



Modern bioenergy use rises to 100 EJ in 2050, meeting almost 20% of total energy needs. Global demand in 2050 is well below the assessed sustainable potential

Notes: TES = Total energy supply. Conversion losses occur during the production of biofuels and biogases.

Modern solid bioenergy use rises by about 3% each year on average to 2050. In the electricity sector, where demand reaches 35 EJ in 2050, solid bioenergy provides flexible low-emissions generation to complement generation from solar PV and wind, and it removes CO_2 from the atmosphere when equipped with CCUS. In 2050, electricity generation using bioenergy fuels reaches 3 300 TWh, or 5% of total generation. Bioenergy also provides around 50% of district heat production. In industry, where demand reaches 20 EJ in 2050, solid bioenergy provides high temperature heat and can be co-fired with coal to reduce the emissions intensity of

[15] Modern bioenergy includes biogases, liquid biofuels and modern solid biomass harvested from sustainable sources. It excludes the traditional use of biomass.

existing generation assets. Demand is highest for paper and cement production: in 2050, bioenergy meets 60% of energy demand in the paper sector and 30% of energy demand for cement production. Modern solid bioenergy demand in buildings increases to nearly 10 EJ in 2030, most of it for use in improved cookstoves as unsustainable traditional uses of biomass disappear. Bioenergy is also increasingly used for space and water heating in advanced economies.

Household and village biogas digesters in rural areas provide a source of renewable energy and clean cooking for nearly 500 million households by 2030 in the NZE and total biogas use rises to 5.5 EJ in 2050 (from under 2 EJ in 2020).[16] Biomethane demand grows to 8.5 EJ, thanks to blending mandates for gas networks, with average blending rates increasing to above 80% in many regions by 2050. Half of total biomethane use is in the industry sector, where biomethane replaces natural gas as a source of process heat. The buildings and transport sectors each account for around a further 20% of biomethane consumption in 2050.

One of the key advantages of bioenergy is that it can use existing infrastructure. For example, biomethane can use existing natural gas pipelines and end-user equipment, while many drop-in liquid biofuels can use existing oil distribution networks and be used in vehicles with only minor or limited alterations. BioLPG – LPG derived from renewable feedstocks – is identical to conventional LPG and so can be blended and distributed in the same way. Sustainable bioenergy also provides a valuable source of employment and income for rural communities, reduces undue burdens on women often tasked with fuel collection, brings health benefits from reduced air pollution and proper waste management, and reduces methane emissions from inefficient combustion and the decomposition of waste.

Liquid biofuel consumption rises from 1.6 mboe/d in 2020 to 6 mboe/d in 2030 in the NZE, mainly used in road transport. After 2030, liquid biofuels grow more slowly to around 7 mboe/d in 2050 and their use shifts to shipping and aviation as electricity increasingly dominates road transport. Almost half of liquid biofuel use in 2050 is for aviation, where bio-kerosene accounts for around 45% of total fuel use in aircraft.

Bioenergy with carbon capture and storage (BECCS) plays a critical role in the NZE in offsetting emissions from sectors where the full elimination of emissions is very difficult to achieve. In 2050, around 10% of total bioenergy is used in facilities equipped with CCUS and around 1.3 Gt CO_2 is captured using BECCS. Around 45% of this CO_2 is captured in biofuels production, 40% in the electricity sector and the rest in heavy industry, notably cement production.

[16] Biogas is a mixture of methane, CO_2 and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen free environment. Biomethane is a near pure source of methane produced either by removing CO_2 and other contaminants from biogas or through the gasification of solid biomass (IEA, 2020b).

Table 2.8 ▷ Key deployment milestones for bioenergy

	2020	2030	2050
Total energy supply (EJ)	**63**	**72**	**102**
Share of advanced biomass feedstock	27%	85%	97%
Modern gaseous bioenergy (EJ)	**2.1**	**5.4**	**13.7**
Biomethane	0.3	2.3	8.3
Modern liquid bioenergy (mboe/d)	**1.6**	**6.0**	**7.0**
Advanced biofuels	0.1	2.7	6.2
Modern solid bioenergy (EJ)	**32**	**54**	**74**
Traditional use of solid biomass (EJ)	**25**	**0**	**0**
Million people using traditional biomass for cooking	2 340	0	0

Notes: mboe/d = million barrels of oil equivalent per day. Bioenergy from forest plantings is considered advanced when forests are sustainably managed (see section 2.7.2).

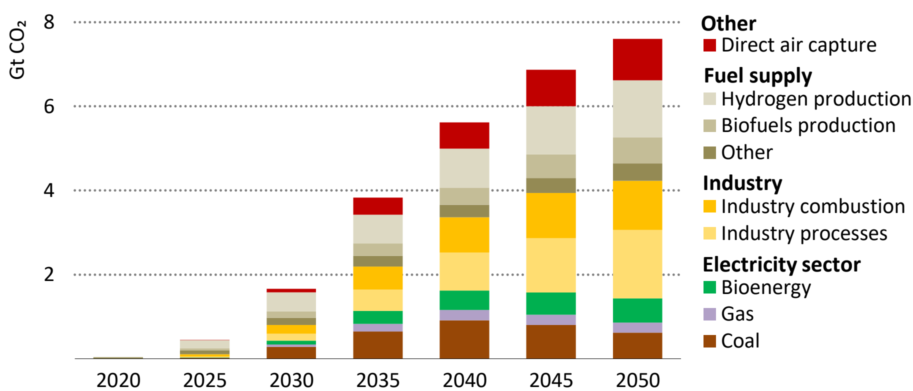
2.5.7 Carbon capture, utilisation and storage

CCUS can facilitate the transition to net-zero CO_2 emissions by: tackling emissions from existing assets; providing a way to address emissions from some of the most challenging sectors; providing a cost-effective pathway to scale up low-carbon hydrogen production rapidly; and allowing for CO_2 removal from the atmosphere through BECCS and DACCS.

