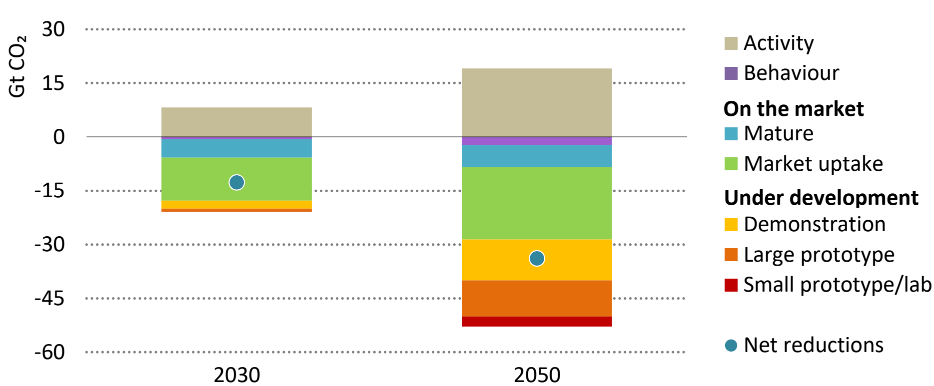
- **Increasing taxation on electricity**. Higher taxes on all electricity sales could generate substantial revenues, especially since large increases in price often have little effect on consumption. This might be counterproductive, however, as it would reduce the cost-effectiveness of both EVs and heat pumps, which could slow their adoption, although this risk could be mitigated by the introduction of CO_2 prices.

Natural gas is currently less taxed than transport fuels in most countries. Introducing and raising CO_2 prices for natural gas used in buildings, mostly for heating, would accelerate energy efficiency improvements and boost government revenues, although care would be needed to avoid disproportionately impacting low-income households. Taxing natural gas used in industry would improve the competitiveness of less carbon-intensive fuels and technologies such as hydrogen, but would run the risk of undermining the international competitiveness of energy-intensive sectors and carbon leakage in the absence of co-ordinated global action or border carbon-tax adjustments.

4.5.4 Innovation

Without a major acceleration in clean energy innovation, reaching net-zero emissions by 2050 will not be achievable. Technologies that are available on the market today provide nearly all of the emissions reductions required to 2030 in the NZE to put the world on track for net-zero emissions by 2050. However, reaching net-zero emissions will require the widespread use after 2030 of technologies that are still under development today. In 2050, almost 50% of CO_2 emissions reductions in the NZE come from technologies currently at demonstration or prototype stage (Figure 4.22). This share is even higher in sectors such as heavy industry and long-distance transport. Major innovation efforts are vital in this decade so that the technologies necessary for net-zero emissions reach markets as soon as possible.

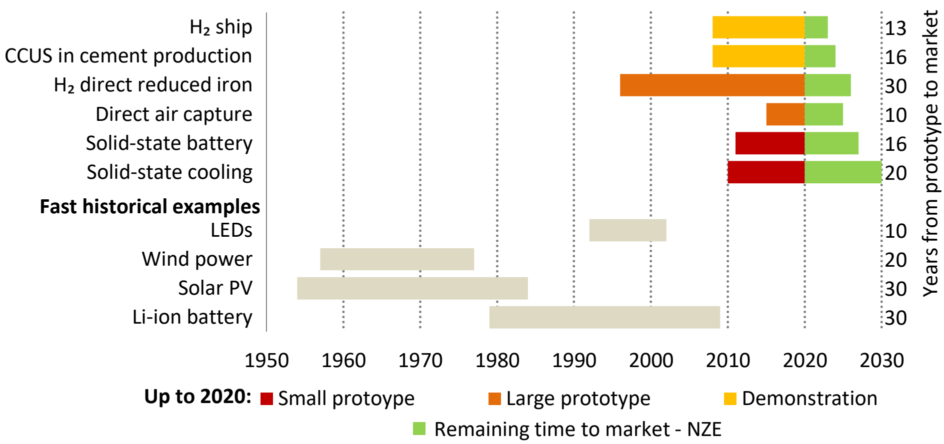
Figure 4.22 ▷ Global CO_2 emissions changes by technology maturity category in the NZE



While the emissions reductions in 2030 mostly rely on technologies on the market, those under development today account for almost half of the emissions reductions in 2050

Innovation cycles for early stage clean energy technologies are much more rapid in the NZE than what has typically been achieved historically, and most clean energy technologies that have not been demonstrated at scale today reach markets by 2030 at the latest. This means the time from first prototype to market introduction is on average 20% faster than the fastest energy technology developments in the past, and around 40% faster than was the case for solar PV (Figure 4.23). Technologies at the demonstration stage, such as CCUS in cement production or low-emissions ammonia-fuelled ships, are brought into the market in the next three to four years. Hydrogen-based steel production, direct air capture (DAC) and other technologies at the large prototype stage reach the market in about six years, while most technologies at small prototype stage – such as solid state refrigerant-free cooling or solid state batteries – do so within the coming nine years.

Figure 4.23 ▷ Time from first prototype to market introduction for selected technologies in the NZE and historical examples



Technology development cycles are cut by around 20% from the fastest developments seen in the past

Note: H_2 = hydrogen; CCUS = carbon capture, utilisation and storage; LED = light-emitting diode; Li-ion = lithium-ion.

Sources: IEA analysis based on Carbon Engineering, 2021; Greco, 2019; Tenova, 2018; Gross, 2018; European Cement Research Academy, 2012; Kamaya, 2011; Zemships, 2008.

An acceleration of this magnitude is clearly ambitious. It requires technologies that are not yet available on the market to be demonstrated very quickly at scale in multiple configurations and in various regional contexts. In most cases, these demonstrations are run in parallel in the NZE. This is in stark contrast with typical practice in technology development: learning is usually transferred across consecutive demonstration projects in different contexts to build confidence before widespread deployment commences.

