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Exxon Mobil Corporation

(Name of Registrant as Specified in Its Charter)

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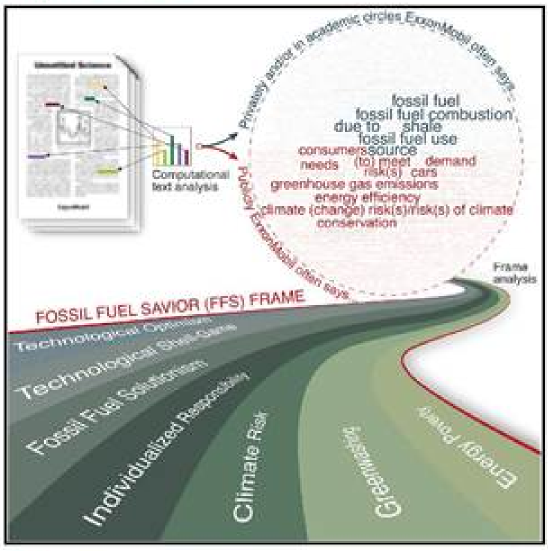
Exhibit 1

One Earth

Article

Rhetoric and frame analysis of ExxonMobil's climate change communications

Graphical abstract



Highlights

- ExxonMobil's public climate change messaging mimics tobacco industry propaganda
- Rhetoric of climate "risk" downplays the reality and seriousness of climate change
- Rhetoric of consumer "demand" (versus fossil fuel supply) individualizes responsibility
- Fossil Fuel Savior frame uses "risk" and "demand" to justify fossil fuels, blame customers

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In brief

This is the first computational assessment of how ExxonMobil has used language to subtly yet systematically frame public discourse about climate change. We show that ExxonMobil uses rhetoric mimicking the tobacco industry to downplay the reality and seriousness of climate change, to present fossil fuel dominance as reasonable and inevitable, and to shift responsibility for climate change away from itself and onto consumers. Our work is relevant to lawsuits, policy proposals, and grassroots activism seeking to hold fossil fuel companies accountable for deceptive marketing.

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Article

Rhetoric and frame analysis of ExxonMobil's climate change communications

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SCIENCE FOR SOCIETY A dominant public narrative about climate change is that "we are all to blame." Another is that society must inevitably rely on fossil fuels for the foreseeable future. How did these become conventional wisdom? We show that one source of these arguments is fossil fuel industry propaganda. ExxonMobil advertisements worked to shift responsibility for global warming away from the fossil fuel industry and onto consumers. They also said that climate change was a "risk," rather than a reality, that renewable energy is unreliable, and that the fossil fuel industry offered meaningful leadership on climate change. We show that much of this rhetoric is similar to that used by the tobacco industry. Our research suggests warning signs that the fossil fuel industry is using the subtle micro-politics of language to downplay its role in the climate crisis and to continue to undermine climate litigation, regulation, and activism.

SUMMARY

This paper investigates how ExxonMobil uses rhetoric and framing to shape public discourse on climate change. We present an algorithmic corpus comparison and machine-learning topic model of 180 ExxonMobil climate change communications, including peer-reviewed publications, internal company documents, and advertorials in *The New York Times*. We also investigate advertorials using inductive frame analysis. We find that the company has publicly overemphasized some terms and topics while avoiding others. Most notably, they have used rhetoric of climate "risk" and consumer energy "demand" to construct a "Fossil Fuel Savior" (FFS) frame that downplays the reality and seriousness of climate change, normalizes fossil fuel lock-in, and individualizes responsibility. These patterns mimic the tobacco industry's documented strategy of shifting responsibility away from corporations—which knowingly sold a deadly product while denying its harms—and onto consumers. This historical parallel foreshadows the fossil fuel industry's use of demand-as-blame arguments to oppose litigation, regulation, and activism.

INTRODUCTION

In previous work, we have shown that Exxon, Mobil, and ExxonMobil Corp misled the public about anthropogenic global warming (AGW) by contributing to climate science through academic and internal research, while promoting doubt about it in advertorials and other propaganda.[1–3] (We refer to Exxon Corporation as Exxon, Mobil Oil Corporation as Mobil, ExxonMobil Corporation as ExxonMobil Corp, and generically refer to all three as ExxonMobil.) We have also observed that, starting in the mid-2000s, ExxonMobil's statements of explicit doubt about climate science and its implications (for example, that "there does not appear to be a consensus among scientists about the effect of fossil fuel use on climate"[4]) gave way to implicit acknowledgments couched in ambiguous statements about climate "risk" (such as discussion of lower-carbon fuels for "addressing the risks posed by rising greenhouse gas emissions,"[5] without mention of AGW). This invites research as to how, beyond outright disinformation, ExxonMobil may have employed rhetoric and framing to construct misleading public narratives about AGW. Here, we take up this question.

"Framing" is a term of art in communications science that refers to how an issue is portrayed and understood.[6–9] Frames construct meaning by selecting "some aspects of a perceived reality" and making them "more salient in a communicating text, in such a way as to promote a particular problem definition, causal interpretation, moral evaluation, and/or treatment recommendation."[10] (Here and throughout, we strictly refer to "emphasis frames" rather than "equivalency frames.")[11] Analyzing which frames are present and absent in public discourse helps to reveal how actors have tried to shape policy debates by setting agendas and legitimating certain participants

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and responses, while discouraging or precluding others.[12–15] Framing of responsibility, for example, can determine whether society calls upon individuals, industry, or government to take action.[16]

One of the fossil fuel industry's primary AGW frames has been scientific uncertainty.[17] Researchers have documented in detail industry's over-emphasis of uncertainty to deny climate science and delay action.[1,2,17–25] Subtler forms of rhetoric and framing, which dominate today's AGW discourse, are only just beginning to receive similar attention.[7,26–29] Fossil fuel interests have spent billions of dollars on AGW public affairs, yet their role in perpetuating these narratives is underexplored.[30,31]

In this paper, we analyze how ExxonMobil has publicly constructed AGW frames by selectively emphasizing some terms and topics while avoiding others. Our analysis compares the terms and topics between ExxonMobil's different AGW communications, including peer-reviewed publications, internal documents, and paid, editorial-style advertisements—known as advertorials—published on the Op-Ed page of *The New York Times* (NYT). We also identify frames in the latter. These well-defined, longitudinal corpora are conducive to a rigorous case study of fossil fuel industry messaging on AGW.

Our study offers the first computational assessment of how ExxonMobil has used language to frame public discourse about AGW. By bringing to bear the mixed-methods of computational linguistics and inductive frame analysis, our results add to (1) analyses of ExxonMobil's public affairs practices,[32–44] (2) qualitative accounts of the company's AGW communications,[23,45–49] and (3) the application of discourse and (algorithmic) content analysis to AGW communications by ExxonMobil and the wider climate countermovement.[1,2,17–19,26,27,29,50–57] A "distant"—that is, quantitative, statistical, and macroscopic—reading of ExxonMobil's AGW communications offers three practical advantages.[58] First, it complements the qualitative and/or manual methodologies previously applied to the AGW communications of ExxonMobil and other fossil fuel interests, and corroborates our prior work, which used manual coding to demonstrate systematic discrepancies between ExxonMobil's private and public AGW communications.[1,2] Second, automated methods of textual analysis allow detection of broad, sometimes subtle, patterns of language that would otherwise be unattainable. Third, by using existing corpora to establish the application of computational techniques to the analysis of AGW discourse, we help demonstrate the efficacy of these approaches, which researchers will be able to use to analyze the large numbers of documents that lawsuits against fossil fuel companies are anticipated to generate.

Our analysis is the first computational study illustrating how the fossil fuel industry has encouraged and embodied AGW narratives fixated on individual responsibility. Our findings corroborate the insights of qualitative discourse analyses about the role of fossil fuel interests, and add to what Kent[59] has called an "under-theorised" understanding "of why contemporary interest focuses on individual responsibility for climate change."[26,51] In so doing, this work helps to decrypt the fossil fuel industry's playbook of climate delay framings, illuminating how sense-making schema conveyed by subtle yet systematic deployments of language may have "penetrated public discourse to become naturalized as common sense or unfortunate realities."[13,28] Although misleading frames that deceive the public may be defended on First Amendment grounds, the history of tobacco litigation shows that a misleading framework may also be held in some circumstances to be part of a pattern of fraudulent activities. Our work may, therefore, be relevant to ongoing lawsuits against ExxonMobil alleging "deceptive marketing" and "greenwashing," as well as to calls for policymakers to ban fossil fuel industry advertisements or require that they come with tobacco-style warning labels.[60–65] Our research also adds to an expanding scholarly and journalistic AGW literature—spanning emissions accounting and extreme weather attribution;[66,67] supply-side policy analysis;[68–70] decarbonization theory;[71,72] the history of climate denial, lobbying, and propaganda by fossil fuel interests;[73–83] ethical philosophy;[84,85] and climate litigation[86,87]—challenging the zeitgeist of individualized responsibility. Finally, this study contributes to broader literatures on discourse and content analysis;[88–91] corporate issue management and advocacy marketing;[54,92–96] and the cross-pollination of corporate strategies of public affairs, litigation, and deceit.[13,86,97–100]

We adopt a mixed-method, computational approach to rhetorical frame analysis of 180 ExxonMobil documents previously compiled for manual content analysis[1,2]: 32 internal company documents (1977–2002; from ExxonMobil Corp,[101] *InsideClimate News*,[102] and Climate Investigations Center),[103] 72 peer-reviewed publications (1982–2014; from ExxonMobil Corp),[104] and 76 advertorials in the NYT expressing any positions on AGW (real and human caused, serious, or solvable) (1972–2009; from PolluterWatch and ProQuest).[105,106] To our knowledge, these constitute all publicly available internal and peer-reviewed ExxonMobil documents concerning AGW, including those made available by the company. They also include all discovered ExxonMobil advertorials in the NYT taking any positions on AGW. These corpora thus offer bound sets reflecting ExxonMobil's internal, academic, and public AGW communications, respectively.

Following text pre-processing and vectorization into document-term matrices, we first use frequency score (FS) and Dunning Log likelihood (LL) ratio corpus comparison algorithms to identify statistically distinctive keywords ("divergent terms") that help locate rhetorical frames.[107–110] The FS indicates how often a given term appears in corpus A versus corpus B (accounting for corpus sizes), and ranges from 0 (only in corpus A) to 1 (only in corpus B). The LL ratio (G^2) indicates the statistical significance of the relative frequencies of a given term between corpora A and B, and ranges from large and negative (term is disproportionately common in corpus A) to large and positive (disproportionately common in corpus B). Second, we complement this approach with latent Dirichlet allocation (LDA) topic modeling to identify statistically distinctive, thematically connected texts and vocabularies ("divergent topics"), which are commonly equated to either frames or frame elements.[111–115] Third, we integrate these quantitative tools into an inductive, qualitative approach to constructing frames as "frame packages" in advertorials.[17,116–118] In the discussion, we examine the congruence of our findings with the tobacco industry's rhetorical strategies in public relations and litigation.[13,100,119,120]

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Table 1. Rhetorical tropes and taboos: Highly divergent terms in (left) ExxonMobil Corp advertorials versus (right) Mobil advertorials, by LL ratio (G^2) and FS

ExxonMobil Corp advertorials often say:					Mobil advertorials often say:				
	ExxonMobil Corp	Mobil	G^2	FS		ExxonMobil Corp	Mobil	G^2	FS
"energy"	278	89	110.51	0.76	"nations"	4	79	−74.90	0.05
challenge(s)	52	4	54.33	0.94	plan	0	21	−26.84	0.00
(to) meet	51	14	26.70	0.80	senate	0	16	−20.45	0.00
demand	32	8	18.22	0.82	treaty	0	14	−17.89	0.00
use	60	27	16.78	0.71	in kyoto	0	13	−16.61	0.00
needs	27	9	11.53	0.77	the us [United States]	18	51	−12.99	0.28
"risk(s)"	46	3	50.30	0.94	"co2/carbon dioxide"	33	106	−31.90	0.26
climate (change) risk(s)/ risk(s) of climate	26	0	39.02	1.00	emission(s)	97	197	−24.48	0.35
					greenhouse gases	8	39	−18.96	0.19
longterm	37	3	38.05	0.93	effect	1	18	−16.67	0.06
"research"	75	21	38.53	0.80	global warming	2	21	−16.25	0.10
gcep [Global Climate and Energy Project]	17	0	25.51	1.00	evs [electric vehicles]	0	12	−15.34	0.00
technologies	55	18	24.00	0.77					
solar	24	3	21.02	0.90					
stanford	14	0	21.01	1.00					
policies	27	5	19.17	0.86					
wind	18	3	13.62	0.87					

Terms that appear to be thematically related have been grouped (asterisked, high-scoring terms identify each group). ExxonMobil Corp advertorials often say terms ("tropes") with large positive G^2 scores and rarely say terms ("taboos") with FS scores near 0. Mobil advertorials often say terms with large negative G^2 scores and rarely say terms with FS scores near 1. p values < 0.001 for all G^2 and FS scores.

RESULTS

In the section entitled "divergent terms and topics," we compare divergent terms and topics between pairs of document categories. In "rhetorical frames," we summarize the findings of frame package analysis of advertorials: three dominant frames communicated by 11 constituent discourses. Other sections then focus on two of these complementary discourses, "discourse of climate risk" and "discourse of individualized responsibility," and analyze how they work alongside other discourses to construct one specific frame, Fossil Fuel Savior (FFS) ("FFS frame").

Divergent terms and topics

Table 1 presents a selection of highly divergent terms in ExxonMobil Corp advertorials versus Mobil advertorials, as identified by LL and FS. Likewise, Tables 2 and 3 compare highly divergent terms between all advertorials (Mobil plus ExxonMobil Corp) and, respectively, Exxon internal documents (Table 2) and Exxon/ExxonMobil Corp peer-reviewed publications (Table 3). In all three tables, the highest $|G^2|$-scoring terms, marked with asterisks, are suggestive of distinctive themes around which we group other relevant terms. These themes closely resemble the divergent topics shown in Table 4, which emerge from LL analysis of our LDA topic model solutions in all advertorials (top half of Table 4) and in combined internal and peer-reviewed documents (bottom half). The top 20 words associated with each topic are listed, together with assigned topic labels.

Mobil versus ExxonMobil Corp advertorials

We have previously shown that both Mobil and ExxonMobil Corp advertorials often promoted doubt about climate science.[1,2] Terms conveying explicit doubt are therefore common to both corpora, and so do not appear in Table 1 (for examples, see S2.1, supplemental information). This undercuts ExxonMobil Corp's suggestion that only Mobil, not ExxonMobil Corp, promoted doubt.[2,3] Both did. Moreover, when Exxon and Mobil merged in 1999, ExxonMobil Corp inherited legal and moral responsibility for both parent companies.