In the NZE, policies support a range of measures to establish markets for CCUS investment and to encourage use of shared CO_2 transport and storage infrastructure by those involved in the production of hydrogen and biofuels, the operation of industrial hubs, and retrofitting of existing coal-fired power plants. Capture volumes in the NZE increase marginally over the next five years from the current level of around 40 Mt CO_2 per year, reflecting projects currently under development, but there is a rapid expansion over the following 25 years as policy action bears fruit. By 2030, 1.6 Gt CO_2 per year is captured globally, rising to 7.6 Gt CO_2 in 2050 (Figure 2.21). Around 95% of total CO_2 captured in 2050 is stored in permanent geological storage and 5% is used to provide synthetic fuels. Estimates of global geological storage capacity are considerably above what is necessary to store the cumulative CO_2 captured and stored in the NZE. A total of 2.4 Gt CO_2 is captured in 2050 from the atmosphere through bioenergy with CO_2 capture and direct air capture, of which 1.9 Gt CO_2 is permanently stored and 0.5 Gt CO_2 is used to provide synthetic fuels in particular for aviation.

Energy-related and process CO_2 emissions in industry account for almost 40% of the CO_2 captured in 2050 in the NZE. CCUS is particularly important for cement manufacturing. Although efforts are pursued in the NZE to produce cement more efficiently, CCUS remains central to efforts to limit the process emissions that occur during cement manufacturing. The electricity sector accounts for almost 20% of the CO_2 captured in 2050 (of which around 45% is from coal-fired plants, 40% from bioenergy plants and 15% from gas-fired plants). CCUS-equipped power plants contribute just 3% of total electricity generation in 2050 but the volumes of CO_2 captured are comparatively large. In emerging market and developing economies, where large numbers of coal power plants have been built relatively recently, retrofits play an important role where there are storage opportunities. In advanced economies, gas-fired plants with CCUS play a bigger role, providing dispatchable electricity at relatively low cost in regions with cheap natural gas and existing networks. In 2030, around 50 GW of coal-fired power plants (4% of the total at that time) and 30 GW of natural gas power plants (1% of the total) are equipped with CCUS, and this rises to 220 GW of coal (almost half of the total) and 170 GW of natural gas (7% of the total) capacity in 2050. A further 30% of CO_2 captured in 2050 comes from fuel transformation, including hydrogen and biofuels production as well as oil refining. The remaining 10% is from DAC, which is rapidly scaled up from several of pilot projects today to 90 Mt CO_2 per year in 2030 and just under 1 Gt CO_2 per year by 2050.

Figure 2.21 ▻ Global CO_2 capture by source in the NZE



By 2050, 7.6 Gt of CO_2 is captured per year from a diverse range of sources. A total of 2.4 Gt CO_2 is captured from bioenergy use and DAC, of which 1.9 Gt CO_2 is permanently stored.

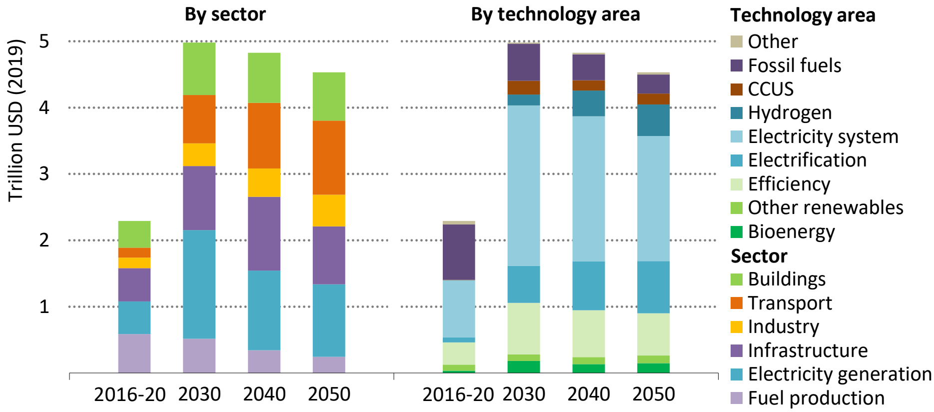
Table 2.9 ▻ Key global milestones for CCUS

	2020	2030	2050
Total CO_2 captured (Mt CO_2)	**40**	**1 670**	**7 600**
CO_2 captured from fossil fuels and processes	39	1 325	5 245
Power	3	340	860
Industry	3	360	2 620
Merchant hydrogen production	3	455	1 355
Non-biofuels production	30	170	410
CO_2 captured from bioenergy	1	255	1 380
Power	0	90	570
Industry	0	15	180
Biofuels production	1	150	625
Direct air capture	0	90	985
Removal	0	70	630

2.6 Investment

The radical transformation of the global energy system required to achieve net-zero CO_2 emissions in 2050 hinges on a big expansion in investment and a big shift in what capital is spent on. The NZE expands annual investment in energy from just over USD 2 trillion globally on average over the last five years to almost USD 5 trillion by 2030 and to USD 4.5 trillion by 2050 (Figure 2.22).[17] Total annual capital investment in energy in the NZE rises from around 2.5% of global GDP in recent years to about 4.5% in 2030 before falling back to 2.5% by 2050.