The acceleration that is needed also requires a large increase in investment in demonstration projects. In the NZE, USD 90 billion is mobilised as soon as possible to complete a portfolio of demonstration projects before 2030: this is much more than the roughly USD 25 billion budgeted by governments to 2030. Most of these projects are concerned with the electrification of end-uses, CCUS, hydrogen and sustainable bioenergy, mainly for long-distance transport and heavy industrial applications.

Increased public funding helps to manage the risks of such first-of-a-kind projects and to leverage private investment in research and development (R&D) in the NZE. This represents a reversal of recent trends: government spending on energy R&D worldwide, including demonstration projects, has fallen as a share of GDP from a peak of almost 0.1% in 1980 to just 0.03% in 2019. Public funding also becomes better aligned with the innovations needed to reach net-zero emissions. In the NZE, electrification, CCUS, hydrogen and sustainable bioenergy account for nearly half of the cumulative emissions reductions to 2050. Just three technologies are critical in enabling around 15% of the cumulative emissions reductions in the NZE between 2030 and 2050: advanced high-energy density batteries, hydrogen electrolysers and DAC.

Governments drive innovation in the NZE

Bringing new energy technologies to market can often take several decades, but the imperative of reaching net-zero emissions globally by 2050 means that progress has to be much faster. Experience has shown that the role of government is crucial in shortening the time needed to bring new technology to market and to diffuse it widely (IEA, 2020i). The government role includes educating people, funding R&D, providing networks for knowledge exchange, protecting intellectual property, using public procurement to boost deployment, helping companies innovate, investing in enabling infrastructure and setting regulatory frameworks for markets and finance.

Knowledge transfer from first-mover countries can also help in the acceleration needed, and is particularly important in the early phases of adoption when new technologies are typically not competitive with incumbent technologies. For example, in the case of solar PV, national laboratories played a key role in the early development phase in the United States, projects supported directly by government in Japan created market niches for initial deployment and government procurement and incentive policies in Germany, Italy, Spain, United States, China, Australia and India fostered a global market. Lithium-ion (Li-ion) batteries were initially developed through public and private research that took place mostly in Japan, their first energy-related commercial operation was made possible in the United States, and mass manufacturing today is primarily in China.

Many of the biggest clean energy technology challenges could benefit from a more targeted approach to speed up progress (Diaz Anadon, 2012; Mazzucato, 2018). In the NZE, concerted government action leverages private sector investment and leads to advances in clean energy technologies that are currently at different stages of development.

- To 2030, the focus of government action is on bringing new zero- or low-emissions technologies to market. For example, in the NZE, steel starts to be produced using low-emissions hydrogen at the scale of a conventional steel plant, large ships start to be fuelled by low-emissions ammonia and electric trucks begin operating on solid state batteries. In parallel, there is rapid acceleration in the deployment of low-emissions technologies that are already available on the market but that have not yet reached mass market scale, bringing down the costs of manufacturing, construction and operating such technologies due to learning-by-doing and economies of scale.

- From 2030 to 2040, technology advances are consolidated to scale up nascent low-emissions technologies and expand clean energy infrastructure. Clean energy technologies that are in the laboratory or at small prototype stage today become commercial. For example, fuels are replaced by electricity in cement kilns and steam crackers for high value chemicals production.
- From 2040 to 2050, technologies at a very early stage of development today are adopted in promising niche markets. By 2050, clean energy technologies that are at demonstration or large prototype stage today become mainstream for purchases and new installations, and they compete with present conventional technologies in all regions. For example, ultra high-energy density batteries are used in aircraft for short flights.

4.5.5 International co-operation

The pathway to net-zero emissions by 2050 will require an unprecedented level of international co-operation between governments. This is not only a matter of all countries participating in efforts to meet the net zero goal, but also of all countries working together in an effective and mutually beneficial manner. Achieving net-zero emissions will be extremely challenging for all countries, but the challenges are toughest and the solutions least easy to deliver in lower income countries, and technical and financial support will be essential to ensure the early stage deployment of key mitigation technologies and infrastructure in many of these countries. Without international co-operation, emissions will not fall to net zero by 2050.

There are four aspects of international co-operation that are particularly important (Victor, Geels and Sharpe, 2019).

- **International demand signals and economies of scale**. International co-operation has been critical to the cost reductions seen in the past for many key energy technologies. It can accelerate knowledge transfer and promote economies of scale. It can also help align the creation of new demand for clean energy technologies and fuels in one region with the development of supply in other regions. These benefits need to be weighed against the importance of creating domestic jobs and industrial capacities, and of ensuring supply chain resilience.
- **Managing trade and competitiveness**. Industries that operate in a number of countries need standardisation to ensure inter-operability. Progress on innovation and clean energy technology deployment in sectors such as heavy industry has been inhibited in the past by uncoordinated national policies and a lack of internationally agreed

standards. The development of such standards could accelerate energy technology development and deployment.