Comparison of advertorials over time can nevertheless be insightful in revealing other rhetorical trends. In this regard, Mobil and ExxonMobil Corp advertorial corpora serve as well-defined longitudinal proxies.

Table 1 shows, for example, that earlier, Mobil advertorials disproportionately contested climate science head-on, discussing emission(s) of CO_2/carbon dioxide and the global warming effect (terms exhibiting statistically significant divergence are underlined throughout). Mobil advertorials also notably engaged in climate policy debates concerning the role of the US (and Senate) compared with other nations as part of the Kyoto treaty plan. By contrast, ExxonMobil Corp advertorials no longer referred to "global warming": the term became taboo (FS = 0.10). Relative usage of "climate change" versus "global warming" went from 3-to-1 pre-merger to 34-to-1 post merger. Indeed, ExxonMobil Corp mostly sidestepped detailed discussions about climate science, acknowledging only the long-term risks of climate change before reframing it as a challenge to meet the public's energy demand and needs. ExxonMobil

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Table 2. Rhetorical tropes and taboos: Highly divergent terms in (left) advertorials versus (right) internal documents, by LL ratio (G^2) and FS

Advertorials often say:					Internal documents often say:				
	Advertorials	Internal	G^2	FS		Advertorials	Internal	G^2	FS
"emission(s)"	294	97	293.80	0.86	"co2/carbon dioxide"	138	1,053	−291.63	0.21
risk(s)	49	7	72.48	0.93	atmosher(e/ic)	36	458	−187.01	0.14
greenhouse gas emissions	42	7	58.90	0.92	fossil fuel	9	144	−66.26	0.11
climate (change) risk(s)/risk(s) of climate	26	0	57.89	1.00	ppm	0	78	−62.12	0.00
climate change	124	103	45.39	0.71	co2 concentration	1	61	−40.57	0.03
dont [don't]	24	2	40.93	0.96	fossil fuel combustion	1	48	−30.69	0.04
know	32	8	37.59	0.89	co2 increase	0	28	−22.30	0.00
longterm	40	17	33.14	0.83	source	6	39	−9.08	0.24
doom(sday/sdayers)/apocalypse/hype/scare	11	0	24.49	1.00	"effect(s)"	27	359	−150.31	0.13
debate	26	12	20.05	0.82	temperature	15	270	−130.89	0.10
(un)know(/n/ing/ledge)	57	66	9.63	0.64	doubling	2	83	−51.60	0.05
"energy"	378	222	227.73	0.78	greenhouse effect	10	119	−46.69	0.15
(to) meet	65	2	128.34	0.99	ocean	15	135	−43.38	0.19
challenge(s)	56	5	94.08	0.96	due to	5	89	−42.94	0.10
energy efficiency	30	1	58.76	0.98	ph [pH]	0	44	−35.04	0.00
electricity	29	1	56.60	0.98	radiation	1	44	−27.68	0.04
consumers	21	0	46.76	1.00	co2 greenhouse	0	33	−26.28	0.00
oil and natural gas	18	0	40.08	1.00	sea	6	65	−23.99	0.16
energy use	23	4	31.75	0.92	global temperature	0	30	−23.89	0.00
demand	40	21	27.24	0.80	2050	0	30	−23.89	0.00
needs	36	22	20.69	0.77	temperature increase	3	50	−23.44	0.11
for generations/foreseeable future/several	12	3	14.10	0.89	polar	1	28	−15.83	0.07
decades/decades to come/next 25 years					"program"	12	195	−90.37	0.11
"countries/nations"	157	17	251.77	0.95	natuna	0	67	−53.36	0.00
developing/poorer countries/world/nations	53	3	97.01	0.97	doe [Department of Energy]	0	38	−30.26	0.00
kyoto	59	7	92.31	0.95	tanker	1	35	−20.96	0.06
targets	26	4	37.52	0.93	"model(s)"	30	309	−110.12	0.17
"econom(y/ic)"	148	22	216.08	0.93	figure	0	112	−89.19	0.00
economic growth/impact	29	2	51.34	0.97	rate	2	122	−81.13	0.03
prosperity	15	0	33.40	1.00	data	10	98	−33.68	0.17
jobs	13	0	28.95	1.00	vugraph	0	41	−32.65	0.00
prices	12	0	26.72	1.00	scenario	1	42	−26.17	0.05
cost	33	17	22.92	0.80					
tax	15	2	22.68	0.94					
living standard(s)/standard(s) of living/quality of life	10	0	22.27	1.00					
"steps"	36	1	71.76	0.99					
reduce emissions	23	0	51.21	1.00					
voluntary	18	0	40.08	1.00					
wise(r)/prudent/reasonable/responsible/sound(er)	39	21	25.87	0.79					
"technolog(y/ies)"	198	40	257.20	0.91					
vehicles	33	0	73.48	1.00					

(Continued on next page)

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Table 2. *Continued*

Advertorials often say:					Internal documents often say:				
	Advertorials	Internal	G^2	FS		Advertorials	Internal	G^2	FS
natural gas	48	18	43.87	0.85					
trees	24	2	40.93	0.96					
invest(ing/ment(s))	27	4	39.46	0.93					
gcep [Global Climate and Energy Project]	17	0	37.85	1.00					
evs [electric vehicles]	16	0	35.63	1.00					
gasoline	20	2	32.72	0.95					
innovat(e/ion(s))	17	1	30.93	0.97					
solutions	26	7	29.36	0.88					
renewables	13	0	28.95	1.00					
wind	21	5	25.29	0.90					

Terms that appear to be thematically related have been grouped (asterisked, high-scoring terms identify each group). Advertorials often say terms ("tropes") with large positive G^2 scores and rarely say terms ("taboos") with FS scores near 0. Internal documents often say terms with large negative G^2 scores and rarely say terms with FS scores near 1. p values < 0.001 for all G^2 and FS scores.

Corp advertorials emphasized the need for more climate and energy technologies research, such as the company's sponsorship of the GCEP (Global Climate and Energy Project) at Stanford University. Current solar and wind technologies were presented as inadequate.

Advertorials versus internal documents

Comparing divergent terms in all advertorials against those in internal documents, a combination of the above advertorial themes emerges (Tables 2 and 4). Numerous Mobil and ExxonMobil Corp advertorials promoted explicit doubt about whether AGW is real and human caused. They emphasized debate and focused on what scientists "do and don't know" [*Climate science uncertainty*] (topic labels from Table 4 are indicated in bracketed italics throughout). This eventually gave way to rhetoric about potential long-term risks of AGW (after several years of overlap in ~2000–2005 and 2007), juxtaposed against the challenge to meet demand [*Energy/emissions challenge*]. The energy use and needs of consumers, such as electricity and oil and natural gas, are presented as necessitating greater energy efficiency and new technologies [*Energy/emissions challenge*; *Vehicles*]. The public is told about how ExxonMobil Corp is partnering with GCEP at Stanford to develop solutions such as more efficient gasoline vehicles and "clean…natural gas" [*Vehicles*; *Energy technologies*]. ExxonMobil Corp touts its efforts to plant trees, but renewables such as wind and electric vehicles/EVs are given short thrift [*Conservation*; *Energy technologies*]. Algorithmic analysis also documents Mobil's public rhetoric on the Kyoto Protocol: targets that exempt developing countries threaten American jobs, prosperity, and economic growth; instead, governments and industry should pursue market-based, voluntary steps to reduce emissions [*Climate policy*].

Compared with Mobil advertorials, which promoted debate about climate science, and ExxonMobil Corp advertorials, which did the same or ignored it, Exxon's internal conversations focused on it. Internal documents are notable for their detailed articulation of the causes and consequences of AGW. The source of the observed CO_2 increase in the atmosphere was fossil fuel combustion [*AGW science/projections*]. Effects of the resulting greenhouse effect would include a global temperature increase. Internal discussions adopted a rigor absent from the company's public communications, including reference to climate models, scenarios, and rates of change [*Climate modeling*]. One scenario they examined—the doubling of atmospheric CO_2 concentration by 2050—threatened melting of the polar icecaps, a decrease in ocean pH, and rising sea levels [*AGW science/projections*]. ExxonMobil advertorials disputed or remained silent about not just this early knowledge of climate science and its implications but also Exxon's "CO_2 program" that helped acquire and apply that knowledge [*AGW science/projections*]. Internal memos report that this program included measuring CO_2 with a tanker, monitoring DOE (US Department of Energy) climate science, and evaluating the CO_2 emissions from their natural gas project in Natuna, Indonesia [*Climate research programs*].

Advertorials versus peer-reviewed publications

Table 3 compares divergent terms in all advertorials against those in peer-reviewed publications. Advertorials are distinguished by the same rhetorical themes as in "advertorials versus internal documents"; indeed, the contrast against academic articles is more pronounced. Independently and collectively, Mobil and ExxonMobil Corp advertorials offset the risks of manmade climate change by also promoting debate about complex science [*Climate science uncertainty*]. Advertorials are again seen to frame AGW as a challenge to meet the needs of consumers for more energy from fossil fuels, while seeking to allay concerns by publicizing the promise of advanced technology innovation (including cogeneration) [*Energy/emissions challenge*; *Energy technologies*]. In comparison with peer-reviewed papers, advertorials stand out for their emphasis of corporate environmental programs to reduce emissions through energy efficiency and conservation [*Conservation*].

While advertorials talk about the scientific process—research, science, and the extent of scientists' knowledge are disproportionately discussed—peer-reviewed publications actually engage in it. As expected, academic articles—even more so than internal documents—are distinguished by their articulation of AGW science. Observed atmospheric CO_2 concentrations are

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Table 3. Rhetorical tropes and taboos: Highly divergent terms in (left) advertorials versus (right) peer-reviewed documents, by LL ratio (G^2) and FS

Advertorials often say:					Peer-reviewed documents often say:				
	Advertorials	Peer reviewed	G^2	FS		Advertorials	Peer reviewed	G^2	FS
"energy"	378	1,777	500.41	0.82	et al	0	4,001	−372.50	0.00
(to) meet	65	98	191.64	0.93	model	5	3,000	−236.23	0.03
challenge(s)	56	100	151.75	0.92	figure	0	1,475	−137.32	0.00
needs	36	71	92.45	0.91	table	1	909	−75.18	0.02
more energy	21	12	87.65	0.97	rate	2	823	−60.90	0.05
consumers	21	33	60.70	0.93	estimates	5	978	−59.17	0.10
energy use	23	83	39.00	0.85	observed	1	715	−57.00	0.03
energy efficiency	30	152	36.65	0.81	scenario	1	562	−43.84	0.04
for generations/foreseeable future/several	12	28	27.91	0.90	noise	0	311	−28.95	0.00
decades/decades to come/next 25 years					projections	0	273	−25.42	0.00
fossil fuels	24	149	22.89	0.77	ipcc [Intergovernmental Panel on Climate Change]	4	505	−25.00	0.14
gasoline	20	117	20.61	0.78	error	1	317	−22.17	0.06
demand	40	422	14.35	0.67	"co2"	69	5,161	−172.61	0.22
"research"	96	209	232.87	0.91	ocean	15	2,412	−134.77	0.12
science	61	74	198.02	0.95	transport	0	825	−76.81	0.00
scientists	39	25	157.74	0.97	carbon cycle	0	462	−43.01	0.00
dont [don't]	24	0	148.34	1.00	ghg [greenhouse gas]	0	446	−41.52	0.00
greenhouse gas emissions	42	60	126.97	0.94	ppm	0	397	−36.96	0.00
carbon dioxide	69	227	126.15	0.86	atmospheric co2	1	480	−36.52	0.04
know	32	25	121.96	0.96	ch4	0	272	−25.32	0.00
climate (change) risk(s)/risk(s) of climate	26	10	119.09	0.98	gt [gigaton]	0	243	−22.62	0.00
debate	26	30	86.15	0.95	"temperature"	15	1,836	−89.31	0.15
manmade	15	2	80.58	0.99	anthropogenic	0	609	−56.70	0.00
climate change	124	1,122	63.41	0.70	effect(s)	27	1,727	−48.70	0.25
(un)know(/n/ing/ledge)	57	330	59.52	0.78	due to	5	731	−39.08	0.13
risk(s)	49	261	56.56	0.80	radiative forcing	0	338	−31.47	0.00
ong term	40	282	31.82	0.75	climate sensitivity	0	219	−20.39	0.00
gap(s)	11	39	18.93	0.86	temperature change	0	198	−18.43	0.00
better science/understanding	6	10	16.85	0.93	"mitigation"	4	880	−55.49	0.09
complex	14	120	7.97	0.71	injection	0	443	−41.24	0.00
"technolog(y/ies)"	198	1,016	238.49	0.80	ccs	0	374	−34.82	0.00
gcep [Global Climate and Energy Project]	17	1	97.44	1.00	dissolution	0	270	−25.14	0.00
promise	20	12	82.39	0.97	alkalinity	0	260	−24.21	0.00
evs [electric vehicles]	16	11	63.42	0.97	caco3	0	251	−23.37	0.00
trees	24	48	61.15	0.91	budget	0	180	−16.76	0.00
cars	24	59	54.00	0.90	cement	1	237	−15.31	0.08
solutions	26	78	51.00	0.87					
nuclear	26	82	49.12	0.87					
renewables	13	18	39.86	0.94					
wind	21	82	33.25	0.84					
cogeneration	12	26	29.19	0.91					
innovat(e/ion(s))	17	93	19.02	0.79					

(Continued on next page)

Table 3. Continued

Advertorials often say:					Peer-reviewed documents often say:				
	Advertorials	Peer reviewed	G^2	FS		Advertorials	Peer reviewed	G^2	FS
invest(ing/ment(s))	27	243	13.96	0.70					
steps	36	36	126.05	0.95					
programs	28	14	120.90	0.98					
reduce emissions	23	25	78.03	0.95					
wise(r)/prudent/reasonable/ responsible/sound(er)	39	119	75.54	0.87					
environmental	56	384	46.45	0.75					
conservation	15	66	21.23	0.83					
nations	83	110	259.48	0.94					
kyoto	59	182	113.35	0.87					
governments	36	62	99.41	0.92					
senate	16	0	98.89	1.00					
developing/poorer countries/ world/nations	53	196	88.01	0.85					
econom(y/ic)	148	714	190.67	0.81					
prosperity	15	1	85.32	1.00					
economic growth/impact	29	74	63.68	0.89					
living standard(s)/standard(s) of living/quality of life	10	0	61.81	1.00					
voluntary	18	32	48.89	0.92					
jobs	13	11	48.27	0.96					

Terms that appear to be thematically related have been grouped (asterisked, high-scoring terms identify each group). Advertorials often say terms ("tropes") with large positive G^2 scores and rarely say terms ("taboos") with FS scores near 0. Peer-reviewed documents often say terms with large negative G^2 scores and rarely say terms with FS scores near 1. p values < 0.001 for all G^2 and FS scores.

reported in ppm (parts per million), anthropogenic temperature change due to radiative forcing by GHG (greenhouse gases) such as CO_2 and CH_4 is acknowledged, and AGW model projections are run for different scenarios based on climate sensitivity [*AGW science/projections*]. The academic language of estimates and noise and references to the IPCC (Intergovernmental Panel on Climate Change) are commonplace [*Climate modeling*]. While advertorials offer unfocused representations of technologies such as renewables, nuclear, and EVs as variously promising, hypothetical, or insufficient, Exxon/ExxonMobil Corp supported peer-reviewed studies that squarely centered AGW mitigation around approaches consistent with continued reliance on fossil fuels: CCS (carbon capture and storage); and the injection of CO_2 into oceans through dissolution of minerals such as $CaCO_3$ to increase alkalinity [*CO_2 disposal/storage*; *Carbon cycles*]. As a recent literature review observed, the "use of enhanced ocean alkalinity for C storage was first proposed by [chief Exxon climate scientist Haroon] Kheshgi."[122]

Like internal documents, peer-reviewed publications attribute GHG emissions and/or AGW to fossil fuels significantly more often than advertorials ($p < 0.01–0.03$). Common terms include fossil fuel emissions, fossil fuel CO_2, and fossil fuel combustion [*AGW science/projections*] (see Table 5).