Figure 2.22 ▹ Annual average capital investment in the NZE



Capital investment in energy rises from 2.5% of GDP in recent years to 4.5% by 2030; the majority is spent on electricity generation, networks and electric end-user equipment

Notes: Infrastructure includes electricity networks, public EV charging, CO_2 pipelines and storage facilities, direct air capture and storage facilities, hydrogen refuelling stations, and import and export terminals for hydrogen, fossil fuels pipelines and terminals. End-use efficiency investments are the incremental cost of improving the energy performance of equipment relative to a conventional design. Electricity systems include electricity generation, storage and distribution, and public EV charging. Electrification investments include spending in batteries for vehicles, heat pumps and industrial equipment for electricity-based material production routes.

The shift in what capital is spent on leads to annual investment in electricity generation rising from just over USD 500 billion over the last five years to more than USD 1 600 billion in 2030, before falling back as the cost of renewable energy technologies continues to decline. Annual nuclear investment rises too: it more than doubles by 2050 compared with current levels. Annual investment in fuel supply however drops from about USD 575 billion on average over

[17] Investment levels presented in this report include a broader accounting of efficiency improvements in buildings than reported in the IEA World Energy Investment (IEA, 2020c) and so differ from the numbers presented there.

the last half-decade to USD 315 billion in 2030 and USD 110 billion in 2050. The share of fossil fuel supply in total energy sector investment drops from its 25% level in recent years to just 7% by 2050: this is partly offset by the rise in spending on low-emissions fuel supply, such as hydrogen, hydrogen-based fuels and bioenergy. Annual investment in these fuels increases to nearly USD 140 billion in 2050. Investment in transport increases significantly in the NZE from USD 150 per year in recent years to more than USD 1 100 billion in 2050: this stems mainly from the upfront cost of electric cars compared with conventional vehicles despite the decline in the cost of batteries.

By technology area, electrification is the dominant focus in the NZE. In addition to more investment in electricity generation, there is a huge increase in investment in expansion and modernisation of electricity networks. Annual investment rises from USD 260 billion on average in recent years to around USD 800 billion in 2030 and remains about that level to 2050. Such investment is needed to ensure electricity security in the face of rising electricity demand and the proportion of variable generation in the power mix. There is also a large increase in investment in the electrification of end-use sectors, which includes spending on EV batteries, heat pumps and electricity-based industrial equipment. In addition to investment in electrification, there is a moderate increase in investment in hydrogen to 2030 as production facilities are scaled up, and larger increases after as hydrogen use in transport expands: annual investment in hydrogen, including production facilities, refuelling stations and end-user equipment, reaches USD 165 billion in 2030 and over USD 470 billion in 2050. There is also an increase in global investment in CCUS (annual investment exceeds USD 160 billion by 2050 and in efficiency (around USD 640 billion annual investment by 2050, mostly for deep building retrofits and efficient appliances in the industry and buildings sectors).

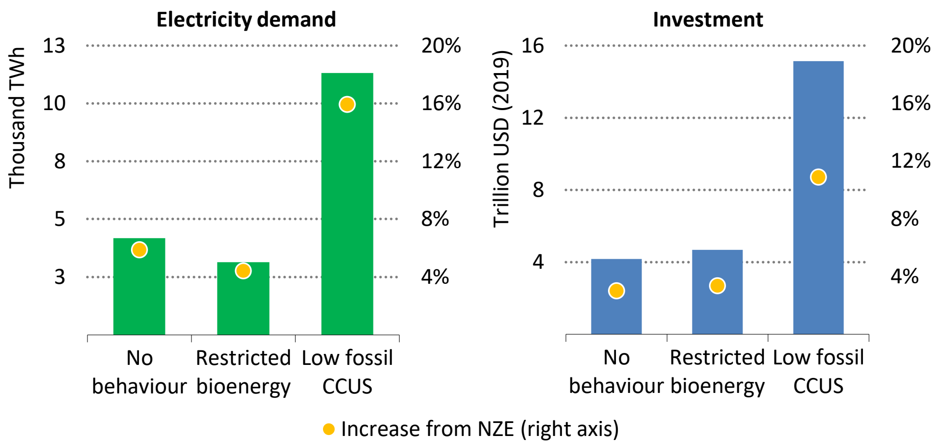
Financing the investment needed in the NZE involves redirecting existing capital towards clean energy technologies and substantially increasing the overall level of investment in energy. Most of this increase in investment comes from private sources, mobilised by public policies that create incentives, set appropriate regulatory frameworks and reform energy taxes. However, direct government financing is also needed to boost the development of new infrastructure projects and to accelerate innovation in technologies that are in the demonstration or prototype phase today. Projects in many emerging market and developing economies are often relatively reliant on public financing, and policies that ensure a predictable flow of bankable projects have an important role in boosting private investment in these economies, as does the scaling up of concessional debt financing and the use of development finance. There are extensive cross-country co-operation efforts in the NZE to facilitate the international flow of capital.