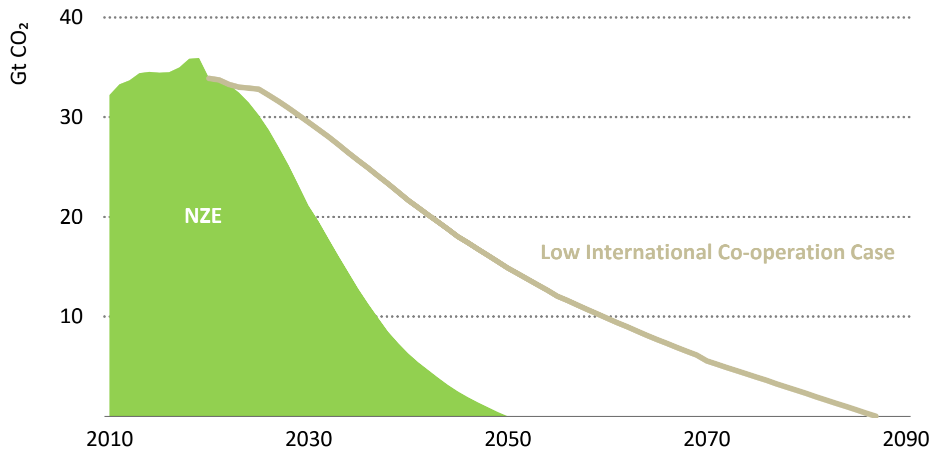
- **Innovation, demonstration and diffusion**. Clean energy R&D and patenting is currently concentrated in a handful of places: United States, Europe, Japan, Korea and China accounted for more than 90% of clean energy patents in 2014-18. Progress towards net-zero emissions would be increased by moving swiftly to extend experience and knowledge of clean energy technologies in countries that are not involved in their initial development, and by funding first-of-a-kind demonstration projects in emerging market and developing economies. International programmes to fund demonstration projects, especially in sectors where technologies are large and complex, would accelerate the innovation process (IEA, 2020i).
- **Carbon dioxide removal (CDR) programmes**. CDR technologies such as bioenergy and DAC equipped with CCUS are essential to provide emissions reductions at a global level. International co-operation is needed to fund and certify these programmes, so as to make the most of suitable land, renewable energy potential and storage resources, wherever they may be. International emissions trading mechanisms could play a role in offsetting emissions in some sectors or areas with negative emissions, though any such mechanisms would require a high degree of co-ordination to ensure market functioning and integrity.

The NZE assumes that international co-operation policies, measures and efforts are introduced to overcome these hurdles. To explore the potential implications of a failure to do so, we have devised a *Low International Co-operation Case* (Box 4.2). This examines what would happen if national efforts to mitigate climate change ramp up in line with the level of effort in the NZE but co-operation frameworks are not developed at the same speed. It shows that the lack of international co-operation has a major impact on innovation, technology demonstration, market co-ordination and ultimately on the emissions pathway.

Box 4.2 ▹ Framing the Low International Co-operation Case

To develop the *Low International Co-operation Case*, technologies and mitigation options were assessed and grouped based on their current degree of maturity and the importance of international co-operation to their deployment. Mature technologies in markets that are firmly established and that have a low exposure to international co-operation are assumed to have the same deployment pathways as in the NZE. Technologies and mitigation options where co-operation is needed to achieve scale and avoid duplication, that have a large exposure to international trade and competitiveness, that depend on large and very capital-intensive demonstration programmes, or that require support to create market pull and standardisation to ensure inter-operability, are assumed to be deployed more slowly (Malhotra and Schmidt, 2020). Compared with the NZE, these technologies are delayed by 5-10 years in their initial deployment in advanced economies and by 10-15 years in emerging market and developing economies.

Figure 4.24 ▷ CO_2 emissions in the Low International Co-operation Case and the NZE

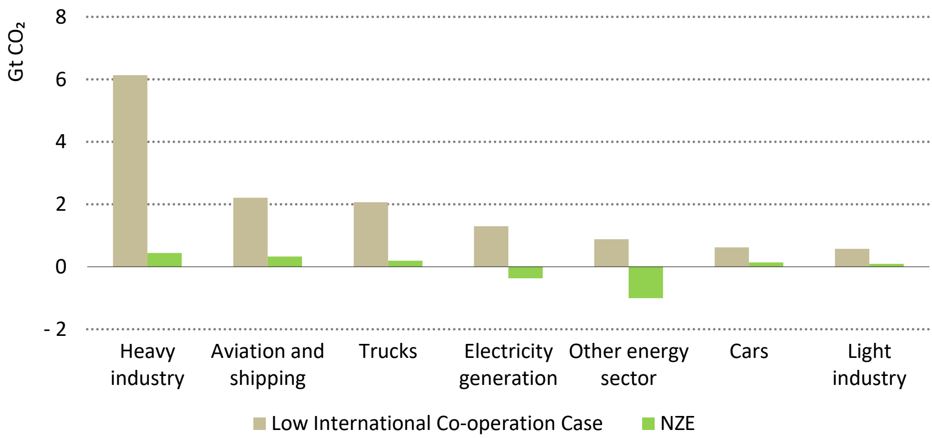


Without international co-operation, the transition to net zero would be delayed by decades

Weak international co-operation slows the deployment of mitigation options that are currently in the demonstration phase (Figure 4.24). This includes emissions reductions in heavy industry, trucks, aviation, shipping and CDR. The energy transition proceeds unevenly as a result. Over the next 20 years in the Low International Co-operation Case, emissions decline at a rapid but still slower pace than in the NZE in electricity generation, cars, light industry and buildings. However, emissions reductions are much slower in other areas. After the mid-2030s, the pace of emissions reductions worldwide slows markedly relative to the NZE, and the transition to net zero is delayed by decades. Just over 40% of the 15 Gt CO_2 of emissions remaining in 2050 are in heavy industry, where the slower pace of demonstration and diffusion of mitigation technologies is particularly significant (Figure 4.25). A further one-third of the residual emissions in 2050 are from aviation, shipping and trucks. Here the slower scale up and diffusion of advanced biofuels, hydrogen-based fuels and high-energy density batteries hinders progress. The absence of co-operation to support the deployment of new projects in emerging market and developing economies means that emissions reductions there are much slower than in the NZE.

These results highlight the importance for governments of strengthening international co-operation. A strong push is needed to accelerate innovation and the demonstration of key technologies, especially for complex technologies in emerging market and developing economies where costs for first-of-a-kind projects are generally higher, and to address concerns about international trade and competitiveness so as to ensure a just transition for all.

Figure 4.25 ▷ CO_2 emissions in the Low International Co-operation Case and the NZE in selected sectors in 2050



CO_2 emissions in 2050 in the Low International Co-operation Case are concentrated in the industry and transport sectors

Note: Other energy sector = fuel production and direct air capture.

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 scenario for the following data sets: energy supply, energy demand, gross electricity generation and electrical capacity, carbon dioxide (CO_2) emissions from fossil fuel combustion and industrial processes, and selected economic and activity indicators.