Rhetorical frames

Frame package analysis leads us to identify three dominant frames in ExxonMobil's advertorials, which we name (1) Scientific Uncertainty, (2) Socioeconomic Threat, and (3) Fossil Fuel Savior (FFS) (for details, see S4, supplemental information). The Scientific Uncertainty frame presents AGW as unproven and advocates additional climate science research. The Socioeconomic Threat frame argues that binding climate policies (such as the Kyoto Protocol) are alarmist and threaten prosperity, urging voluntary measures instead. The FFS frame describes AGW as the inevitable (and implicitly acceptable) risk of meeting consumer energy demand with fossil fuels for the foreseeable future, and presents technological innovation as the long-term solution.

These frames are constructed of reasoning and framing devices variously communicated by the 11 discourses listed in Figure 1. Figure 1 is a Venn diagram representing the chain of logic (i.e., reasoning devices) of each frame as defined by Entman:[10] problem, cause, moral evaluation, and solution (as indicated, these reasoning devices are the logical bases challenged by denials that AGW is real, human caused, serious, and solvable, respectively).[10] Discourses are manifest in one or more framing devices (e.g., lexical choices, catchphrases, depictions), and their positions in Figure 1 depict their contributions to the reasoning devices of each frame (definitions and examples of each frame's reasoning and framing devices are provided in S4 and S5, supplemental information). For example, discourses of Technological Shell Game, which, as Schneider et al.[27] define them, use "misdirection that relies on strategic ambiguity about the feasibility, costs, and successful implementation of technologies," serve to downplay the need for public and political concern by trivializing

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Table 4. Topical tropes: Highly divergent topics in (top) advertorials versus (bottom) internal and peer-reviewed documents, by LL ratio (G^2) of topics identified by LDA topic modeling

Category	Topic labels	G^2	Top terms
Advertorials	energy/ emissions challenge	10,271.93	*energy, *technolog(y/ies), *emission(s), *efficien(t/tly/cy), *world, *global, fuel(s), *improv(e/es/ed/ing/ements), *develop(ing), *environment(/al/ally), *econom(y/ic), *need(s), *challenge(s), *percent, *demand, *risk(s), *gas, *reduce, *invest(/ing/ment/ments), future, [*meet, *longterm]
	climate policy	6,045.82	*countries/nations, *kyoto, *emission(s), *econom(y/ic), *protocol, *targets, *gases, *agree(ment)/consensus, *industrialized, *administration, *reduction*, *participat(e/tion/ing), *senate, *plan, *measures*, *governments, *developed, *develop(ing), *public, *treaty [*jobs/*employment, *cost(/s/ly/lier/liest)*, *bind(ing), lifestyle(s), *voluntary]
	vehicles	1,992.81	*vehicles, *evs/electric vehicles, *vehicle*, *gasoline, *cars, *diesel*, *citizenship, *math, corporate, *engine, *performance, *road, *engines, *social, car, *science, *education, balancing, dieselpowered, spills
	energy technologies	1,627.41	nuclear, *power, solar/photovoltaic(s), *oil, *renewable(s), trillion, *natural*, cell, brooklyn, reserves, barrels, turbine, *wind, generate, *gas, petroleum, fine, hydropower, inexhaustible, vote [*offshore*, onshore, ethanol, biofuels]
	conservation	304.39	*tree(s), forest(s), *plant(/ing), *helped, buildings, lands, sequestration, star, *protect(/ion/ing), acres, eco(logical/system), enhance, conservancy, epas [EPA's], habitat, planted, threat, *conservation, agricultural, carefully [diversity, eagle, indigenous, preservation, restoring, wildlife]
	climate science uncertainty	201.47	climate, *change*, research, scientific, science, human, uncertain(/ty/ties), *(un)* *know(/n/ing/ledge), national, *scientists, earths, predict, *debate, underst(and/anding/ood), variability, weather, impacts, consequences, ability, *development* [program(s), *policy, compl(ex/exity/icated), *universit(y/ies)]
Internal and peer reviewed	AGW science/ projections	−4,554.30	*co2/carbon dioxide, atmospher(e/ic), *effect(s), *fossil*, *temperature, fuel(s), *concentration, *increase*, *concentrations, carbon, *rate, global, *ocean, *ppm, *average*, level, *due, *oceans, combust(ion)/burn(ing), *biosphere [*scenarios, impact]
	climate modeling	−3,897.21	*model(s), results, *forc(e/ed/ing)*, climate, *data, *estimates, response, variability, *temperature, *shown, *flux, anthropogenic, range, *projections, emission(s), detection, parameter, *estimated, studies, based
	CO_2 disposal/ storage	−2,668.42	*co2/carbon dioxide, *ph [pH], *figure, *time*, *seawater, *depth, *km*, *vertical, *retention*, *model(s), seafloor, *sparger*, *degassing*, diffusive, *natuna*, release, flow, *mixed, *surface, fraction [*injection]
	mitigation assessments	−1,917.80	*transport, mitigation, price, cost(/s/ly/lier/liest), biomass, *waste*, *al, infrastructure, china, usa, wastewater, reduction, potentially, forestry, losses, sector, availability, capture, direct, sectors
	climate research programs	−1,259.86	*dr*, *program(s)*, *exxon*, *tanker*, *era*, *phase*, federal, fund(/ed/ing), plan, division, *weinberg* [Harold Weinberg], additional, mass, academy, interface, underway, wines, organization, *shaw* [Henry Shaw], engineering [*committee*, funds, scoping]
	carbon cycles	−1,215.66	*al, *ocean, deep, carbon, broecker [Wallace Broecker], upwelling, bbsr, stocks, uptake, land, gt, vegetation, bermuda, landuse, *cycles*, jain, station, transient, biospheric, column [dissolved, *water, inventory]
	oil and gas production	−1,034.26	*ccs, hs, gas, acid, cement, n2 [N2], processing, date, *natuna*, park, project, earliest, eor, field, oil, mw, recovery, describes, liquid, substantial [pipeline]

For each emergent topic, a topic label and its corresponding top 20 terms are listed (additional informative terms are in brackets). Top 20 terms are ordered according to the relevance metric proposed by Sievert and Shirley,[121] which accounts for both per-term (w)-per-topic (k) probabilities ($\varphi_{w,k}$) and the marginal probability of each term in the corpus (p_w). We indicate divergent terms, as identified earlier by G^2 and FS, between advertorials versus (italics) internal documents, (underlining) peer-reviewed publications, and (asterisks) internal and peer-reviewed documents. p values < 0.001 for all G^2 and FS scores.

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Table 5. Rhetoric of individualized responsibility: Highly divergent terms in (top) advertorials and (bottom) internal and/or peer-reviewed documents, by LL ratio (G^2) and FS

	Advertorials	Internal	Peer reviewed	G^2 (Int./P.r.)	FS (Int./P.r.)	Example
Advertorials often say:						
(to) meet	65	2	98	128.34/191.64	0.99/0.93	"To meet this demand, while addressing the risks posed by rising greenhouse gas emissions, we'll need to call upon broad mix of energy sources"[5]
vehicles	33	0	240	73.48/25.02	1/0.74	"[T]he cars and trucks we drive aren't just vehicles, they're opportunities to solve the world's energy and environmental challenges"[123]
greenhouse gas emissions	42	7	60	58.9/126.97	0.92/0.94	"We're supporting research and technology efforts, curtailing our own greenhouse gas emissions and helping customers scale back their emissions of carbon dioxide"[124]
energy efficiency	30	1	152	58.76/36.65	0.98/0.81	"We have invested $1.5 billion since 2004 in activities to increase energy efficiency and reduce greenhouse gas emissions. We are on track to improve energy efficiency in our worldwide refining and chemical operations …"[125,126]
cars	24	0	59	53.44/54	1/0.9	"By enabling cars and trucks to travel farther on a gallon of fuel, drivers not only spend less money per mile, they also emit less carbon dioxide (CO_2) per mile"[127]
reduce emissions	23	0	25	51.21/78.03	1/0.95	"During the fact-finding period, governments should encourage and promote voluntary actions by industry and citizens that reduce emissions and use energy wisely. Governments can do much to raise public awareness of the importance of energy conservation"[128]
consumers	21	0	33	46.76/60.7	1/0.93	"We also are developing new vehicle technologies that can help consumers use energy more efficiently"[125,126]
world	91	64	338	43.45/150.55	0.74/0.85	"By 2030, experts predict that the world will require about 60 percent more energy than in 2000 … As a result, greenhouse gas emissions are predicted to increase too …"[129]
developing countries	27	3	162	43/26.94	0.95/0.78	Through 2030, "developing countries … will rely on relatively carbon-intensive fuels like coal to meet their needs"[5]
transportation	23	2	121	38.87/26.93	0.96/0.8	"Ongoing advances in vehicle and fuel technology will be critical to meeting global demand for transportation fuels. They will also help address the risk posed by rising greenhouse-gas emissions"[123]
energy use	23	4	83	31.75/39	0.92/0.85	"Central to any future policy should be the understanding that man-made greenhouse gas emissions arise from essential energy use in the everyday activities of people, governments and businesses"[130]
people	30	11	61	27.87/75.73	0.85/0.91	"Thus, we're pleased to extend our support of … American Forests … whose 'Global Releaf 2000' program is mobilizing people around the world to plant and care for trees"[131]
demand	40	21	422	27.24/14.35	0.8/0.67	"[I]n the electric power sector, growing demand will boost CO_2 emissions …"[132]

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Table 5. Continued

	Advertorials	Internal	Peer reviewed	G^2 (Int./P.r.)	FS (Int./P.r.)	Example
needs	36	22	71	20.69/92.45	0.77/0.91	"... fossil fuels must be relied upon to meet society's immediate and near-term needs"[133]
conservation	15	5	66	14.89/21.23	0.86/0.83	"Prudent measures such as conservation and investment in energy-efficient technology make sense, but embarking on regulatory [climate/energy] policies that may prove wasteful or counterproductive does not"[134]
energy demand	15	14	59	4.38**/23.59	0.69**/0.84	"[I]ncreasing prosperity in the developing world [is] the main driver of greater energy demand (and consequently rising CO_2 emissions) over the coming decades"[135]
Internal and/or peer-reviewed documents often say:						
fossil fuel	9	144	359	−66.26/−4.48**	0.11/0.34***	"Release of this amount of CO_2 to the atmosphere raises concern with respect to its effect on the CO_2 greenhouse problem. Global fossil fuel emissions of CO_2 currently amount to about 1.8×10^{13} metric tons per year ..."[136]
						"Arrhenius put forth the idea that CO2 from fossil fuel burning could ... warm the Earth ... fossil fuel greenhouse warming ... fossil fuel greenhouse effect ..."[137]
natuna	0	67	NA	−53.36/NA	0/NA	"This would make Natuna the world's largest point source emitter of CO_2 and raises concern for the possible incremental impact of Natuna on the CO_2 greenhouse problem"[136]
due to	5	89	731	−42.94/−39.08	0.1/0.13	"The CO_2 concentration in the atmosphere has increased ... The most widely held theory is that: the increase is due to fossil fuel combustion"[138]
						"About three-quarters of the anthropogenic emissions of CO_2 to the atmosphere during the past 20 years is due to fossil fuel burning"[139]
fossil fuel combustion	1	48	NA	−30.68/NA	0.04/NA	"[T]here is the potential for our [climate] research to attract the attention of the popular news media because of the connection between Exxon's major business and the role of fossil fuel combustion in contributing to the increase of atmospheric CO_2"[140]
shale	1	41	NA	−25.43/NA	0.05/NA	"The quantity of CO_2 emitted by various fuels in shown in Table 1 ... They show the high CO_2/energy ratio for coal and shale ... ["Shale oil"] is not predicted to be a major future energy source due to ... rather large amounts of CO_2 emitted per unit energy generated (see Table 1)"[136]
ccs	0	NA	374	NA/−34.82	NA/0	"CCS includes applying technologies that capture the CO_2 whether generated by combustion of carbon-based fuels or by the separation of CO_2 from natural gas with a high CO_2 concentration"[141]
source	6	39	322	−9.08*/−7.16**	0.24*/0.28**	"[F]ossil fuel combustion is the only readily identifiable source [of CO_2] which is (1) growing at the same rate, (2) large enough to account for the observed increases ..."[142]

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Table 5. *Continued*

	Advertorials	Internal	Peer reviewed	G^2 (Int./P.r.)	FS (Int./P.r.)	Example
						Table 1 presents "coal combustion" and "natural gas combustion" as the "source[s]" of CO_2, CH_4, SO_2[143]
fossil fuel use	0	13	NA	−10.35*/NA	0**/NA	"[F]or scenarios with higher fossil fuel use (hence, higher carbon dioxide emissions ..."[139]
fossil fuel CO_2	0	NA	64	NA/−5.96**	NA/0***	"This long tail on the fossil fuel CO_2 forcing of climate may well be more significant to the future glacial/interglacial timescale evolution of Earth's climate ..."[144]
fossil fuel emissions	0	NA	54	NA/−5.03**	NA/0***	"We use our Integrated Science Model to ... estimate the time variation fossil fuel emissions of CO_2 ... required to match the [IPCC] concentration stabilization scenarios"[145]

Divergent terms in advertorials are identified by frame package analysis as framing devices of individualized responsibility discourse. Example quotations illustrate how advertorials use divergent terms to disproportionately present: (1) consumer demand for energy as the cause of—and culpable for—fossil fuel use, greenhouse gas emissions, and/or AGW; and (2) individual/demand-side actions as accountable for mitigating AGW. By contrast, divergent terms in internal and/or peer-reviewed documents often articulate the causality and culpability of fossil fuel combustion. p values < 0.001 for all G^2 and FS scores except: * <0.005; ** <0.05; *** ≥ 0.05. NA, not available.

the seriousness and solvability of AGW. Technological Shell Game discourse is therefore placed in the overlapping areas of Moral evaluation ("Serious") and Solutions ("Solvable") in Figure 1.