The large increase in capital investment in the NZE is partly compensated for by lower operating expenditure. Operating costs account today for a large share of the total cost of upstream fuel supply projects and fossil fuel generation projects: the clean technologies that play an increasing role in the NZE are characterised by much lower operating costs.

2.7 Key uncertainties

The road to net-zero emissions is uncertain for many reasons: we cannot be sure how underlying economic conditions will change, which policies will be most effective, how people and businesses will respond to market and policy signals, or how technologies and their costs will evolve from within or outside the energy sector. The NZE therefore is just one possible pathway to achieve net-zero emissions by 2050. Against this background, this section looks at what the implications would be if the assumptions in the NZE turn out to be off the mark with respect to behavioural change, bioenergy and CCUS for fossil fuels. These three areas were selected because the assumptions made about them involve a high degree of uncertainty and because of their critical contributions to achieve net-zero emissions by 2050.

Figure 2.23 ▷ Additional electricity demand in 2050 and additional investment between 2021-2050 for selected areas of uncertainty



The absence of behaviour change, restrictions on bioenergy use and failure to develop fossil fuel CCUS would each raise investment to meet net-zero emissions by USD 4-15 trillion

Notes: No behaviour assumes none of the behavioural changes included in the NZE. Restricted bioenergy assumes no increase in land use for bioenergy production. Low fossil CCUS assumes no increase in fossil fuel-based CCUS apart from projects already approved or under construction.

Our analysis clearly highlights that more pessimistic assumptions would add considerably to both the costs and difficulty of achieving net-zero emissions by 2050 (Figure 2.23).

- Behavioural changes are important in reducing energy demand in transport, buildings and industry. If the changes in behaviour assumed in the NZE were not attainable, emissions would be around 2.6 Gt CO_2 higher in 2050. Avoiding these emissions through the use of additional low-carbon electricity and hydrogen would cost an additional USD 4 trillion.

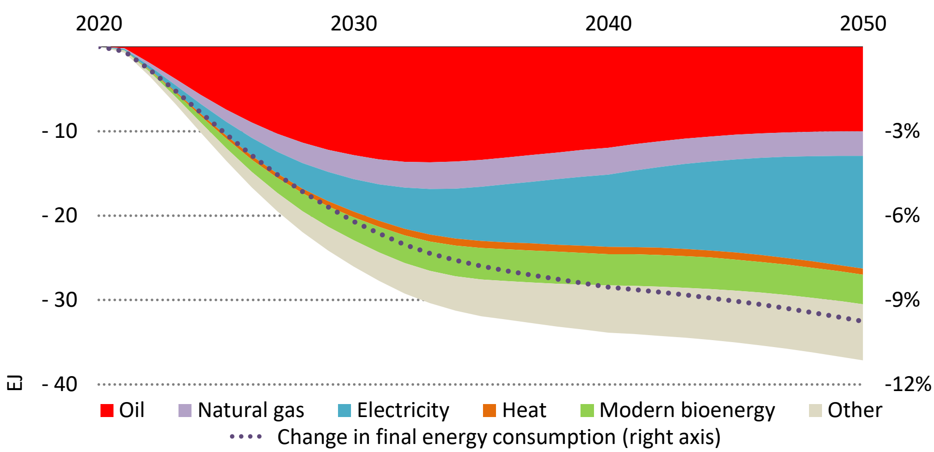
- Bioenergy use grows by 60% between 2020 and 2050 in the NZE and land use for its propagation increases by around 25%. Bioenergy use in 2050 in the NZE is well below current best estimates of global sustainable bioenergy potential, but there is a high degree of uncertainty concerning this level. If land use for bioenergy remains at today's level, bioenergy use in 2050 would be around 10% lower, and achieving net-zero emissions in 2050 would require USD 4.5 trillion extra investment.
- A failure to develop CCUS for fossil fuels would substantially increase the risk of stranded assets and would require around USD 15 trillion of additional investment in wind, solar and electrolyser capacity to achieve the same level of emissions reductions. It could also critically delay progress on BECCS and DACCS: if these cannot be deployed at scale, then achieving net-zero emissions by 2050 would be very much harder.

2.7.1 Behavioural change

Impact of behavioural changes in selected sectors in the NZE

Changes in the behaviour of energy consumers play an important role in cutting CO_2 emissions and energy demand growth in the NZE. Behavioural changes reduce global energy demand by 37 EJ in 2050, a 10% reduction in energy demand at that time, and without them cumulative emissions between 2021 and 2050 would be around 10% higher (Figure 2.24). Behavioural change plays a particularly important role in the transport sector.