The definitions for fuels and sectors are in Annex C. Common abbreviations used in the tables include: EJ = exajoules; CAAGR = compound average annual growth rate; CCUS = carbon capture, utilisation and storage. Consumption of fossil fuels in facilities without CCUS are classified as “unabated”.

Both in the text of this report and in the 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 “-”.

To download the tables in Excel format go to: **iea.li/nzedata**.

Data sources

The formal base year for the scenario projections is 2019, as this is the last year for which a complete picture of energy demand and production is available. However, we have used more recent data when available, and we include our 2020 estimates for energy production and demand in this annex. Estimates for the year 2020 are based on updates of the IEA’s Global Energy Review reports which are derived from a number of sources, including the latest monthly data submissions to the IEA’s 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.

Historical data for gross electrical capacity are drawn from the S&P Global Market Intelligence World Electric Power Plants Database (March 2020 version) and the International Atomic Energy Agency PRIS database.

Definitional note: A.1. Energy supply and transformation table

Total energy supply (TES) is equivalent to electricity and heat generation plus “other energy sector” excluding electricity and heat, plus total final consumption (TFC) excluding electricity and heat. TES does not include ambient heat from heat pumps or electricity trade. Solar in TES includes solar PV generation, concentrating solar power and final consumption of solar thermal. Other renewables in TES include geothermal, and marine (tide and wave) energy for electricity and heat generation. Hydrogen production and biofuels production in the other energy sector account for the energy input required to produce merchant hydrogen (mainly natural gas and electricity) and for the conversion losses to produce biofuels (mainly primary solid biomass) used in the energy sector. While not itemised separately, non-renewable waste and other sources are included in TES.

Definitional note: A.2. Energy demand table

Sectors comprising total final consumption (TFC) include industry (energy use and feedstock), transport, buildings (residential, services and non-specified other) and other (agriculture and other non-energy use). Energy demand from international marine and aviation bunkers are included in transport totals.

Definitional note: A.3. Electricity tables

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.

Definitional note: A.4. CO_2 emissions table

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) as well as CO_2 removals. Three types of CO_2 removals are presented:

- Captured and stored emissions from the combustion of bioenergy and renewable wastes (typically electricity generation).
- Captured and stored process emissions from biofuels production.
- Captured and stored carbon dioxide from the atmosphere, which is reported as direct air carbon capture and storage (DACCS).

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.

Definitional note: A.5. Economic and activity indicators

The emission intensity expressed in kilogrammes of carbon dioxide per kilowatt-hour (kg CO_2/kWh) is calculated based on electricity-only plants and the electricity component of combined heat and power (CHP) plants. [1]

Other abbreviations used include: PPP = purchasing power parity; GJ = gigajoules; Mt = million tonnes; pkm = passenger-kilometres; tkm = tonnes-kilometres; m^2 = square metres.

[1] 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: Energy supply and transformation

	Energy supply (EJ)					Shares (%)			CAAGR (%)	
	2019	2020	2030	2040	2050	2020	2030	2050	2020-2030	2020-2050
Total energy supply	**612**	**587**	**547**	**535**	**543**	**100**	**100**	**100**	**-0.7**	**-0.3**
Renewables	67	69	167	295	362	12	30	67	9.3	5.7
Solar	4	5	32	78	109	1	6	20	21	11
Wind	5	6	29	67	89	1	5	16	17	9.6
Hydro	15	16	21	27	30	3	4	6	2.9	2.2
Modern solid bioenergy	31	32	54	73	73	5	10	14	5.3	2.8
Modern liquid bioenergy	4	3	12	14	15	1	2	3	14	4.9
Modern gaseous bioenergy	2	2	5	10	14	0	1	3	10	6.4
Other renewables	4	5	13	24	32	1	2	6	11	6.7
Traditional use of biomass	25	25	-	-	-	4	-	-	n.a.	n.a.
Nuclear	30	29	41	54	61	5	8	11	3.5	2.4
Unabated natural gas	139	136	116	44	17	23	21	3	-1.6	-6.6
Natural gas with CCUS	0	1	13	31	43	0	2	8	37	16
Oil	190	173	137	79	42	29	25	8	-2.3	-4.6
of which non-energy use	28	27	32	31	29	5	6	5	1.4	0.2
Unabated coal	160	154	68	16	3	26	12	1	-7.9	-12
Coal with CCUS	0	0	4	16	14	0	1	3	60	22
Electricity and heat sectors	**233**	**230**	**240**	**308**	**371**	**100**	**100**	**100**	**0.4**	**1.6**
Renewables	36	38	107	220	284	17	44	77	11	6.9
Solar PV	2	3	25	61	84	1	10	23	24	12
Wind	5	6	29	67	89	2	12	24	17	9.6
Hydro	15	16	21	27	30	7	9	8	2.9	2.2
Bioenergy	9	10	18	35	39	4	8	10	6.3	4.6
Other renewables	4	4	14	30	42	2	6	11	14	8.5
Hydrogen	-	-	5	11	11	-	2	3	n.a.	n.a.
Ammonia	-	-	1	2	2	-	0	0	n.a.	n.a.
Nuclear	30	29	41	54	61	13	17	16	3.5	2.4
Unabated natural gas	56	55	49	4	2	24	21	0	-1.1	-11
Natural gas with CCUS	-	-	1	5	5	-	1	1	n.a.	n.a.
Oil	9	8	2	0	0	4	1	0	-12	-14
Unabated coal	102	100	30	0	0	43	12	0	-11	-34
Coal with CCUS	0	0	3	10	7	0	1	2	55	19
Other energy sector	**57**	**57**	**61**	**76**	**91**	**100**	**100**	**100**	**0.7**	**1.5**
Hydrogen production	-	0	21	49	70	0	35	77	66	23
Biofuels production	5	6	12	15	12	10	20	13	8	2.7