The frame of Scientific Uncertainty—and its underlying taxonomy of explicit doubt about climate science and its implications—has previously received detailed scrutiny and is here discussed further only in S4.1, supplemental information.[1,2,17–24] By contrast, frames of Socioeconomic Threat and FFS—and the subtler discourses of delay that underpin them—are underexplored.[17,26–28] For further discussion of the Socioeconomic Threat frame, see S4.2, supplemental information. In the remainder of this paper, we focus on the role of two specific, complementary discourses, Climate Risk and Individualized Responsibility, in constructing the FFS frame. As Figure 1 suggests, these discourses serve as rhetorical gateways connecting the problem and cause of the FFS frame to its moral evaluation and solution.

Discourse of climate risk

We have previously noted that, accompanying the emergence in the mid-2000s of implicit acknowledgments by some ExxonMobil Corp advertorials that AGW is real and human caused, there appeared to be a rhetorical framework focused on risk.[2] Algorithmic analyses here demonstrate that this was part of a wider trend in which, following the merger of Exxon and Mobil at the end of 1999, "risk" was incorporated into advertorials communicating explicit doubt. Specifically, LL and FS results in Table 1 show that "risk(s)" is among the terms that most statistically distinguish Mobil advertorials from ExxonMobil Corp advertorials. Within all advertorials published prior to the merger and expressing any positions on AGW (as real and human caused, serious, or solvable), "risk(s)" appears three times, only once in reference to the risk(s) of AGW or greenhouse gases. By contrast, from 2000 onwards, such "risk(s)" are cited 46 times: an average of once per advertorial; 10 times higher than an average NYT article.[146] Permutations include "risk," "risks," "potential risks," "long-term risk," "long-term risks," "legitimate long-term risk," "legitimate long-term risks," and "potential long-term risks."

In 2000, for instance, ExxonMobil Corp's first post-merger advertorial in our corpus promoted "scientific uncertainty" that AGW is real, human caused, serious, and solvable, acknowledging only that it "may pose a legitimate long-term risk, and that more needs to be learned about it".[147] By the time the company took out its last advertorial expressing a position on AGW in 2009, its tune had changed but "risk" rhetoric remained. The advertorial was entitled, "Tackling climate risks with technology," followed by the subtitle, "Support for oil and natural gas innovation can reduce emissions."[148]

The function of "risk" rhetoric in moderating the conveyed status of AGW or greenhouse gases is unambiguous. First, "risks" is among the top terms characterizing the LDA-generated topic of energy/emissions challenge, which is the primary topic that introduces readers to AGW (and compares it with energy demand; see "discourse of individualized responsibility") (Table 4). Second, "climate (change) risk(s)/risk(s) of climate" is, like "risk(s)" itself, a statistically distinctive term of ExxonMobil Corp advertorials versus Mobil advertorials, internal documents, and peer-reviewed publications (Tables 1, 2, and 3). Indeed, automated collocation analysis reveals that the highest scoring collocate of "climate change" and "global warming" in ExxonMobil Corp advertorials is "risk(s)." By contrast, in Mobil advertorials, it is "science" (followed by "gases" and "debate") (Table S18).

Discourse of individualized responsibility

Table 5 (top half) collates terms that are (1) identified by frame package analysis as framing devices communicating Individualized Responsibility in advertorials, and (2) highly divergent

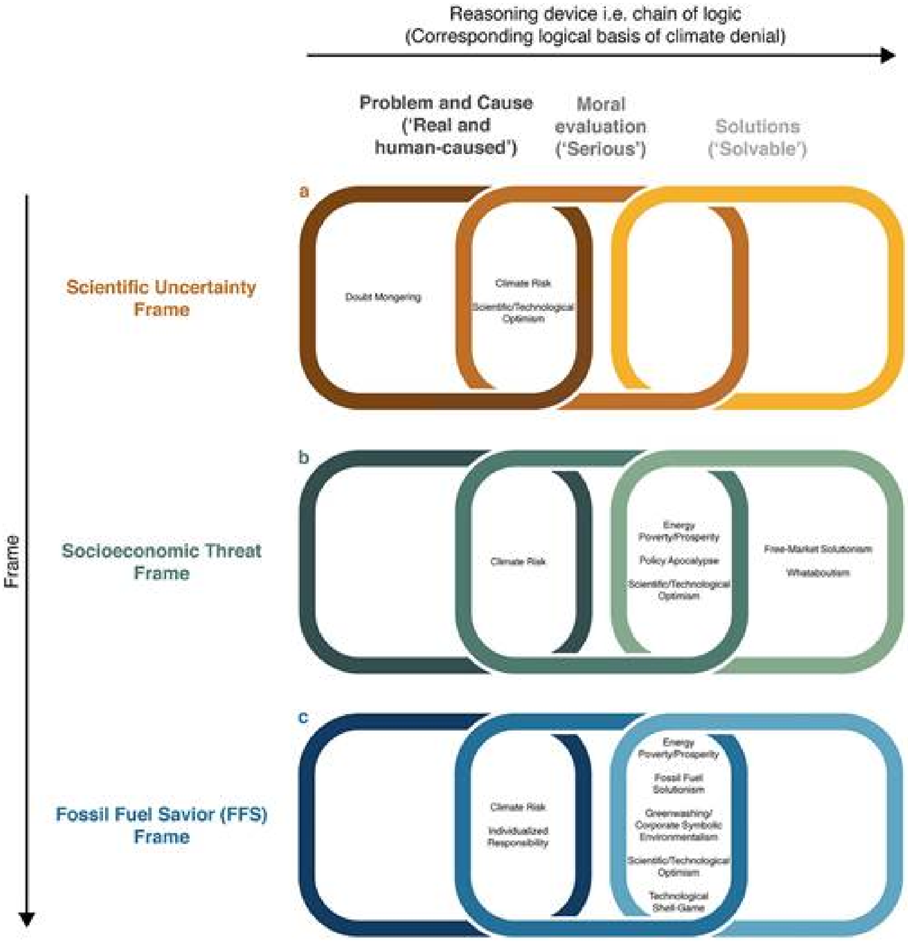

Figure 1. Typology of discourses of climate denial and delay

Using frame package analysis, we identify three dominant frames in ExxonMobil's advertorials: (a, top) Scientific Uncertainty; (b, middle) Socioeconomic Threat; and (c, bottom) Fossil Fuel Savior (FFS). For each frame, a Venn diagram is presented corresponding to the reasoning devices (i.e., chains of logic) defined by Entman:[72] (left) problem and cause; (middle) moral evaluation; and (right) solution (as indicated, these reasoning devices are the logical bases challenged by denials that AGW is real, human caused, serious, and solvable, respectively). Each reasoning device is communicated by one or more of the 11 discourses of climate denial and delay listed within each chain of logic. Although not shown, these discourses are manifest in one or more framing devices (e.g., lexical choices, catchphrases, depictions), as identified in S4, supplemental information. As an example, discourses of Technological Shell Game, which, as Schneider et al.[27] define them, use "misdirection that relies on strategic ambiguity about the feasibility, costs, and successful implementation of technologies," serve to downplay the need for public and political concern by trivializing the seriousness and solvability of AGW. Technological Shell Game discourse is therefore placed in the overlapping areas of Moral evaluation ("Serious") and Solutions ("Solvable") in the diagram. For definitions and examples of all reasoning devices, framing devices, and discourses, see S4 and S5, supplemental information.

between all advertorials and internal and/or peer-reviewed documents according to LL and FS analyses. Two patterns emerge.

First, we observe that advertorials disproportionately employ terms that present consumer demand for energy (rather than corporate supply of oil, coal, and gas) as the cause of fossil fuel production, greenhouse gas emissions, and/or AGW. A characteristic example of this "(energy) demand" rhetoric is a 2008 ExxonMobil Corp advertorial stating: "By 2030, global energy demand will be about 30 percent higher than it is today… oil and natural gas will be called upon to meet…the world's energy requirements."[149] Another, in 2007, says that "increasing prosperity in the developing world [will be] the main driver of greater energy demand (and consequently rising CO_2 emissions)…"[135] A 1999 Mobil advertorial is even blunter: "[G]rowing demand will boost CO_2 emissions."[132] In other words, they present growing energy demand as inevitable, and imply that it can only be met with fossil fuels.

Synonyms for "(energy) demand" include "needs" ("…fossil fuels must be relied upon to meet society's immediate and near-term needs") and "energy use" ("man-made greenhouse gas emissions arise from essential energy use in the everyday activities of people, governments and businesses"). Fossil fuels are either presented as passively responding "to meet this demand" of consumers, developing countries, and the world; or they are left out of the equation entirely: "[A]s populations and economies have grown, energy use has increased, and so have greenhouse gas emissions."[150]

Second, we observe that, to the extent that advertorials admit the need for AGW mitigation, they disproportionately introduce terms conveying individual and/or demand-side actions as the appropriate response. Even while promoting explicit doubt about the reality of AGW, advertorials focus on downstream energy efficiency and greenhouse gas emissions, rather than upstream supply of fossil fuels, as the appropriate target of mitigation efforts. "During the [climate science] fact-finding period," a 1997 advertorial states, "governments should encourage and promote voluntary actions by industry and citizens that reduce emissions and use energy wisely. Governments can do much to raise public awareness of the importance of energy conservation."[128] Twelve years later, advertorials continued to equate the "global environmental challenge" with "curbing greenhouse gas emissions," but not with constraining fossil fuel supply.[151] As one 2000 advertorial put it: "Prudent measures such as conservation and investment in energy-efficient technology make sense, but embarking on regulatory [energy] policies that may prove wasteful or counter-productive does not."[134]

Advertorials repeatedly highlighted ways the public could, as one in 1998 put it, "show a little voluntary 'can do.'"[152] A 2008 advertorial suggested that the "cars and trucks we drive aren't just vehicles, they're opportunities to solve the world's energy and environmental challenges."[123] A 2007 advertorial offered readers "simple steps to consider": "Be smart about electricity use"; "Heat and cool your home efficiently"; "Improve your gas mileage"; "Check your home's greenhouse gas emissions" using an online calculator.[153] Mobil and ExxonMobil Corp presented themselves as facilitating, and participating in, such demand-side AGW mitigation. A 1997 advertorial laid the groundwork: "We're supporting research and technology efforts, curtailing our own greenhouse gas emissions and helping customers scale back their emissions of carbon dioxide."[124] In 1999, Mobil announced that "we're pleased to extend our support of … American Forests … whose 'Global Releaf 2000' program is mobilizing people around the world to plant and care for trees."[131] This narrative was echoed by advertorials a decade later: "By enabling cars and trucks to travel farther on a gallon of fuel, drivers…emit less carbon dioxide (CO_2) per mile," said a 2008 advertorial.[127] "We also are developing new vehicle technologies that can help consumers use energy more efficiently," said two more the following year.[125,126]

By contrast, Exxon and ExxonMobil Corp's internal and/or academic communications recognized AGW and/or greenhouse gases as also an upstream problem caused by fossil fuel supply and burning (see also S2.2, supplemental information). "[F]ossil fuel combustion is the only readily identifiable source [of CO_2 consistent with the rate and scale of] observed increases…," observed Exxon scientist James Black[142] in a 1978 presentation to the Exxon Corporation Management Committee. Other internal (1979) and peer-reviewed (2001) documents likewise attributed CO_2 accumulation in the atmosphere as "due tofossil fuel burning" and "fossil fuel combustion."[138,139] A 1984 internal report and a 1994 academic article spoke of "fossil fuel emissions of CO_2," while a 1998 paper referred to "fossil fuel CO_2 forcing of climate."[136,144,145] A 1982 internal memo went further, acknowledging "the connection between Exxon's major business and the role of fossil fuel combustion in contributing to the increase of atmospheric CO_2."[140] The 1979 and 1984 internal documents discuss the CO_2 emissions of specific fossil fuel sources such as shale oil and Exxon's natural gas reservoir off Natuna Island in Indonesia.[136,138]

In sum, ExxonMobil's advertorials statistically overuse terms that reduce AGW to a downstream problem caused by consumer energy demand, to be solved primarily by energy efficiency to reduce greenhouse gas emissions. In contrast, their private and academic documents disproportionately recognize that AGW is an upstream problem caused by fossil fuel supply.

As we show in S6.2, supplemental information, this statistical dichotomy extends throughout all of ExxonMobil Corp's flagship reports concerning AGW spanning 2002–2019 compared with the firm's internal and academic publications.

FFS frame

In addition to Climate Risk and Individualized Responsibility, the FFS frame comprises the five other discourses shown in Figure 1 and defined in S5, supplemental information. Together, they establish the frame's chain of logic (i.e., reasoning devices, see Table S4, supplemental information).

First, as shown in the previous two sections, discourses of Climate Risk and Individualized Responsibility present AGW as the inevitable "risk" of meeting consumer energy demand.

In response to this problem definition and causal attribution, discourses of Scientific/Technological Optimism (which gives primacy to scientific or technological breakthroughs as the solutions to AGW) and Greenwashing/Corporate Symbolic Environmentalism (which is when companies make changes for environmental reasons that, in the case of greenwashing, are merely and deliberately symbolic) lend what Plec and Pettenger[52] (2012) call "an aura of scientific and technical authority," which "resigns us

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to putting our faith in the power of industry, technology, and science" (see also Schneider et al.[29]). "[W]e believe that technology provides the key avenue to solutions that manage long-term risk and preserve prosperity," says the voice of reason presented by a 2002 advertorial entitled "A responsible path forward on climate." "[This] will almost certainly require decades....''[154] ExxonMobil asserts its leadership in this challenge with advertorials citing "our industry-leading investments in research and development,"[149] such as "supporting climate-related research efforts at major universities, including Stanford and MIT."[155] Visual images such as graphs, charts, and science iconography reinforce this impression.