Figure 2.24 ▷ Reduction in total final consumption due to behavioural changes by fuel in the NZE



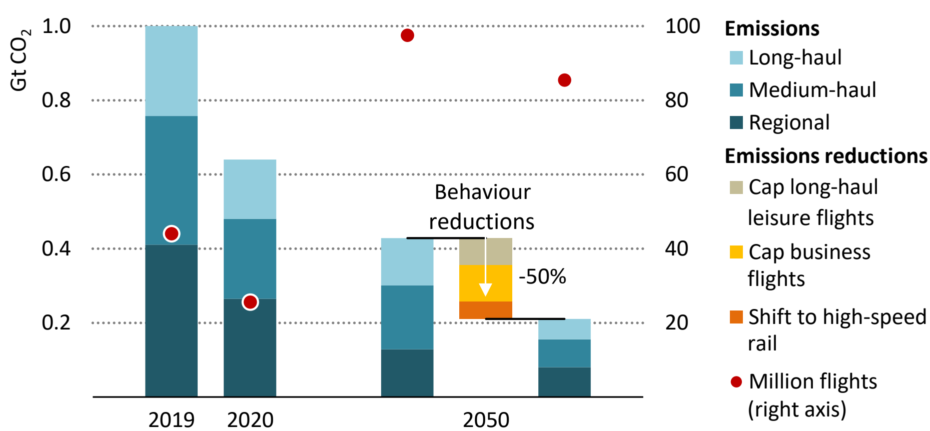
The impact of behaviour changes and materials efficiency on final energy consumption increases over time

Note: Other includes coal, hydrogen, geothermal, solar thermal, synthetic oil and synthetic gas.

Passenger aviation. Demand would grow more than threefold globally between 2020 and 2050 in the absence of the assumed changes in behaviour in the NZE. About 60% of this growth would occur in emerging market and developing economies. In the NZE, three changes lead to a 50% reduction in emissions from aviation in 2050, while reducing the number of flights by only 12% (Figure 2.25).

- Keeping air travel for business purposes at 2019 levels. Although business trips fell to almost zero in 2020, they accounted for just over one-quarter of air travel before the pandemic. This avoids around 110 Mt CO_2 in 2050 in the NZE.
- Keeping long-haul flights (more than six hours) for leisure purposes at 2019 levels. Emissions from an average long-haul flight are 35-times greater than from a regional flight (less than one hour). This affects less than 2% of flights but avoids 70 Mt CO_2 in 2050.
- A shift to high-speed rail. The opportunities for shifting regional flights to high-speed rail vary by region. Globally, we estimate that around 15% of regional flights in 2019 could have been shifted given existing rail infrastructure; future high-speed rail lines ensure that by 2050 around 17% could be shifted (IEA, 2019).[18] This would reduce emissions by around 45 Mt CO_2 in 2050 (high-speed trains generate no emissions in 2050 in the NZE).

Figure 2.25 ▻ Global CO_2 emissions from aviation and impact of behavioural changes in the NZE



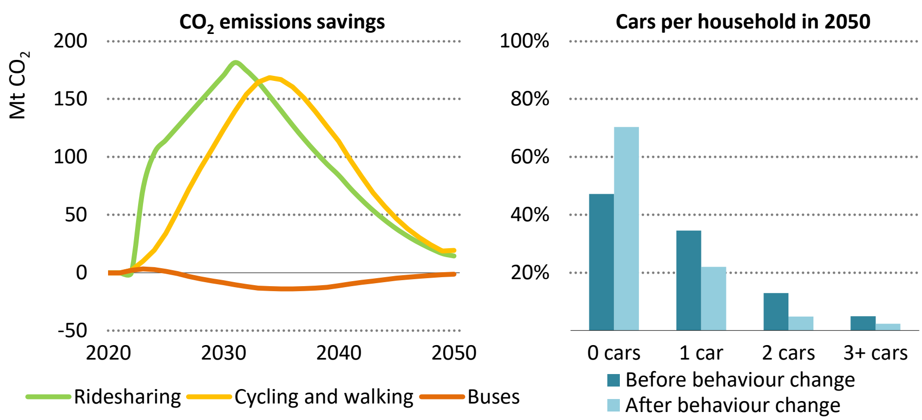
Demand for passenger aviation is set to grow significantly by 2050, but behavioural changes reduce emissions by 50% in 2050 despite reducing flights by only 12%

Notes: Long-haul = more than 6 hour flight; medium-haul = 1-6 hour flight; regional = less than 1 hour. Business flights = trips for work purposes; leisure flights = trips for leisure purposes. Average speeds vary by flight distance and range from 680-750 km/h.

[18] This assumes that: new rail routes avoid water bodies and tunnelling through elevated terrain; travel times are similar to aviation; and centres of demand are sufficiently large to ensure that high-speed rail is economically viable.

Car use. A variety of new measures that aim to reduce the use of cars in cities and overall car ownership levels are assumed in the NZE. They lead to rapid growth in the rideshare market in urban areas, as well as phasing out polluting cars in large cities and replacing them with cycling, walking and public transport. The timing of these changes in the NZE depends on cities having the necessary infrastructure and public support to ensure a shift away from private car use. Between 20-50% of car trips are shifted to buses, depending on the city in question, with the remainder replaced by cycling, walking and public transport. These changes reduce emissions from cars in cities by more than 320 Mt CO_2 in total in the mid-2030s (Figure 2.26). Their impact on emissions fades over time as cars are increasingly electrified, but they still have a significant impact on curbing energy use in 2050.