Table A.2: Energy demand

	Energy demand (EJ)					Shares (%)			CAAGR (%)	
	2019	2020	2030	2040	2050	2020	2030	2050	2020-2030	2020-2050
Total final consumption	**435**	**412**	**394**	**363**	**344**	**100**	**100**	**100**	**-0.4**	**-0.6**
Electricity	82	81	103	140	169	20	26	49	2.4	2.5
Liquid fuels	175	158	143	96	66	38	36	19	-1.0	-2.9
Biofuels	4	3	12	14	15	1	3	4	14	4.9
Ammonia	-	-	1	3	5	-	0	1	n.a.	n.a.
Synthetic oil	-	-	0	2	5	-	0	1	n.a.	n.a.
Oil	171	154	129	77	42	37	33	12	-1.8	-4.2
Gaseous fuels	70	68	68	60	53	16	17	15	0.1	-0.8
Biomethane	0	0	2	5	8	0	1	2	25	13
Hydrogen	0	0	6	12	20	0	2	6	54	20
Synthetic methane	-	-	0	1	4	-	0	1	n.a.	n.a.
Natural gas	70	67	58	40	20	16	15	6	-1.4	-4.0
Solid fuels	92	89	61	46	35	22	16	10	-3.6	-3.0
Biomass	39	39	24	25	25	9	6	7	-4.8	-1.4
Coal	53	50	38	21	10	12	10	3	-2.8	-5.3
Heat	13	13	12	9	6	3	3	2	-1.2	-2.7
Other	3	3	7	11	15	1	2	4	8.2	5.2
Industry	**162**	**157**	**170**	**169**	**160**	**100**	**100**	**100**	**0.8**	**0.1**
Electricity	35	35	47	62	74	22	28	46	3.0	2.5
Liquid fuels	31	31	31	27	23	20	18	15	-0.2	-0.9
Oil	31	31	31	27	23	20	18	15	-0.2	-0.9
Gaseous fuels	32	32	35	34	28	20	21	18	1.0	-0.4
Biomethane	0	0	1	2	4	0	0	3	22	15
Hydrogen	-	0	3	4	5	0	2	3	44	15
Unabated natural gas	32	32	30	22	9	20	18	6	-0.5	-4.0
Natural gas with CCUS	0	0	1	5	7	0	1	4	38	18
Solid fuels	58	52	51	40	30	34	30	18	-0.3	-1.9
Biomass	10	9	15	19	20	6	9	13	5.2	2.8
Unabated coal	48	44	35	15	3	28	20	2	-2.3	-9.0
Coal with CCUS	0	0	1	5	7	0	1	4	91	31
Heat	6	6	6	3	2	4	3	1	-1.2	-4.5
Other	0	0	1	3	4	0	1	2	33	14
Iron and steel	36	33	37	36	32	21	22	20	1.1	-0.2
Chemicals	22	20	26	26	25	13	15	15	2.7	0.7
Cement	12	16	11	11	10	10	7	7	-3.3	-1.3

Table A.2: Energy demand

	Energy demand (EJ)					Shares (%)			CAAGR (%)	
	2019	2020	2030	2040	2050	2020	2030	2050	2020-2030	2020-2050
Transport	**122**	**105**	**102**	**85**	**80**	**100**	**100**	**100**	**-0.3**	**-0.9**
Electricity	1	1	7	22	35	1	7	44	17	11
Liquid fuels	115	99	89	53	30	94	87	38	-1.0	-3.9
Biofuels	4	3	13	16	16	3	13	21	15	5.6
Oil	111	96	76	35	9	91	74	12	-2.2	-7.4
Gaseous fuels	5	5	6	10	15	5	6	18	2.1	3.7
Biomethane	0	0	1	1	2	0	0	2	23	11
Hydrogen	0	0	1	6	13	0	1	16	92	34
Natural gas	5	5	4	2	0	5	4	0	-1.5	-11
Road	90	81	73	57	50	77	72	63	-0.9	-1.6
Passenger cars	47	41	30	19	17	39	29	21	-3.1	-2.9
Trucks	27	25	28	24	22	24	27	28	1.1	-0.4
Aviation	14	8	13	13	14	8	13	18	4.6	1.7
Shipping	12	11	11	10	10	10	11	12	0.4	-0.3
Buildings	**129**	**127**	**99**	**89**	**86**	**100**	**100**	**100**	**-2.4**	**-1.3**
Electricity	43	42	45	51	57	33	46	66	0.7	1.0
Liquid fuels	13	13	9	4	2	10	10	2	-3.2	-6.0
Biofuels	0	0	0	1	1	0	0	1	26	12
Oil	13	13	9	4	1	10	9	1	-3.4	-7.7
Gaseous fuels	30	28	23	13	6	22	23	7	-2.1	-4.9
Biomethane	0	0	1	2	2	0	1	2	29	11
Hydrogen	-	0	2	2	2	0	2	2	103	27
Natural gas	30	28	19	7	1	22	20	1	-3.8	-12
Solid fuels	34	34	10	7	6	27	10	7	-11	-5.5
Modern biomass	5	5	9	7	6	4	9	7	6.9	0.9
Traditional use of biomass	25	25	-	-	-	20	-	-	n.a.	n.a.
Coal	4	4	1	0	0	3	1	0	-12	-21
Heat	7	7	6	5	4	5	6	5	-1.2	-1.6
Other	2	3	5	8	11	2	5	12	7.1	4.8
Residential	91	90	67	59	58	71	67	67	-3.0	-1.5
Services	38	36	32	30	28	29	33	33	-1.2	-0.9
Other	**22**	**23**	**22**	**20**	**18**	**100**	**100**	**100**	**-0.5**	**-0.9**