This technocratic authority helps legitimize accompanying discourses of Fossil Fuel Solutionism and Technological Shell Game, which join the dots between energy demand and continued reliance on fossil fuels. An example of Fossil Fuel Solutionism (which presents fossil fuels and their industry as an essential and inevitable part of the solution to AGW) is a 2007 advertorial that unequivocally depicts the future: "Coal, oil, and natural gas will remain indispensable to meeting total projected energy demand growth" through 2030.[156] "Oil and gas will be essential to meeting demand," reiterates another in 2008.[5] "Meeting this growing long-term demand requires that we develop all economic sources of energy – oil, natural gas, coal, nuclear and alternatives," says a third in 2009.[151]

The non-fossil fuel alternatives are then dismissed by Technological Shell Game discourse promoting doubt and confusion about AGW's technological solvability, such as three advertorials in 2005 depicting, again unequivocally, how "Wind and solar...meet about 1% of total world demand by 2030."[157–159] Another, 3 years later, updates the figure to "only 2 percent" (including biofuels).[5] ExxonMobil also takes aim at clean energy subsidies and renewable energy's "highly variable output" and "enormous land-use requirements."[133,154,160] Meanwhile, the three 2005 advertorials, and another in 2009, falsely promote natural gas as "clean-burning" and "clean," respectively.[157–159]

In a 2009 advertorial, ExxonMobil acknowledges that there is "a dual challenge" to "provide energy" and "protect the environment" (notably, they say that this challenge concerns energy rather than fossil fuels, and that it applies to "all of us").[150] But then they tip the scales by pitting concrete, unequivocal benefits ("[Energy] lights our homes. Fuels our transportation. Powers our industries...[D]riv[es] our economy and rais[es] living standards") against amorphous, uncertain costs (the "risks of climate change"). Two 2007 advertorials similarly compare "economic growth and human development" against undefined "risks of climate change."[161,162]

In cases such as these, discourses of Energy Poverty/Prosperity and Policy Apocalypse (which respectively articulate social justices of energy access and alleged socioeconomic tolls of decarbonization – the latter strictly assigned to the socioeconomic threat frame), contrasted against that of Climate Risk, work to affirm the moral evaluation of the FFS frame that fossil fuel lock-in is righteous and reasonable.

DISCUSSION

The patterns observed in "results" are similar to those documented in the tobacco industry. In "risk rhetoric facilitates ExxonMobil's have-it-both-ways position on AGW" and "energy demand rhetoric individualizes AGW responsibility," we discuss the strategic functions of AGW "risk" rhetoric and individualized responsibility framings, respectively, in comparison with the history of the tobacco industry. "Energy demand rhetoric individualizes AGW responsibility" distinguishes how consumer energy demand is presented in public ("demand as fossil fuel lock-in in public relations") versus in legal defense ("demand as blame in litigation"). "Historical contexts, ramifications, and trajectories of ExxonMobil's communication tactics" explores the historical contexts, ramifications, and trajectories of ExxonMobil's "risk" rhetoric ("risk") and individualized responsibility framings ("individualized responsibility").

Risk rhetoric facilitates ExxonMobil's have-it-both-ways position on AGW

Our identification of ExxonMobil's discursive shift to "risk" rhetoric (see "discourse of climate risk") is broadly consistent with independent findings. Jaworska[51] observes the emergence of "risk" as one of the most frequent collocations of "climate change" in the late 2000s within the corporate social responsibility reports of the world's major oil corporations, including ExxonMobil. Grantham and Vieira,[44] examining "welcome letters" from ExxonMobil's CEO in the company's Corporate Citizenship Reports, note that "risk" is one of the most influential words coinciding with emphasis on the "planet." Schlichting[17] concludes that, over the course of the 2000s, industry actors increasingly adopted the framing that "climate change [might be/is] a risk."

ExxonMobil's rhetorical pattern of stressing "risk" is consistent with the company's effort in the mid-2000s, chronicled by journalist Steve Coll,[48] "to reposition ExxonMobil's arguments about warming to more fully account for consensus scientific opinion, without admitting that any of the corporation's previous positions had been mistaken, for that might open a door to lawsuits."

This approach resembles the tobacco industry's well-documented response to the scientific consensus on the harms of tobacco use, described by historian Allen Brandt[163] as a "shift" in focus from scientific "uncertainty" to "(alleged) risks" of smoking (see also Proctor[164,165]). This scientific hedging strategy was made explicit in a 1996 Reynolds training manual instructing new employees to tell reporters that smoking was "a risk factor" but "not a proven cause."[165] In 1998, for example, Philip Morris's CEO Geoffrey Bible conceded a "possible risk" but not a "proven cause," the distinction being in what historian Robert Proctor[165] calls "a kind of legal having-it-both-ways: an admission strong enough to ward off accusations of having failed to warn, yet weak enough to exculpate from charges of having marketed a deadly product." This carefully parsed conclusion became the industry's new official position.[163]

"Risk" facilitates ExxonMobil's have-it-both-ways position on AGW. It is a "'good' candidate to serve various rhetorical purposes," Jaworska[51] notes, because it "opens up many semantic slots." Fillmore and Atkins'[166] work on the conceptual meaning of risk, for example, shows that "risk" has two dominant sub-frames, "Chance" and "Harm," and many optional valence description categories. "Chance" is defined as "uncertainty about the future," such that risk rhetoric (1) implies inherent uncertainty and (2) is subject to temporal discounting heuristics.[167–169] "The essence

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of risk is not that it *is* happening, but that it *might* be happening."[170,171]

"Risk" is never clearly or consistently defined by ExxonMobil. The presence and absence of risk's various sub-frames introduce so-called strategic ambiguity—and therefore flexibility—in contemporaneous and retrospective interpretations of what ExxonMobil wants us to see as a "risk" rather than a "reality."[97,172] For instance, does the "Chance" sub-frame of "risk"—and therefore the implication of uncertainty—apply to whether AGW is happening, human caused, serious, or solvable? Sub-frames of Harm, Actor, Victim, and Valued Object are also rarely articulated: who assumes the risk(s) of AGW: the public, the company, its shareholders, or others? What might be the consequences, and when? In contrast, the "Gain," "Beneficiary," and "Motivation" sub-frames of risk taking, manifest in discourse of Policy Apocalypse, are stated explicitly, as discussed in "demand as fossil fuel lock-in in public relations."

Like its weaponized rhetorical cousins - such as "uncertainty," "sound science," and "more research," and the hedging words "may," "potential," etc., - "risk" has the strategic advantage of not necessarily implying intent to deny or delay, because it is coopted from common academic, regulatory, journalistic, and colloquial parlance (S1.4.2, Supran and Oreskes[1]).[15,148,167,173,174] It can be used correctly (for example, to refer to expected *future* damages and stranded fossil fuel assets - a risk that we have previously shown ExxonMobil was publicly silent about) or incorrectly (for example, to describe AGW and past/present climatic changes such as sea level rise as risks rather than realities).[1]

ExxonMobil employs almost identical "risk" language in advertorials promoting explicit doubt about AGW as in those that implicitly acknowledge it. For example, they refer to "the risk of global warming" in 1989 (accompanied by explicit doubt); the "risk(s)" "that climate changes may pose" in 2000 (alongside explicit doubt); and "the risks of climate change" in 2009 (which, in the absence of doubt, is coded as an implicit acknowledgment).[150,175,176] This is not limited to advertorials (for wide-ranging examples, see table 3 of Supran and Oreskes[5]). In ExxonMobil Corp's *2005 Corporate Citizenship Report*, for instance, which extensively questions whether AGW is human caused and serious, a member of the public asks: "Why won't ExxonMobil recognize that climate change is *real*…?" The company replies: "ExxonMobil recognizes the *risk* of climate change and its *potential* impact…" (emphases added).[177] By shifting the conversation from the semantics of reality to the semantics of risk, they inject uncertainty into the AGW narrative, even while superficially appearing not to.

Energy demand rhetoric individualizes AGW responsibility

Two dimensions of issue responsibility are commonly identified in communications and psychological research: causality and treatment.[16,178] Causality responsibility addresses the source of a problem—who or what causes it. Treatment responsibility identifies who or what has the power to alleviate the problem, and should be held responsible for doing so. Studies of responsibility framing and attribution theory argue that attribution of these responsibilities broadly takes two conflicting forms: individual versus social.[16,179,180] Expressing our findings in "discourse of individualized responsibility" through this analytical lens, ExxonMobil's public advertorials are biased toward individualist framings of both causality and treatment responsibilities for AGW as compared with their private and academic representations.

Jaworska[51] has observed similar appeals to energy demand as the driving force behind greenhouse gas emissions in the corporate citizenship reports of ExxonMobil Corp and other fossil fuel companies, noting that they are "an example of differentiation, which shifts the responsibility to other constituencies." Princen et al.[72] similarly argue that a focus on carbon and greenhouse gases—and away from fossil fuels—is reductionist. "This chemical framing," they note, "implies that the problem arises after a chemical transformation, after fuels are burned. It effectively absolves of responsibility all those who organize to extract, process, and distribute…So constructed…the burden of harm and responsibility for amelioration falls on governments and consumers rather than extractors."

"The most effective propaganda," Parenti[181] contends, "is that which relies on framing rather than on falsehood." As with the language of risk, a rhetorical power of narratives that individualize responsibility is that they do not require the statement of outright falsehoods. After all, consumer demand is one valid and universally recognized aspect of the AGW problem and its solution, and not all advertorials entirely disregard the role of fossil fuels. On balance, however, the disproportionate public fixation of ExxonMobil, a supplier company, on demand-side causation and accountability (as shown in "discourse of individualized responsibility") fulfills the fundamental function of emphasis frames to "call attention to some aspects of reality while obscuring other elements."[10] It is in this selection process that the individualized responsibility framing device creates a false dichotomy, leading readers toward AGW problem definitions, evaluations, and solutions skewed toward consumer demand and away from industry supply.[11,16,178]

ExxonMobil's framing is reminiscent of the tobacco industry's effort "to diminish its own responsibility (and culpability) by casting itself as a kind of neutral innocent, buffeted by the forces of consumer demand."[185] It is widely recognized that the tobacco industry used, and continues to use, narrative frames of personal responsibility—often marketed as "freedom of choice"—to combat public criticism, influence policy debates, and defend against litigation and regulation.[13,100,119,164,182–184] Friedman et al.[13] recently demonstrated that tobacco companies use "freedom of choice" to imply two distinct concepts: liberty and blame. In their public relations messaging, industry asserts smokers' rights as individuals who are at liberty to smoke. In the context of litigation, industry asserts that those who choose to smoke are solely to blame for their injuries.

In the following two subsections, we further explore the congruence between ExxonMobil's public responsibility framing and these tobacco tactics ("demand as fossil fuel lock-in in public relations"; "demand as fossil fuel lock-in in public relations"). We discuss how this Individualized Responsibility discourse is rationalized and reinforced by the semantic duality of "risk."

Demand as fossil fuel lock-in in public relations

In "FFS frame," we showed that ExxonMobil's FFS frame insists—typically as self-fulfilling fact rather than opinion—upon society's inevitable and indefinite reliance on fossil fuels. Rather than asserting that demand is a personal choice and liberty, ExxonMobil's public "(energy) demand" rhetoric inverts the tobacco industry's "freedom of choice" messaging. Liberty becomes lock-in.

Within this frame, discourses of Energy Poverty/Prosperity and Policy Apocalypse contrast against that of Climate Risk ("FFS frame"). The role of "risk" rhetoric here is to downplay the downside, namely AGW, of this alleged dichotomy: fossil fuels are essential, whereas the potential effects—indeed realities—of AGW are uncertain.[28] Such assertions, St. John III[35] notes, extend Mobil's messaging in its 'Observations' columns "about what constitutes reasonable risk." Observations were "pithy, easy-to-read" advertorials that Mobil ran in Sunday newspaper supplements between 1975 and 1980.[35,185] In a 1980 'Observations' column, for example, Mobil lamented that "the country seems to be afflicted with the Chicken Little Syndrome" of "cry[ing] that 'The sky is falling!'"[186] "Hardly a day passes," they said, without "fresh perils" like "harmful rain" or "cancerous sunshine." But a "risk-free society" through government regulation is impossible, the advertorial reasoned, because "everything people do everyday involves a slight measure of risk" (emphasis in original). The company concluded with the warning that to "avoid risk, fight change" may be a short-term solution, "but for the long pull, it's a way to certain stagnation." Tobacco industry apologists made the same arguments, calling it "the menace of daily life."[187]

To the extent that advertorials concede AGW may be a problem, the "risk" angle helps frame AGW as unpredictable, positioning the oil industry "not as a contributor but as a victim" alongside consumers.[51] As a 2009 advertorial put it, "[we'll need] a global approach to managing the risks of climate change. Everyone has a role to play – industry, governments, individuals."[150] This complemented Mobil's broader use of advertorials to rhetorically reframe itself as what Kerr[42] terms a "corporate citizen." "A citizen of many lands" is how Mobil described itself in a 1999 advertorial.[131] "Climate change: we're all in this together," another was titled in 1996.[188] With this narrative of an "empathetic fellow traveler," St. John III[35] argues, "Mobil offers up the reasonable, risk-taking corporate persona who is willing to take the initiative to provide a beneficial product to all Americans…[B]y appealing to Americans' penchant for valorizing the self-starting individual, such a message of energy harvesting as never being 100% safe could well explain how a significant amount of Americans today do not see fossil fuel-induced climate change as a significant risk."[36]

ExxonMobil's advertorials say almost nothing about the seriousness of AGW.[1,2] Nor do they mention the concepts of carbon budgets and stranded fossil fuel assets, which are part of the argument for the fundamental incompatibility of unrestricted fossil fuel supply with climate mitigation.

Overall, the didactic framing of demand as fossil fuel lock-in communicates what Plec and Pettenger[52] describe as "a rhetoric of resignation, naturalizing consumption of resources and teaching us to put our trust in industry solutions to energy problems." Or as Schneider et al.[27] and Cahill[28] put it, quoting the neoliberal bromide: "There is no alternative" to the *status quo*.

Demand as blame in litigation

Although the tobacco industry sells "freedom of choice" as *liberty* in public relations, in litigation they equate it with *blame* toward individuals who exercised their choice to smoke.[13,164,183,184] Climate litigation is nascent, yet the fossil fuel industry has already successfully repackaged demand as *lock-in* to instead impute *blame* on customers for being individually responsible.