Figure 2.26 ▷ Global CO_2 emissions savings and car ownership per household due to behavioural change in the NZE



Policies discouraging car use in cities lead to rapid reductions in CO_2 emissions and lower car ownership levels, though the impact diminishes over time as cars are electrified

The gradual move away from cars in cities also has an impact on car ownership levels. Survey data indicates that car-share schemes and the provision of public transport reduces car ownership by up to 35%, with the biggest changes taking place in multiple car households (Jochem et al., 2020; Martin, Shaheen and Lidiker, 2010). Without behavioural changes, 35% of households would have a car in 2050; with behavioural changes this share falls to around 20% in the NZE, and two-car households fall from 13% of the total to less than 5%.

The changing patterns of mobility in cities in NZE have implications for materials demand. Reduced car ownership leads to a small drop in steel demand in 2050, saving around 40 Mt CO_2 in steel production. Increased cycling would need to be supported by building an estimated 80 000 km of new cycle lanes globally over the period to 2050, generating increased demand for cement and bitumen. This effect is small, however: the extra emissions associated with this would be less than 5% of the emissions avoided by lower car use.

How to bring about the behavioural changes in NZE

Regulations and mandates could enable roughly 70% of the emissions saved by behavioural changes in the NZE. Examples include:

- Upper speed limits, which are reduced over time in the NZE from their current levels to 100 km/h, cutting emissions from road vehicles by 3% in 2050.
- Appliance standards, which maximise energy efficiency in the buildings sector.
- Regulations covering heating temperatures in offices and default cooling temperatures for air conditioning units, which reduce excessive thermal demand.
- Changes initially tackled by market-based mechanisms, e.g. swapping regional flights for high-speed rail,[19] which can be addressed by regulation over time to mirror changes in public sentiment and consumer norms.

Market-based instruments use a mix of financial incentives and disincentives to influence decision making. They could enable around two-thirds of the emissions saved by behavioural changes in the NZE. Examples include:

- Congestion pricing and targeted interventions differentiated by vehicle type,[20] such as charges aimed at the most polluting vehicles, or preferential parking for clean cars.
- Transport demand measures that reduce travel, such as fuel taxes and distance-based vehicle insurance and registration fees (Byars, Wei and Handy, 2017).
- Information measures that help consumers to drive change, such as mandatory labelling of embodied or lifecycle emissions in manufacturing and a requirement for companies to disclose their carbon emissions.

Information and awareness measures could enable around 30% of the emissions saved by behavioural changes in the NZE. Examples include:

- Personalised and real-time travel planning information, which facilitates a switch to walking, cycling and public transport.
- Product labelling and public awareness campaigns in combination, which help make recycling widespread and habitual.
- Comparisons with consumption patterns of similar households, which can reduce wasteful energy use by up to 20% (Aydin, Brounen and Kok, 2018).

Not all the behavioural changes in the NZE would be equally easy to achieve everywhere, and policy interventions would need to draw on insights from behavioural science and take into account existing behavioural norms and cultural preferences. Some behavioural changes may be more socially acceptable than others. Citizen assemblies in the United Kingdom and

[19] A law banning domestic flights where a rail alternative of under two-and-a-half hours exists has been proposed in France (Assemblee Nationale, 2021).

[20] Congestion charging is currently used in 11 major cities and has been shown to reduce traffic volumes by up to 27%. Low-emissions zones charge vehicles to enter urban zones based vehicle type and currently exist in 15 countries (TFL, 2021; Tools of Change, 2014; European Commission, 2021).

France indicate a large level of support for taxes on frequent and long-distance flyers and for banning polluting vehicles from city centres; conversely, measures that limit car ownership or reduce speed limits have gained less acceptance (Convention Citoyenne pour le Climat, 2021; Climate Assembly UK, 2020). Behavioural changes which reduce energy use in homes may be particularly well supported: a recent survey showed 85% support for line-drying clothes and switching off appliances, and only 20% of people felt that reducing temperature settings in homes was undesirable (Newgate Research and Cambridge Zero, 2021).