Table A.3: Electricity

	Electricity Generation (TWh)					Shares (%)			CAAGR (%)	
	2019	2020	2030	2040	2050	2020	2030	2050	2020-2030	2020-2050
Total generation	**26 922**	**26 778**	**37 316**	**56 553**	**71 164**	**100**	**100**	**100**	**3.4**	**3.3**
Renewables	7 153	7 660	22 817	47 521	62 333	29	61	88	12	7.2
Solar PV	665	821	6 970	17 031	23 469	3	19	33	24	12
Wind	1 423	1 592	8 008	18 787	24 785	6	21	35	18	9.6
Hydro	4 294	4 418	5 870	7 445	8 461	17	16	12	2.9	2.2
Bioenergy	665	718	1 407	2 676	3 279	3	4	5	7.0	5.2
of which BECCS	*-*	*-*	*129*	*673*	*842*	*-*	*0*	*1*	*n.a.*	*n.a.*
CSP	14	14	204	880	1 386	0	1	2	31	17
Geothermal	92	94	330	625	821	0	1	1	13	7.5
Marine	1	2	27	77	132	0	0	0	28	14
Nuclear	2 792	2 698	3 777	4 855	5 497	10	10	8	3.4	2.4
Hydrogen-based	-	-	875	1 857	1 713	-	2	2	n.a.	n.a.
Fossil fuels with CCUS	1	4	459	1 659	1 332	0	1	2	61	21
Coal with CCUS	1	4	289	966	663	0	1	1	54	19
Natural gas with CCUS	-	-	170	694	669	-	0	1	n.a.	n.a.
Unabated fossil fuels	16 941	16 382	9 358	632	259	61	25	0	-5.4	-13
Coal	9 832	9 426	2 947	0	0	35	8	0	-11	-40
Natural gas	6 314	6 200	6 222	626	253	23	17	0	0.0	-10
Oil	795	756	189	6	6	3	1	0	-13	-15

	Electrical Capacity (GW)					Shares (%)			CAAGR (%)	
	2019	2020	2030	2040	2050	2020	2030	2050	2020-2030	2020-2050
Total capacity	**7 484**	**7 795**	**14 933**	**26 384**	**33 415**	**100**	**100**	**100**	**6.7**	**5.0**
Renewables	2 707	2 994	10 293	20 732	26 568	38	69	80	13	7.5
Solar PV	603	737	4 956	10 980	14 458	9	33	43	21	10
Wind	623	737	3 101	6 525	8 265	9	21	25	15	8.4
Hydro	1 306	1 327	1 804	2 282	2 599	17	12	8	3.1	2.3
Bioenergy	153	171	297	534	640	2	2	2	5.7	4.5
of which BECCS	*-*	*-*	*28*	*125*	*152*	*-*	*0*	*0*	*n.a.*	*n.a.*
CSP	6	6	73	281	426	0	0	1	28	15
Geothermal	15	15	52	98	126	0	0	0	13	7.4
Marine	1	1	11	32	55	0	0	0	34	16
Nuclear	415	415	515	730	812	5	3	2	2.2	2.3
Hydrogen-based	-	-	139	1 455	1 867	-	1	6	n.a.	n.a.
Fossil fuels with CCUS	0	1	81	312	394	0	1	1	66	25
Coal with CCUS	0	1	53	182	222	0	0	1	59	22
Natural gas with CCUS	-	-	28	130	171	-	0	1	n.a.	n.a.
Unabated fossil fuels	4 351	4 368	3 320	1 151	677	56	22	2	-2.7	-6.0
Coal	2 124	2 117	1 192	432	158	27	8	0	-5.6	-8.3
Natural gas	1 788	1 829	1 950	679	495	23	13	1	0.6	-4.3
Oil	440	422	178	39	25	5	1	0	-8.3	-9.0
Battery storage	11	18	585	2 005	3 097	0	4	9	42	19

Table A.4: CO_2 emissions

	CO_2 emissions (Mt CO_2)					CAAGR (%)	
	2019	2020	2030	2040	2050	2020-2030	2020-2050
Total CO_2*	**35 926**	**33 903**	**21 147**	**6 316**	**0**	**-4.6**	**-55.4**
Combustion activities (+)	**33 499**	**31 582**	**19 254**	**6 030**	**940**	**-4.8**	**-11**
Coal	14 660	14 110	5 915	1 299	195	-8.3	-13
Oil	11 505	10 264	7 426	3 329	928	-3.2	-7.7
Natural gas	7 259	7 138	5 960	1 929	566	-1.8	-8.1
Bioenergy and waste	75	71	- 48	- 528	- 748	n.a.	n.a.
Industry removals (-)	**1**	**1**	**214**	**914**	**1 186**	**75**	**28**
Biofuels production	1	1	142	385	553	68	24
Direct air capture	-	-	71	528	633	n.a.	n.a.
Electricity and heat sectors	**13 821**	**13 504**	**5 816**	**- 81**	**- 369**	**-8.1**	**n.a.**
Coal	10 035	9 786	2 950	102	69	-11	-15
Oil	655	628	173	6	6	-12	-14
Natural gas	3 131	3 089	2 781	268	128	-1.0	-10
Bioenergy and waste	-	-	- 87	- 457	- 572	n.a.	n.a.
Other energy sector*	**1 457**	**1 472**	**679**	**- 85**	**- 368**	**-7.4**	**n.a.**
Final consumption*	**20 647**	**18 928**	**14 723**	**7 011**	**1 370**	**-2.5**	**-8.4**
Coal	4 486	4 171	2 935	1 186	117	-3.5	-11
Oil	10 272	9 077	6 973	3 242	880	-2.6	-7.5
Natural gas	3 451	3 332	2 668	1 453	303	-2.2	-7.7
Bioenergy and waste	75	71	40	- 70	- 176	-5.6	n.a.
Industry*	8 903	8 478	6 892	3 485	519	-2.0	-8.9
Iron and steel	2 507	2 349	1 778	859	220	-2.7	-7.6
Chemicals	1 344	1 296	1 199	654	66	-0.8	-9.5
Cement	2 461	2 334	1 899	906	133	-2.0	-9.1
Transport	8 290	7 153	5 719	2 686	689	-2.2	-7.5
Road	6 116	5 483	4 077	1 793	340	-2.9	-8.9
Passenger cars	3 121	2 746	1 626	547	85	-5.1	-11
Trucks	1 835	1 721	1 614	890	198	-0.6	-6.9
Aviation	1 019	621	783	469	210	2.4	-3.5
Shipping	883	800	705	348	122	-1.3	-6.1
Buildings	3 007	2 860	1 809	685	122	-4.5	-10
Residential	2 030	1 968	1 377	541	108	-3.5	-9.2
Services	977	892	432	144	14	-7.0	-13
Total CO_2 removals	**1**	**1**	**317**	**1 457**	**1 936**	**79**	**29**
Total CO_2 captured	**40**	**40**	**1 665**	**5 619**	**7 602**	**45**	**19**