In 2018, arguing in defense of five oil companies (including ExxonMobil Corp) against a lawsuit brought by California cities seeking climate damages, Chevron lawyer Theodore Boutrous Jr. offered his interpretation of the IPCC's latest report: "I think the IPCC does not say it's the production and extraction of oil that is driving these emissions. It's the energy use. It's economic activity that creates demand for energy." "It's the way people are living their lives."[189] The judge's dismissal of the case accepted this framing: "[W]ould it really be fair to now ignore our own responsibility in the use of fossil fuels and place the blame for global warming on those who supplied what we demanded?"[190]

Even if plaintiffs prove their case, fossil fuel companies can invoke "affirmative defenses"—as tobacco companies often have—such as "common knowledge" and "assumption of the risk."[164,183] These respectively argue (1) "that the plaintiff had engaged in an activity [such as smoking] that involved obvious or widely known risks," and (2) "that the plaintiff knew about and voluntarily undertook the risk."[13] As Brandt[163] explains it, "If there was a risk, even though 'unproven,' it nonetheless must be the smoker's risk, since the smoker had been fully informed of the 'controversy.' The industry had secured the best of both worlds."

By way of the FFS frame, ExxonMobil appears to have constructed an ability to do the same. On the one hand, "risk" rhetoric is weak enough to allow the company to maintain a position on climate science that is ambiguous, flexible, and unalarming ("risk rhetoric facilitates ExxonMobil's have-it-both-ways position on AGW"). On the other, it is strong enough—and prominent enough, in NYT advertorials and elsewhere—that ExxonMobil may claim that the public has been well informed about AGW. This duality has been a cornerstone of the tobacco industry's legal position on the "risks" of smoking: "Everyone knew but no one had proof."[183,184] Akin to early, tepidly worded warning labels on cigarette packages, ExxonMobil's advertorials in America's newspaper of record help establish this claim, sometimes explicitly: "*Most people acknowledge* that human-induced climate change is a long-term *risk*," a 2001 advertorial states[13,130] (emphases added). "The *risk* of climate change and its *potential* impacts on society and the ecosystem are *widely recognized*," says another the following year.[191] As Baker[192] has pointed out about the socialization of risk, "a transfer of risk is also a transfer of responsibility…[R]isk *creates* responsibility…."

The fossil fuel industry's use of demand-as-blame framing is not limited to its legal defenses. As Schneider et al.[27] describe, fossil fuel interests have likewise sought to delegitimize AGW activism, such as the fossil fuel divestment movement, by deploying a rhetorical "hypocrite's trap [that] performs the disciplinary work of individualizing responsibility" (see also Ayling[193]).

Historical contexts, ramifications, and trajectories of ExxonMobil's communication tactics

ExxonMobil's selective use of rhetoric and discourse to frame AGW epitomizes the first "general principle" of effective public affairs according to Herbert Schmertz,[185] Mobil Oil's Vice

President of Public Affairs (1969–1988) and the pioneer of their advertorials: "Grab the good words – and the good concepts – for yourself."[185] "[B]e sensitive to semantic infiltration, the process whereby language does the dirty work of politics…Be sensitive to these word choices, and be competitive in how you use them. Your objective is to wrap yourself in the good phrases while sticking your opponents with the bad ones."

Risk

ExxonMobil Corp's systematic introduction of "risk" rhetoric into its doubt-mongering advertorials coincided with the 1999 merger of Exxon and Mobil, suggestive of a strategic shift in public relations.

A second shift, in the mid-2000s, from explicit doubt to implicit acknowledgment confused by "risk" rhetoric, coincides with what one ExxonMobil Corp manager saw as "an effort by [then CEO Rex] Tillerson to carefully reset the corporation's profile on climate positions so that it would be more sustainable and less exposed."[48]

To this day, ExxonMobil Corp's (also Chevron's and ConocoPhillips') refrain on AGW, and the primary basis on which the company is now widely perceived to accept basic climate science, is that it is a "risk."[26,194,195] Across all of ExxonMobil Corp's flagship reports concerning AGW, by far the highest scoring collocate of "climate change" and "global warming" is "risk(s)" (S6.1, supplemental information). Compared with internal and peer-reviewed documents, terms in flagship reports invoking "risks of climate change" are highly divergent (S6.1). As with advertorials, none say that climate change is real and human caused.

Individualized responsibility

The findings in the results section lead us to conclude that ExxonMobil advertorials used frames of individualized responsibility and the rhetoric of "risk" to construct what St. John III[35] calls a "sense-making corporate persona" that appealed to the enduring principles of "rugged individualism" and self-reliance that pervade US culture and ideology.[35,196–201] Their public affairs campaign coincided with solidifying, intertwined notions of distributed risks and individualized responsibility in western public policy debates since the 1970s, which have been driven by the global embrace of neoliberalism and globalization[27,197,202,203] and encouraged by reductive, episodic news framings[16,179] (and which are conceptualized by social theories[59,204,205] such as Beck et al.'s "risk society,"[179,206,207] Douglas et al.'s "risk culture,"[208] and Foucault et al.'s "governmentality").[209,210] ExxonMobil tapped into this trend toward the individualization of social risks, and brought it to bear on AGW.[59,206,211]

ExxonMobil is part of a lineage of industrial producers of harmful commodities that have used personal responsibility framings to disavow themselves.[212–214] Among them: tobacco companies[13,119,120]; the National Association of Manufacturers[215]; plastics producers (including Exxon, Mobil, and ExxonMobil Corp), packaging and beverage manufacturers, and waste companies[197,216–222]; and purveyors of sugar-sweetened beverages and junk food,[98,99,214] leaded products,[223,224] motor vehicles,[94,225] alcohol,[12,226] electronic gambling,[227] and firearms.[228]

Among, in particular, the public AGW communications of major fossil fuel companies, individualized responsibility framings—and the accompanying narrative of fossil fuel lock-in—have become seemingly ubiquitous.[26,51] The very notion of a personal "carbon footprint," for example, was first popularized in 2004–2006 by oil firm BP as part of its $100+ million per year "beyond petroleum" US media campaign.[229–235] Discourse analysis of this campaign led Doyle[236] to conclude that "BP places responsibility for combatting climate change upon the individual consumer." Smerecnik and Renegar[57] have shown that subsequent BP branding activities similarly "plac[e] participatory emphasis on consumer conservation behavior as opposed to corporate responsibility." This industry framing continues to dominate today.[26,51] In 2019, for instance, BP launched a new "Know your Carbon Footprint" publicity campaign.[237] In 2020, the CEO of Total said that "Change will not come from changing the source of supply. You have to reduce demand."[238] Until 2020, all major oil and gas companies disregarded or disavowed accountability for all Scope 3 greenhouse gas emissions resulting from the use of their products. ExxonMobil Corp, Chevron, and ConocoPhillips continue to do so.[239]

The result is that fossil fuel industry discourse on AGW appears to have encouraged and embodied what Maniates[197] describes as "an accelerating individualization of responsibility" that 'is narrowing, in dangerous ways, our "environmental imagination"' by "ask[ing] that individuals imagine themselves as consumers first and citizens second"[197,26,27,52,58] This depoliticized "capitalistic agency," Smerecnik and Renegar[57] argue, works to "prohibit fundamental social change that would disrupt the fossil fuel industry."[57,59] Experimental evidence appears to support this conclusion. Palm et al.[240], for example, observe that messages framed in terms of individual behavior not only "decreased individuals' willingness to take personal actions" but also "decreased willingness to [take collective action such as to] support pro-climate candidates, reduced belief in the accelerated speed of climate change, and decreased trust in climate scientists." Illustrations of how narratives of individualized responsibility have protected fossil fuel interests from climate action are widespread. One is Yale University's 2014 refusal to divest from fossil fuel companies, which was "predicated on the idea that consumption of fossil fuels, not production, is the root of the climate change problem."[241] Another is the Republican Party's 2020 legislative agenda on AGW, whose premise was that "fossil fuels aren't the enemy. It's emissions."[242,243] A third is that the Paris Agreement "is silent on the topic of fossil fuels."[68]

Summary and conclusion

Available documents show that, during the mid-2000s, ExxonMobil's public AGW communications shifted from explicit doubt (a Scientific Uncertainty frame) to implicit acknowledgment couched in discourses conveying two frames: a Socioeconomic Threat frame, and a Fossil Fuel Savior (FFS) frame. According to the FFS frame:

(1) Everything about AGW is uncertain: a "risk," as contrasted with a reality.
(2) Fossil fuel companies are passive suppliers responding to consumer energy demand.
(3) Continued fossil fuel dominance is (1) inevitable, given the insufficiency of low-carbon technologies; and (2) reasonable and responsible, because fossil fuels lead to

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profound, explicit benefits and only ambiguous, uncertain climate "risk(s)."

(4) Customers are to blame for demanding fossil fuels, whose "risk(s)" were common knowledge. Customers knowingly chose to value the benefits of fossil fuels above their risks.

Ignored and obscured by these perspectives are fossil fuel interests' pervasive marketing, disinformation campaigns, and lobbying against climate and clean energy policies, all of which have served to establish and reinforce infrastructural, institutional, and behavioral carbon lock-ins, thereby undercutting consumer choice and agency.[244,245]

Propaganda tactics of the fossil fuel industry such as these have received less scrutiny than those of their tobacco counterparts. Further attention is needed, because although individualized narratives of risk, responsibility, and the like are less blatant than outright climate science denial, such "discursive grooming" is now pervasive in structuring the agenda of scholars, policymakers, and the public.[59,66,69,197,246]

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and reasonable requests for resources by qualified researchers should be directed to and will be fulfilled by the lead contact, Geoffrey Supran (gjsupran@fas.harvard.edu).

Materials availability

This study did not generate new unique materials.

Data and code availability

Raw data (original PDF internal documents, peer-reviewed publications, and advertorials) for this study cannot be reproduced due to copyright restrictions. However, a catalog of all 180 analyzed documents, and links to public archives containing these data, are provided in S7, supplemental information. Additionally, raw searchable.txt versions of all documents, as well as post-processed flattened text and document term matrices, are deposited on Harvard Dataverse: https://doi.org/10.7910/DVN/XXQUKJ. The datasets and code generated during this study are provided in the same repository. Access will be granted upon reasonable request by qualified researchers.

Corpora

For detailed descriptions of how we previously compiled the 180 ExxonMobil documents analyzed in this study, see Supran and Oreskes.[1,2] For a catalog of all 180 documents, and links to their public archives, see S7, supplemental information. In summary, the 32 internal company documents (1977–2002) were collated from public archives provided by ExxonMobil Corp.,[101] *InsideClimate News*,[102] and Climate Investigations Center.[103] The 72 peer-reviewed publications (1982–2014) were obtained by identifying all peer-reviewed documents among ExxonMobil Corp's lists of Contributed Publications, except for three articles discovered independently during our research. All 72 publications were (co-)authored by at least one ExxonMobil employee.[104] The 76 advertorials (1972–2009) expressing any positions on AGW (real and human caused, serious, or solvable) were identified by manual content analysis of 1,448 ExxonMobil advertorials (1924–2013) collated from PolluterWatch and ProQuest archives.[105,106]

Pre-processing

To enable computational analysis, scanned documents were converted to searchable text files using optical character recognition. Text was stripped of formatting details and punctuation, tokenized, and lowercased (for details, see S1.1, supplemental information). This yielded internal, peer-reviewed, and advertorial corpora comprising 69,802 words, 716,477 words, and 34,141 words (16,121 in Mobil advertorials and 18,020 in ExxonMobil Corp advertorials), respectively.

For divergent term (topic) analysis, we added (substituted) several synthetic tokens that combine: terms of identical cognate form (e.g., "effect" and "effects" became "effect(s)"); and terms judged by the authors to be near-synonyms (e.g., "co2" and "carbon dioxide" became "co2/carbon dioxide"; "countries" and "nations" became "countries/nations")—for all synthetic tokens, see vectorize.R script.[108,247] Document collections were transformed into document-term matrices comprising all: 1- to 5-grams (unique, contiguous word strings of 1–5 tokens in length) for divergent term analysis; and 1-grams for divergent topic analysis.[248]

Divergent term analysis (frequency score and LL ratio)

Internal, peer-reviewed, and advertorial corpora were compared pairwise to identify rhetorical distinctiveness (or divergence) between the terms communicated in each text. (We combine all (Mobil plus ExxonMobil Corp) advertorials before comparing them against internal and peer-reviewed documents from Exxon and Exxon/ExxonMobil Corp, respectively. This simplifies the presentation of results without substantively affecting our findings.) To capture different forms of divergence, we applied two algorithms: frequency score (FS) and Dunning Log-Likelihood (LL) ratio (G^2) score.[108–110] FS and LL are established, complementary tools for word frequency analysis in computational linguistics and digital humanities.[110,249,250]

The FS indicates how often a given term appears in one corpus versus another. The score ranges from 0 (when only corpus A features the term) to 1 (when only corpus B includes the term). To account for the difference in word counts between corpora, we normalized scores by using relative frequencies. For example, a score of 0.8 means that 80% of all normalized instances of a term appear in corpus B. As Risi and Proctor observe, "FSs are useful for identifying taboos: terms generally avoided by one side or the other."[109]

FSs produce immediately interpretable results, yet their reliance on multiplicative ratios—versus additive differences—tends to over-represent rare words.[108] To identify subtle patterns that might otherwise escape notice, we also use the LL (G^2) statistic proposed by Dunning (1993), which is a parametric analysis that primarily identifies "surprising," additively over-represented words, while also giving some weight to multiplication.[108,110,251] Large [G^2] scores indicate terms that have statistically significant relative frequency differences between two corpora. LLs are therefore useful for identifying tropes: terms used disproportionately by one side.

Divergent topic analysis (LDA)

In the field of automated text summarization, divergent terms identified by LL are referred to as "topic signatures."[249,252] In order to identify the topics represented by such terms, and to better understand the roles these terms play in framing each topic, we also examine the documents using topic modeling with LDA.[111] LDA is a computational, unsupervised machine-learning algorithm for discovering hidden thematic structure in collections of texts.[253] *A priori* coding schemes are not supplied. Rather, 'topics' (clusters of words associated with a single theme) emerge inductively based on patterns of co-occurrence of words in a corpus.

We are specifically interested in identifying the topical distinctiveness (or divergence) between document categories. In the main text, we compare topics between (α) all advertorials and (β) combined internal and peer-reviewed documents.

To do so, we first model the distribution of topics over all document categories, by inputting to LDA an aggregated corpus comprising all advertorials, internal documents, and peer-reviewed publications (for details of LDA model selection, topic validation, and labeling, see section S1.2, supplemental information). Once topic-word distributions are obtained, we then take an approach analogous to that for finding divergent terms above, noting that just as LL ratios of term frequencies identify divergent terms, LL ratios of topic weights identify divergent topics. We compute LL ratios of topic weights by constructing document-topic matrices for each of sub-corpora α and β.

Although they are run independently, analyses of divergent terms (by FS and LL) and topics (by LL of LDA) are complementary. The former identifies the distinctive usage of individual n-grams by one corpus versus another. The latter helps contextualize the thematic role that these words together play in communicating and framing topics.