Table 2.10 ▻ Key behavioural changes in the NZE

	Policy options	Related policy-goals	Cost-effectiveness	Timeliness	Social acceptability	CO_2 emissions impact
Low-car cities • Phase out ICE cars from large cities. • Rideshare all urban car trips.	• Low-emissions zones. • Access restrictions. • Parking restrictions. • Registration caps. • Parking pricing. • Congestion charges. • Investment in cycling lanes and public transportation.	• Air pollution mitigation. • Public health. • Reduced congestion. • Urban space. • Beautification and liveability.	🟡	🟡	🟡	🟢
Fuel-efficient driving • Reduce motorway speeds to less than 100 km/h. • Eco-driving. • Raise air conditioning temperature in cars by 3 °C.	• Speed limits. • Real-time fuel efficiency displays. • Awareness campaigns.	• Road safety. • Reduced noise pollution.	🟢	🟢	🟡	🟢
Reduce regional flights • Replace all flights <1h where high-speed rail is a feasible alternative.	• High-speed rail investment. • Subsidies for high-speed rail travel. • Price premiums.	• Lower air pollution. • Lower noise pollution.	🔴	🔴	🟡	🟡
Reduce international flights • Keep air travel for business purposes at 2019 levels. • Keep long-haul flights for leisure at 2019 levels.	• Awareness campaigns. • Price premiums. • Corporate targets. • Frequent-flyer levies.	• Lower air pollution. • Lower noise pollution.	🟢	🟢	🟡	🟢
Space heating • Target average set-point temperatures of 19-20 °C.	• Awareness campaigns. • Consumption feedback. • Corporate targets.	• Public health. • Energy affordability.	🟢	🟢	🟢	🟢
Space cooling • Target average set-point temperatures of 24-25 °C.	• Awareness campaigns. • Consumption feedback. • Corporate targets.	• Public health. • Energy affordability.	🟢	🟢	🟢	🔴

🔴 = poor match 🟡 = neutral match 🟢 = good match

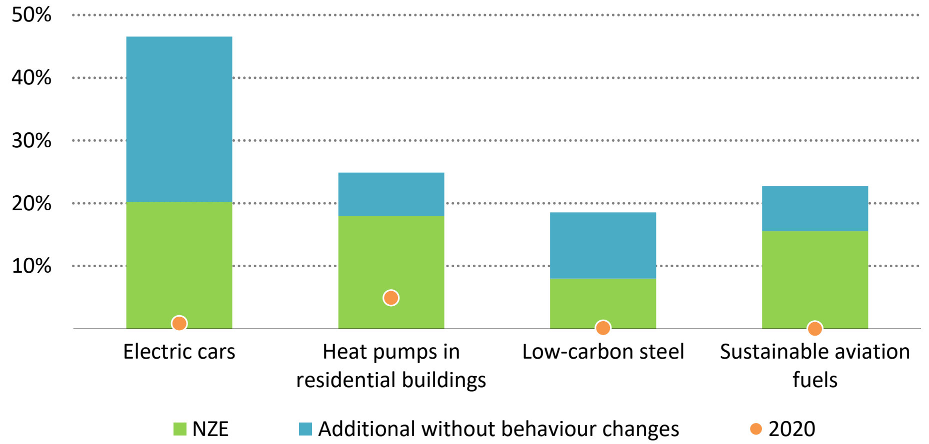
Notes: Large cities = cities over 1 million inhabitants. ICE = internal combustion engine. CO_2 emissions impact = cumulative reductions 2020-2050. Eco-driving = early upshifting as well as avoiding sudden acceleration, stops or idling. The number of jobs that can be done at home varies considerably by region, globally, an average of 20% of jobs can be done at home.

The behavioural changes in the NZE would bring wider benefits in terms of air pollution in cities, road safety, noise pollution, congestion and health. Attitudes to policy interventions can change quickly when co-benefits become apparent. For example, support for congestion charging in Stockholm jumped from less than 40% when the scheme was introduced to around 70% three years later; a similar trend was seen in Singapore, London and other cities, all of which experienced declines in air pollution after the introduction of charging (Tools of Change, 2014; DEFRA, 2012).

Are net-zero emissions by 2050 still possible without behavioural change?

If the behavioural changes described in the NZE were not to materialise, final energy use would be 27 EJ and emissions 1.7 Gt CO_2 higher in 2030, and they would be 37 EJ and 2.6 Gt CO_2 higher in 2050. This would further increase the already unprecedented ramp-up needed in low-carbon technologies. The share of EVs in the global car fleet would need to increase from around 20% in 2030 to 45% to ensure the same level of emissions reductions (Figure 2.27). Achieving the same reduction in emissions in homes would require electric heat pumps sales to reach 680 million in 2030 (compared with 440 million in the NZE). Without gains in materials efficiency, the share of low-carbon primary steel production would need to be more than twice as high in 2030 as in the NZE. In 2050, the use of sustainable aviation fuels would also need to rise to 7 mboe/d (compared with 5 mboe/d in the NZE). Emissions from cement and steel production would be 1.7 Gt CO_2 higher in 2050 than in the NZE, and so require increased deployment of CCUS in industry, deployment of electric arc furnaces and more use of low-carbon hydrogen.

Figure 2.27 ▷ Share of low-carbon technologies and fuels with and without behavioural change in 2030 in the NZE



In the absence of behavioural changes, the share of low-emissions technologies in end-uses in 2030 would need to be much larger to achieve the same emissions as in the NZE

Notes: Electric cars = share of electric cars on the road globally. Sustainable aviation fuels = biojet kerosene and synthetic jet kerosene. Low-carbon steel refers to primary steel production.

2.7.2 Bioenergy and land-use change

Modern forms of bioenergy play a key role in achieving net-zero emissions in the NZE. Bioenergy is a versatile renewable energy source that can be used in all sectors, and it can often make use of existing transmission and distribution infrastructure and end-user equipment. But there are constraints on expanding the supply of bioenergy: with finite potential for bioenergy production from waste streams, there are possible trade-offs between expanding bioenergy production, achieving sustainable development goals and avoiding conflicts with other land uses, notably food production.