**Includes industrial process emissions.*

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Table A.5: Economic and Activity Indicators

	Indicator					CAAGR (%)	
	2019	2020	2030	2040	2050	2020-2030	2020-2050
Population (million)	7 672	7 753	8 505	9 155	9 692	0.9	0.7
GDP (USD 2019 billion, PPP)	134 710	128 276	184 037	246 960	316 411	3.7	3.1
GDP per capita (USD 2019, PPP)	17 558	16 545	21 638	26 975	32 648	2.7	2.3
TES/GDP (GJ per USD 1 000, PPP)	4.543	4.578	2.973	2.164	1.716	-4.2	-3.2
TFC/GDP (GJ per USD 1 000, PPP)	3.231	3.208	2.139	1.468	1.086	-4.0	-3.5
TES per capita (GJ)	79.77	75.74	64.33	58.38	56.03	-1.6	-1.0
CO_2 intensity of electricity generation (kg CO_2 per kWh)	0.468	0.438	0.138	-0.001	-0.005	-11	n.a.

	Activity					CAAGR (%)	
	2019	2020	2030	2040	2050	2020-2030	2020-2050
Industrial production							
Primary chemicals (Mt)	538	529	641	686	688	1.9	0.9
Steel (Mt)	1 869	1 781	1 937	1 958	1 987	0.8	0.4
Cement (Mt)	4 215	4 054	4 258	4 129	4 032	0.5	-0.0
Transport							
Passenger cars (billion pkm)	15 300	14 261	15 775	19 159	24 517	1.0	1.8
Trucks (billion tkm)	26 646	25 761	38 072	49 756	59 990	4.0	2.9
Aviation (billion pkm)	8 506	5 474	10 271	11 573	14 566	6.5	3.3
Shipping (billion tkm)	107 225	109 153	155 621	209 905	291 032	3.6	3.3
Buildings							
Services floor area (million m^2)	49 670	49 825	58 867	68 576	78 157	1.7	1.5
Residential floor area (million m^2)	190 062	192 558	235 745	290 696	345 183	2.0	2.0
Million households	2 095	2 116	2 435	2 765	3 051	1.4	1.2

Technology costs

Electricity generation

Table B.1 ▷ Electricity generation technology costs by selected region in the NZE

	Financing rate (%)	Capital costs ($/kW)			Capacity factor (%)			Fuel, CO_2 and O&M ($/MWh)			LCOE ($/MWh)		
	All	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
United States													
Nuclear	8.0	5 000	4 800	4 500	90	80	75	30	30	30	105	110	110
Coal	8.0	2 100	2 100	2 100	20	*n.a.*	*n.a.*	90	170	235	220	*n.a.*	*n.a.*
Gas CCGT	8.0	1 000	1 000	1 000	55	25	*n.a.*	50	80	105	70	125	*n.a.*
Solar PV	3.7	1 140	620	420	21	22	23	10	10	10	50	30	20
Wind onshore	3.7	1 540	1 420	1 320	42	43	44	10	10	10	35	35	30
Wind offshore	4.5	4 040	2 080	1 480	42	46	48	35	20	15	115	60	40
European Union													
Nuclear	8.0	6 600	5 100	4 500	75	75	70	35	35	35	150	120	115
Coal	8.0	2 000	2 000	2 000	20	*n.a.*	*n.a.*	120	205	275	250	*n.a.*	*n.a.*
Gas CCGT	8.0	1 000	1 000	1 000	40	20	*n.a.*	65	95	120	100	150	*n.a.*
Solar PV	3.2	790	460	340	13	14	14	10	10	10	55	35	25
Wind onshore	3.2	1 540	1 420	1 300	29	30	31	15	15	15	55	45	40
Wind offshore	4.0	3 600	2 020	1 420	51	56	59	15	10	5	75	40	25
China													
Nuclear	7.0	2 800	2 800	2 500	80	80	80	25	25	25	65	65	60
Coal	7.0	800	800	800	60	*n.a.*	*n.a.*	75	135	195	90	*n.a.*	*n.a.*
Gas CCGT	7.0	560	560	560	45	35	*n.a.*	75	100	120	90	115	*n.a.*
Solar PV	3.5	750	400	280	17	18	19	10	5	5	40	25	15
Wind onshore	3.5	1 220	1 120	1 040	26	27	27	15	10	10	45	40	40
Wind offshore	4.3	2 840	1 560	1 000	34	41	43	25	15	10	95	45	30
India													
Nuclear	7.0	2 800	2 800	2 800	70	70	70	30	30	30	75	75	75
Coal	7.0	1 200	1 200	1 200	50	*n.a.*	*n.a.*	35	50	75	65	*n.a.*	*n.a.*
Gas CCGT	7.0	700	700	700	55	50	*n.a.*	45	45	50	55	60	*n.a.*
Solar PV	5.8	580	310	220	20	21	21	5	5	5	35	20	15
Wind onshore	5.8	1 040	980	940	26	28	29	10	10	10	50	45	40
Wind offshore	6.6	2 980	1 680	1 180	32	37	38	25	15	10	130	70	45

Notes: O&M = operation and maintenance; LCOE = levelised cost of electricity; kW = kilowatt; MWh = megawatt-hour; CCGT = combined-cycle gas turbine; n.a. = not applicable. Cost components and LCOE figures are rounded.

Sources: IEA analysis; IRENA Renewable Costing Alliance; IRENA (2020).