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Frame package analysis

Van Gorp[117] argues that the "strongly abstract nature of frames implies that quantitative research methods should be combined with the interpretative prospects of qualitative methods." To this end, we use the distinctive terms and topics identified using computational techniques to then inform an inductive, qualitative approach to constructing frames as frame packages in advertorials. Van Gorp[117] defines frame packages as an integrated structure of framing devices (manifest textual elements that function as indicators of a frame) and reasoning devices (logical chains of causal reasoning), and proposes Strauss and Corbin's[254] three-step coding scheme for identifying frame packages and assembling them into a so-called "frame matrix."[9,10,17,116-118,254] We adopt this approach.

Open coding

The first step is to compile what Van Gorp[118] calls an "inventory of empirical indicators that may contribute to the readers' interpretation of the text," comprising feasible framing or reasoning devices identified in each document. We used FS, LL, and LDA to systematize this process of locating frames and detecting how they are shaped by lexical composition (for details, see S1.3, supplemental information). We further investigated these discursive constructs by performing collocation searches.[51] The logDice statistic was computed to measure collocational association because it permits meaningful comparison of different sized corpora.[255,256]

Axial coding

The second step is to arrange coded devices along "axes of meaning" by comparing and contrasting open-coding results between documents and then reducing the results to broader meanings or dimensions.[115,118] We do so with reference to an inventory of discourses that we assembled based on a literature review of past studies of AGW communications by fossil fuel interests (see S3, supplemental information).[118]

Selective coding

The last step is to enter axial codes into a "frame matrix" that summarizes the framing and reasoning devices of each frame package.[118]

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.04.014.

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AUTHOR CONTRIBUTIONS

Conceptualization, G.S.; methodology, G.S.; validation, G.S. and N.O.; formal analysis, G.S.; investigation, G.S.; writing – original draft, G.S.; writing – review & editing, G.S. and N.O.; visualization, G.S.; supervision, G.S. and N.O.; funding acquisition, G.S. and N.O.

DECLARATION OF INTERESTS

The authors have received speaking and writing fees (and N.O. has received book royalties) for communicating their research, which includes but is not limited to the topics addressed in this paper. The authors have no other relevant financial ties and declare no competing interests.

INCLUSION AND DIVERSITY

While citing references scientifically relevant for this work, we also actively worked to promote gender balance in our reference list.

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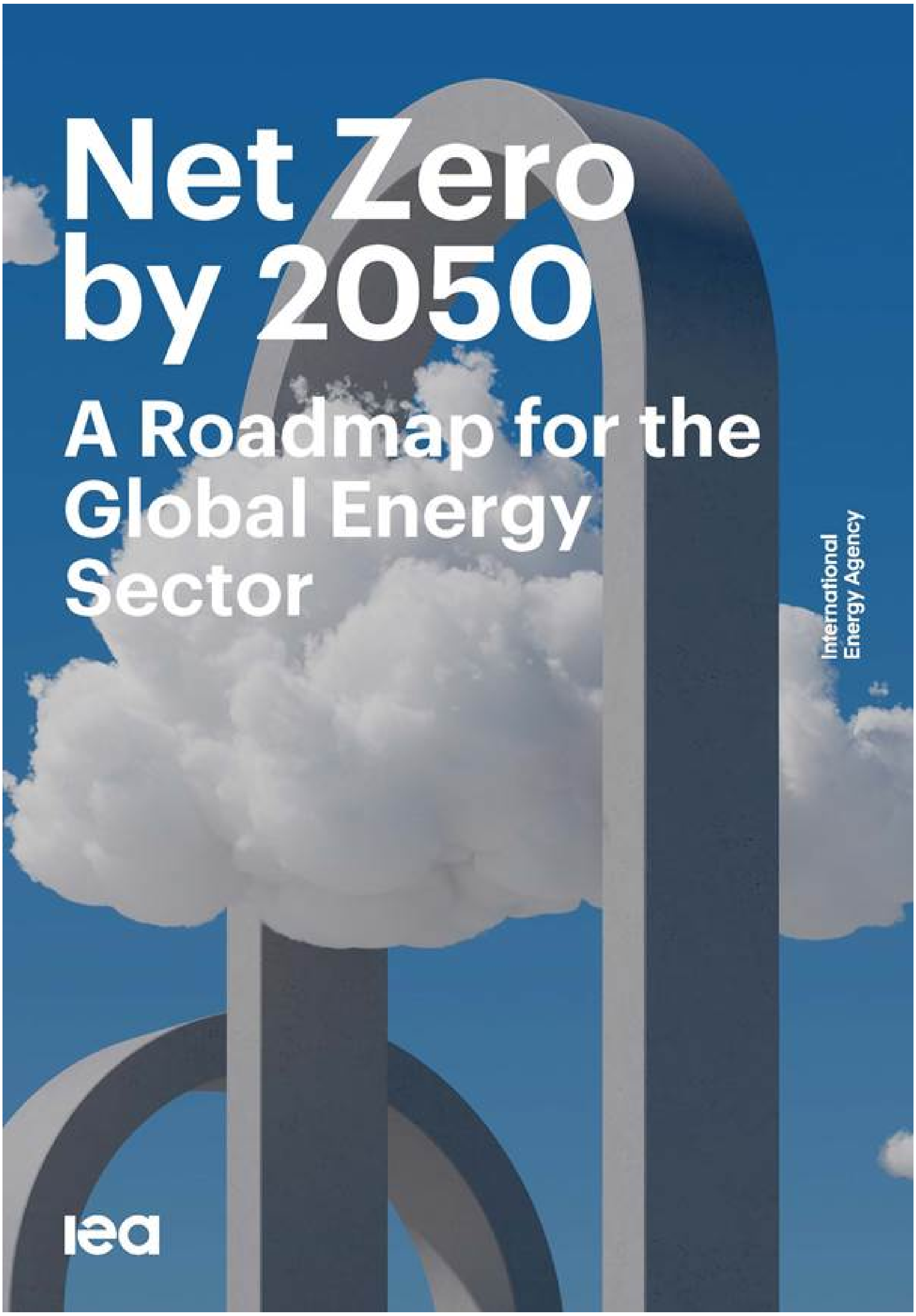
Exhibit 2



Net Zero by 2050

A Roadmap for the Global Energy Sector

International Energy Agency

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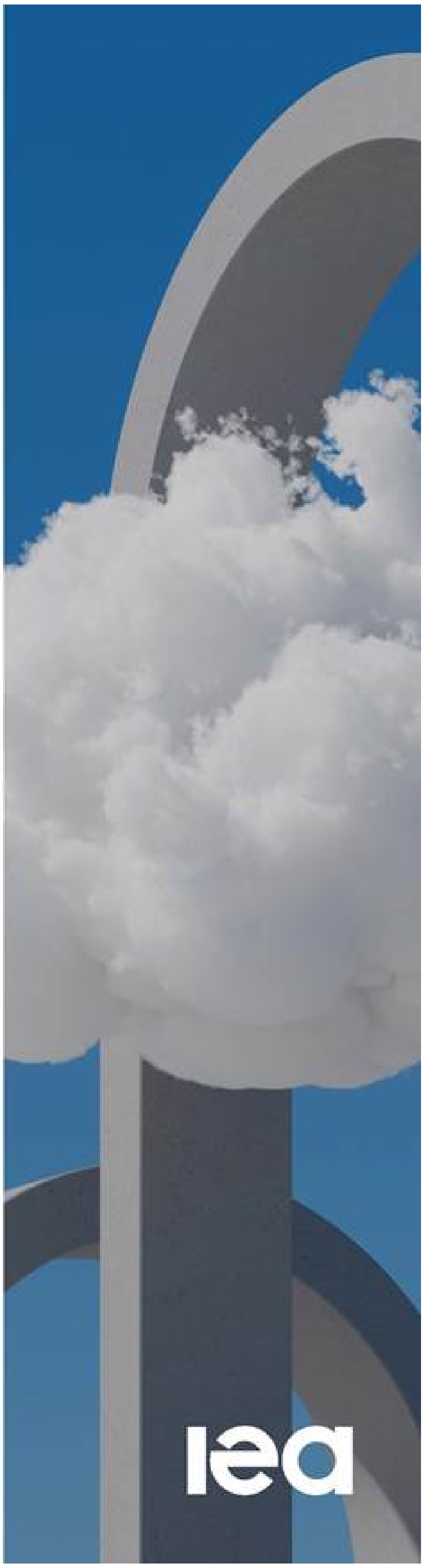

INTERNATIONAL ENERGY AGENCY

The IEA examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 30 member countries, 8 association countries and beyond.

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Foreword

We are approaching a decisive moment for international efforts to tackle the climate crisis – a great challenge of our times. The number of countries that have pledged to reach net-zero emissions by mid-century or soon after continues to grow, but so do global greenhouse gas emissions. This gap between rhetoric and action needs to close if we are to have a fighting chance of reaching net zero by 2050 and limiting the rise in global temperatures to 1.5 °C.

Doing so requires nothing short of a total transformation of the energy systems that underpin our economies. We are in a critical year at the start of a critical decade for these efforts. The 26th Conference of the Parties (COP26) of the United Nations Framework Convention on Climate Change in November is the focal point for strengthening global ambitions and action on climate by building on the foundations of the 2015 Paris Agreement. The International Energy Agency (IEA) has been working hard to support the UK government's COP26 Presidency to help make it the success the world needs. I was delighted to co-host the IEA-COP26 Net Zero Summit with COP26 President Alok Sharma in March, where top energy and climate leaders from more than 40 countries highlighted the global momentum behind clean energy transitions.

The discussions at that event fed into this special report, notably through the Seven Key Principles for Implementing Net Zero that the IEA presented at the Summit, which have been backed by 22 of our member governments to date. This report maps out how the global energy sector can reach net zero by 2050. I believe the report – *Net Zero by 2050: A roadmap for the global energy system* – is one of the most important and challenging undertakings in the IEA's history. The Roadmap is the culmination of the IEA's pioneering work on energy data modelling, combining for the first time the complex models of our two flagship series, the *World Energy Outlook* and *Energy Technology Perspectives*. It will guide the IEA's work and will be an integral part of both those series going forward.

Despite the current gap between rhetoric and reality on emissions, our Roadmap shows that there are still pathways to reach net zero by 2050. The one on which we focus is – in our analysis – the most technically feasible, cost-effective and socially acceptable. Even so, that pathway remains narrow and extremely challenging, requiring all stakeholders – governments, businesses, investors and citizens – to take action this year and every year after so that the goal does not slip out of reach.

This report sets out clear milestones – more than 400 in total, spanning all sectors and technologies – for what needs to happen, and when, to transform the global economy from one dominated by fossil fuels into one powered predominantly by renewable energy like solar and wind. Our pathway requires vast amounts of investment, innovation, skilful policy design and implementation, technology deployment, infrastructure building, international co-operation and efforts across many other areas.

Since the IEA's founding in 1974, one of its core missions has been to promote secure and affordable energy supplies to foster economic growth. This has remained a key concern of our Roadmap, drawing on special analysis carried out with the International Monetary Fund and the International Institute for Applied Systems Analysis. It shows that the enormous challenge of transforming our energy systems is also a huge opportunity for our economies, with the potential to create millions of new jobs and boost economic growth.

Another guiding principle of the Roadmap is that clean energy transitions must be fair and inclusive, leaving nobody behind. We have to ensure that developing economies receive the financing and technological know-how they need to continue building their energy systems to meet the needs of their expanding populations and economies in a sustainable way. It is a moral imperative to bring electricity to the hundreds of millions of people who currently are deprived of access to it, the majority in of them in Africa.

The transition to net zero is for and about people. It is paramount to remain aware that not every worker in the fossil fuel industry can ease into a clean energy job, so governments need to promote training and devote resources to facilitating new opportunities. Citizens must be active participants in the entire process, making them feel part of the transition and not simply subject to it. These themes are among those being explored by the Global Commission on People-Centred Clean Energy Transitions, which I convened at the start of 2021 to examine how to enable citizens to benefit from the opportunities and navigate the disruptions of the shift to a clean energy economy. Headed by Prime Minister Mette Frederiksen of Denmark and composed of government leaders, ministers and prominent thinkers, the Global Commission will make public its key recommendations ahead of COP26 in November.

The pathway laid out in our Roadmap is global in scope, but each country will need to design its own strategy, taking into account its specific circumstances. There is no one-size-fits-all approach to clean energy transitions. Plans need to reflect countries' differing stages of economic development: in our pathway, advanced economies reach net zero before developing economies do. As the world's leading energy authority, the IEA stands ready to provide governments with support and advice as they design and implement their own roadmaps, and to encourage the international co-operation across sectors that is so essential to reaching net zero by 2050.

This landmark report would not have been possible without the extraordinary dedication of the IEA colleagues who have worked so tirelessly and rigorously on it. I would like to thank the entire team under the outstanding leadership of my colleagues Laura Cozzi and Timur Gül.

The world has a huge challenge ahead of it to move net zero by 2050 from a narrow possibility to a practical reality. Global carbon dioxide emissions are already rebounding sharply as economies recover from last year's pandemic-induced shock. It is past time for governments to act, and act decisively to accelerate the clean energy transformation.

As this report shows, we at the IEA are fully committed to leading those efforts.