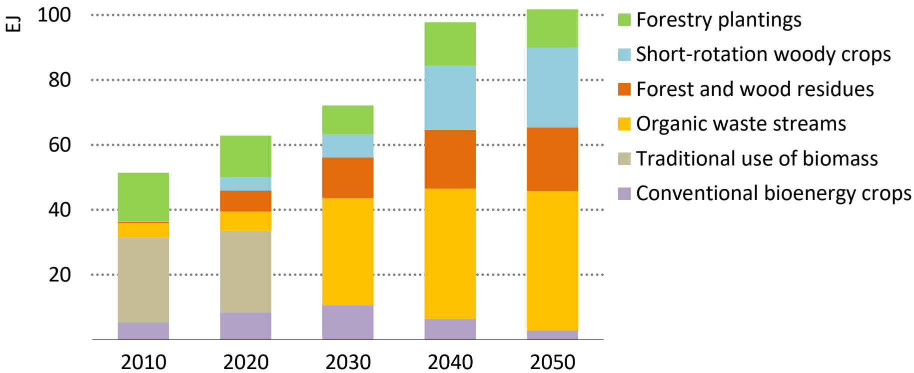
The level of bioenergy use in the NZE takes account of these constraints: bioenergy demand in 2050 is around 100 EJ. The global sustainable bioenergy potential in 2050 has been assessed to be at least 100 EJ (Creutzig, 2015) and recent assessments estimate a potential between 150-170 EJ when integrating relevant UN Sustainable Development Goals (Frank, 2021; IPCC, 2019; IPCC, 2014; Wu, 2019). However, there is a high degree of uncertainty over the precise levels of this potential. Using modelling developed in co-operation with IIASA, here we examine the implications for achieving net-zero CO_2 emissions by 2050 if the available levels of sustainable bioenergy were to be lower. We also examine what would need to be done to achieve large reductions in emissions from agriculture, forestry and other land use (AFOLU).

Ensuring a sustainable supply of bioenergy

Most liquid biofuels produced today come from dedicated bioenergy crops such as sugarcane, corn or oil crops, often known as conventional biofuels. The expanded use of feedstocks and arable land to produce these biofuels can conflict with food production. In the NZE, there is a shift towards the use of sustainable, certified agricultural products and wood. Biofuel production processes in the NZE use advanced conversion technologies coupled with CCUS where possible (see section 3.3.2). The emphasis is also on advanced bioenergy feedstocks, including waste streams from other processes, short-rotation woody crops and feedstocks that do not require the use of arable land. Advanced bioenergy accounts for the vast majority of bioenergy supply in the NZE by 2050. The use of conventional energy crops for biofuel production grows from around 9 EJ in 2020 to around 11 EJ in 2030, but then falls by 70% to 3 EJ in 2050 (including feedstocks consumed in the biofuel production processes).

Advanced bioenergy feedstocks that do not require land include organic waste streams from agriculture and industry, and woody residues from forest harvesting and wood processing. Investment in comprehensive waste collection and sorting in the NZE unlocks around 45 EJ of bioenergy supply from various organic waste streams which is primarily used to produce biogases and advanced biofuels (Figure 2.28). Woody residues from wood processing and forest harvesting provide a further 20 EJ of bioenergy in 2050 in the NZE – less than half of current best estimates of the total sustainable potential. Bioenergy can also be produced from dedicated short-rotation woody crops (25 EJ of bioenergy supply in 2050).[21] Sustainably managed forestry fuelwood or plantations[22] and tree plantings integrated with agricultural production via agroforestry systems that do not conflict with food production or biodiversity provide just over 10 EJ of bioenergy in 2050.

Figure 2.28 ▷ Global bioenergy supply by source in the NZE



Bioenergy use increases by around 60% between 2020 and 2050, while shifting away from conventional feedstocks and the traditional use of biomass

Note: Organic waste streams include agricultural residues, food processing, industrial and municipal organic waste streams; they do not require land area.

Source: IEA analysis based on IIASA data.

The total land area dedicated to bioenergy production in the NZE increases from 330 million hectares (Mha) in 2020 to 410 Mha in 2050. In 2050, around 270 Mha is forest, representing around one-quarter of the total area of global managed forests, and around 5% of total forest area. There is 130 Mha of land used for short-rotation advanced bioenergy crops in 2050 and 10 Mha for conventional bioenergy crops. There is no overall increase in cropland use for bioenergy production in the NZE from today's level and no bioenergy crops are developed on forested land in the NZE.[23] As well as allowing a much greater level of bioenergy crop production on marginal lands, woody energy crops can produce twice as much bioenergy per hectare as conventional bioenergy crops.

[21] Woody short-rotation coppice crops grown on crop land, pasture land or marginal lands not suited to food crops.

[22] Sustainable forestry management ensures that the carbon stock and carbon absorption capability of the forest is expanded or remains unchanged.

[23] Of the 140 Mha land used for bioenergy crops in 2050, 70 Mha are marginal lands or land currently used for livestock grazing and 70 Mha are cropland. There is a 60 Mha increase in cropland use for woody crops to 2050 in the NZE but this is offset by a reduction in cropland use for producing conventional biofuel feedstocks.