- Major contributors to the LCOE include: overnight capital costs; capacity factor that describes the average output over the year relative to the maximum rated capacity (typical values provided); the cost of fuel inputs; plus operation and maintenance. Economic lifetime assumptions are 25 years for solar PV, onshore and offshore wind.
- Weighted average costs of capital (WACC) reflect analysis for utility-scale solar PV in the *World Energy Outlook 2020* (IEA, 2020) and for offshore wind from the *Offshore Wind Outlook 2019* (IEA, 2019). Onshore wind was assumed to have the same WACC as utility-scale solar PV. A standard WACC was assumed for nuclear power, coal- and gas-fired power plants (7-8% based on the stage of economic development).
- Fuel, CO_2 and O&M costs reflect the average over the ten years following the indicated date in the projections.
- The capital costs for nuclear power represent the "nth-of-a-kind" costs for new reactor designs, with substantial cost reductions from the first-of-a-kind projects.

Batteries and hydrogen

Table B.2 ▷ Capital costs for batteries and hydrogen production technologies in the NZE

	2020	2030	2050
Battery packs for transport applications (USD/kWh)	130 - 155	75 - 90	55 - 80
Low-temperature electrolysers (USD/kW_e)	835 - 1 300	255 - 515	200 - 390
Natural gas with CCUS (USD/kW H_2)	1 155 - 2 010	990 - 1 725	935 - 1 625

Notes: kWh = kilowatt-hour; kW_e = kilowatt electric; CCUS = carbon capture, utilisation and storage; H_2 = hydrogen. Capital costs for electrolysers and hydrogen production from natural gas with CCUS are overnight costs.

Source: IEA analysis.

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)
	tCO_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
	kg CO_2/kWh	kilogrammes of carbon dioxide per kilowatt-hour
Energy	EJ	exajoule
	PJ	petajoule
	TJ	terajoule
	GJ	gigajoule
	MJ	megajoule
	boe	barrel of oil equivalent
	toe	tonne of oil equivalent
	ktoe	thousand tonnes of oil equivalent
	Mtoe	million tonnes of oil equivalent
	MBtu	million British thermal units
	kWh	kilowatt-hour
	MWh	megawatt-hour
	GWh	gigawatt-hour
	TWh	terawatt-hour
Gas	bcm	billion cubic metres
	tcm	trillion cubic metres
Mass	kg	kilogramme (1 000 kg = 1 tonne)
	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/tCO_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	GWh
Convert from:	EJ	1	238.8 x 10^6	23.88	9.47.8 x 10^3	2.778 x 10^5
	Gcal	4.1868 x 10^{-9}	1	10^{-7}	3.968	1.163 x 10^{-3}
	Mtoe	4.1868 x 10^{-2}	10^7	1	3.968 x 10^7	11 630
	MBtu	1.0551 x 10^{-9}	0.252	2.52 x 10^{-8}	1	2.931 x 10^{-4}
	GWh	3.6 x 10^{-6}	860	8.6 x 10^{-5}	3 412	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.

Currency conversions

Exchange rates *(2019 annual average)*	1 US dollar (USD) equals:
British Pound	0.78
Chinese Yuan Renminbi	6.91
Euro	0.89
Indian Rupee	70.42
Indonesian Rupiah	14 147.67
Japanese Yen	109.01
Russian Ruble	64.74
South African Rand	14.45

Source: OECD National Accounts Statistics: purchasing power parities and exchange rates dataset, July 2020.

Definitions

Advanced bioenergy: Sustainable fuels produced from non-food crop feedstocks, which are capable of delivering significant lifecycle 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% lifecycle greenhouse gas reduction and which, 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 directly as a fuel in direct combustion process, and in fuel cells or as a hydrogen carrier. To be a low-carbon fuel, ammonia must be produced from low-carbon hydrogen, the nitrogen separated via the Haber process, and electricity needs are met by low-carbon electricity.

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 also 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 back-up electricity generation capacity that, in the event of disruption, can provide electricity. Back-up generators are typically fuelled with diesel or gasoline and 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.

Biodiesel: Diesel-equivalent, processed 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 biomass, liquid biofuels and biogases.

Biogas: A mixture of methane, carbon dioxide and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen-free environment.

Biogases: Include biogas and biomethane.

Biomethane: Biomethane is a near-pure source of methane produced either by upgrading biogas (a process that removes any CO_2 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.

Buildings: The buildings sector includes energy used in residential, commercial and institutional buildings and non-specified other. Building energy use includes space heating and cooling, water heating, lighting, appliances and cooking equipment.

Bunkers: Includes both international marine bunkers and international aviation bunkers.

Capacity credit: Proportion of the capacity that can be reliably expected to generate electricity during times of peak demand in the grid to which it is connected.

Carbon capture, utilisation and storage (CCUS)**:** The process of capturing CO_2 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 to create products.

Clean energy: Includes renewables, energy efficiency, low-carbon fuels, nuclear power, battery storage and carbon capture, utilisation and storage.

Clean cooking facilities: Cooking facilities that are considered safer, more efficient and more environmentally sustainable than the traditional facilities that make use of solid biomass (such as a three-stone fire). This refers primarily to improved solid biomass cookstoves, biogas systems, liquefied petroleum gas stoves, ethanol and solar stoves.

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.

Concentrating solar power (CSP)**:** Solar thermal power/electric generation systems that collect and concentrate sunlight to produce high temperature heat to generate electricity.

Conventional liquid biofuels: Fuels produced from food crop feedstocks. These liquid biofuels are commonly referred to as first generation and include sugar cane ethanol, starch-based ethanol, fatty acid methyl esther (FAME) and straight vegetable oil (SVO).

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. This report 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.

Demand-side response (DSR)**:** Describes actions which can influence the load profile such as shifting the load curve in time without affecting the total electricity demand, or load shedding such as interrupting demand for short duration or adjusting the intensity of demand for a certain amount of time.

Dispatchable generation: Refers to technologies whose power output can be readily controlled - increased to maximum rated capacity or decreased to zero - in order to match supply with demand.

Electricity demand: Defined as total gross electricity generation less own use generation, plus net trade (imports less exports), less transmissions and distribution losses.