Dr Fatih Birol
Executive Director
International Energy Agency

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Summary for policy makers

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

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

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

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

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

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

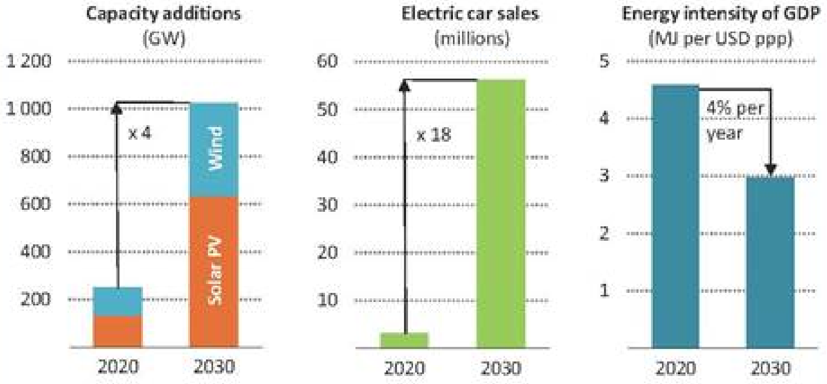
PRIORITY ACTION

Make the 2020s the decade of massive clean energy expansion

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

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

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



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

Net zero by 2050 requires huge leaps in clean energy innovation

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

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

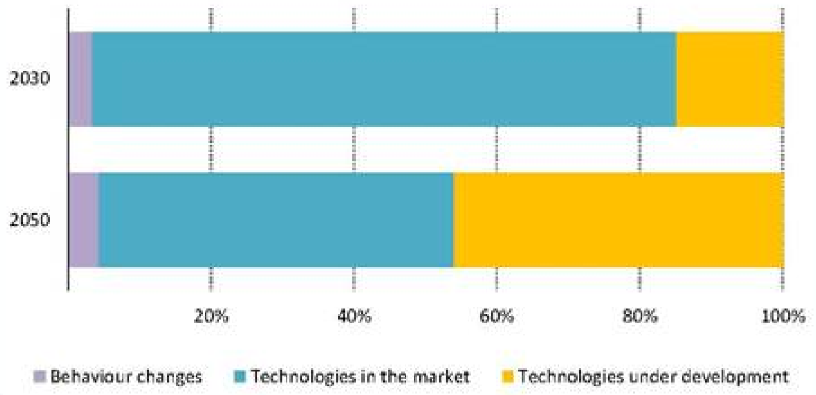
PRIORITY ACTION

Prepare for the next phase of the transition by boosting innovation

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

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

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



The transition to net zero is for and about people

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

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

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

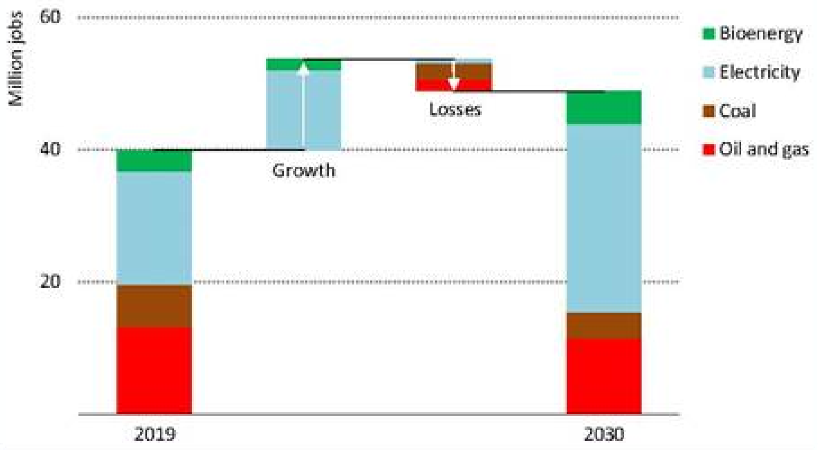
PRIORITY ACTION

Clean energy jobs will grow strongly but must be spread widely

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

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

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



An energy sector dominated by renewables

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

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

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

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

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

PRIORITY ACTION

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

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

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

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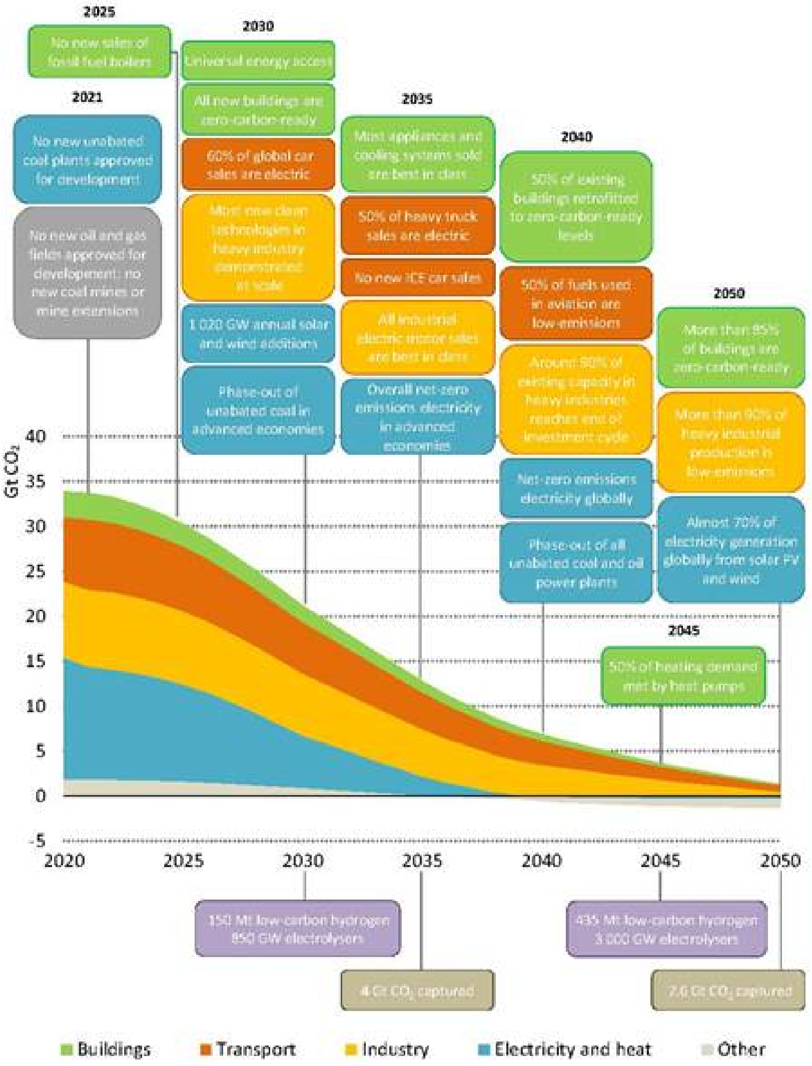
[1] A zero-carbon-ready building is highly energy efficient and either uses renewable energy directly or uses an energy supply that will be fully decarbonised by 2050, such as electricity or district heat.

Key milestones in the pathway to net zero



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

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

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

PRIORITY ACTION

Drive a historic surge in clean energy investment

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

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

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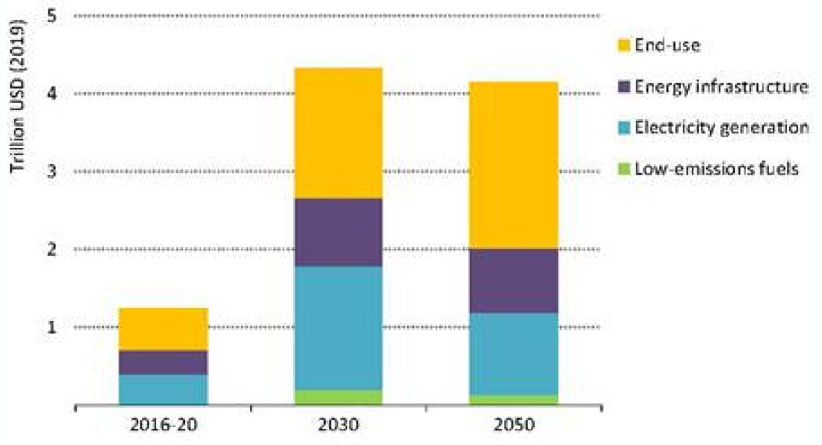
[2] Battery gigafactory capacity assumption = 35 gigawatt-hours per year.

Clean energy investment in the net zero pathway



An unparalleled clean energy investment boom lifts global economic growth

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

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

New energy security concerns emerge, and old ones remain

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

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

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

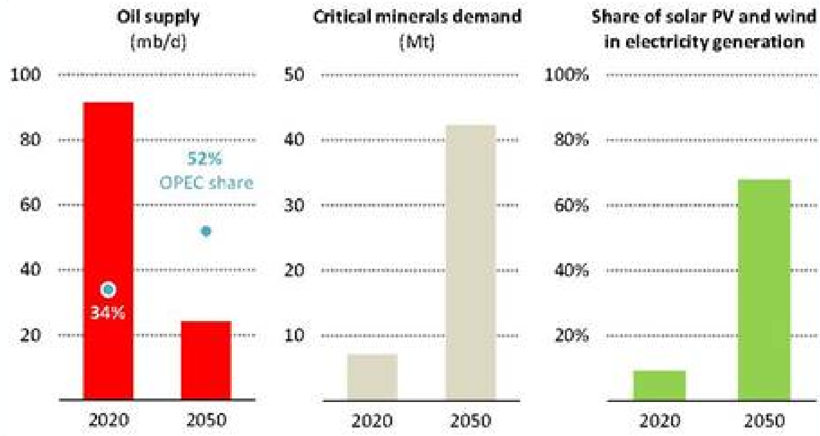
PRIORITY ACTION

Address emerging energy security risks now

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

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

Global energy security indicators in the net zero pathway



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

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

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

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

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

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

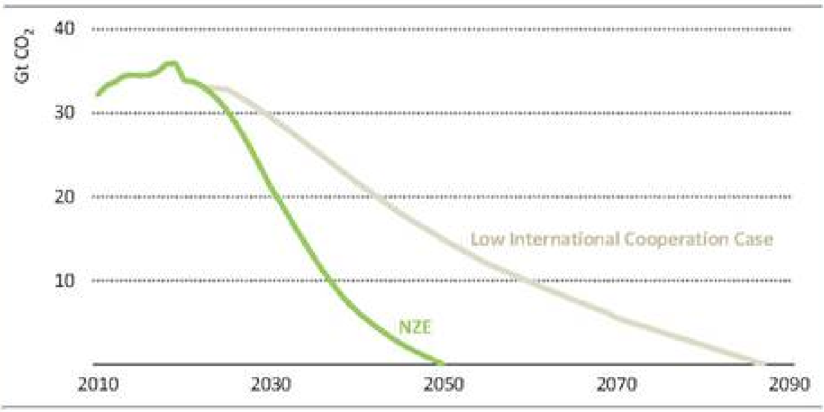
PRIORITY ACTION

Take international co-operation to new heights

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

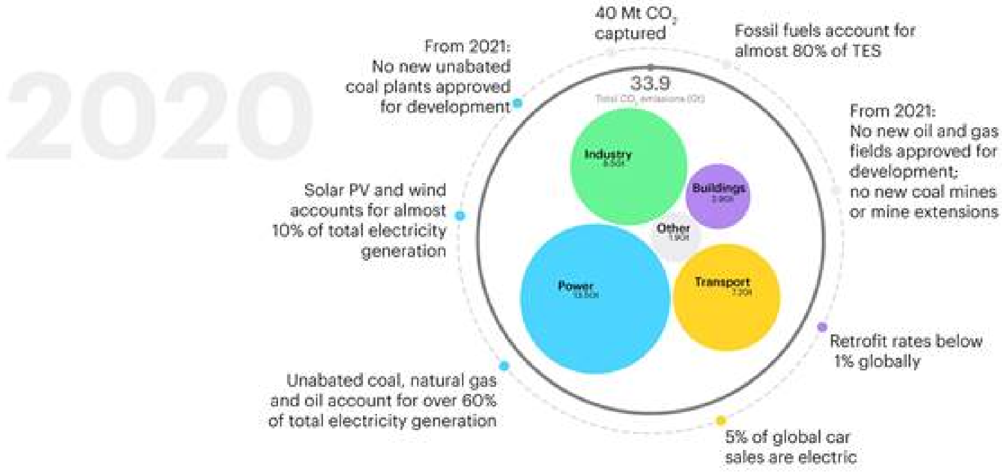
Governments must work together in an effective and mutually beneficial manner to implement coherent measures that cross borders. This includes carefully managing domestic job creation and local commercial advantages with the collective global need for clean energy technology deployment. Accelerating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

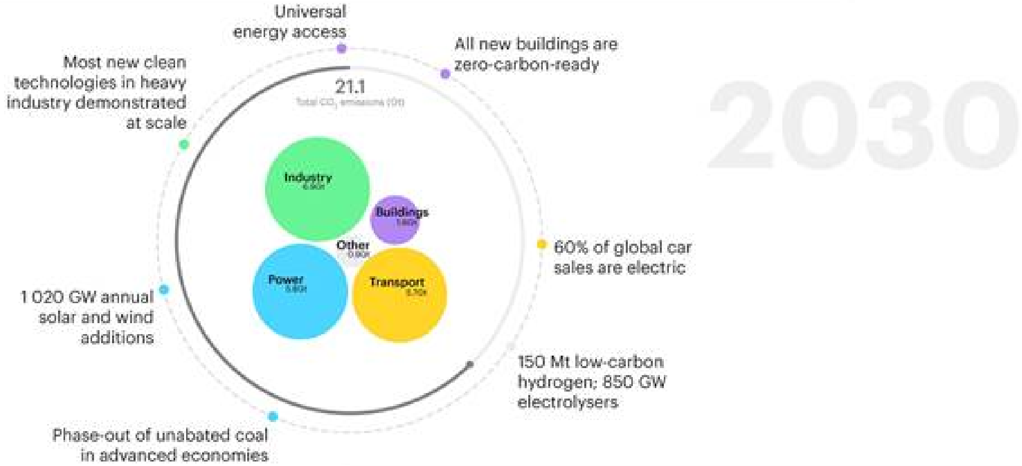
Global energy-related CO_2 emissions in the net zero pathway and Low International Co-operation Case

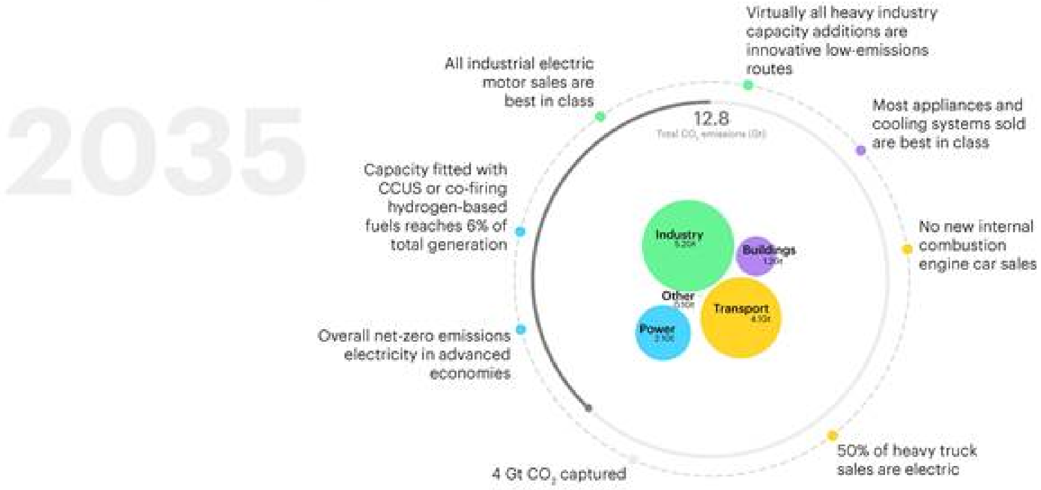


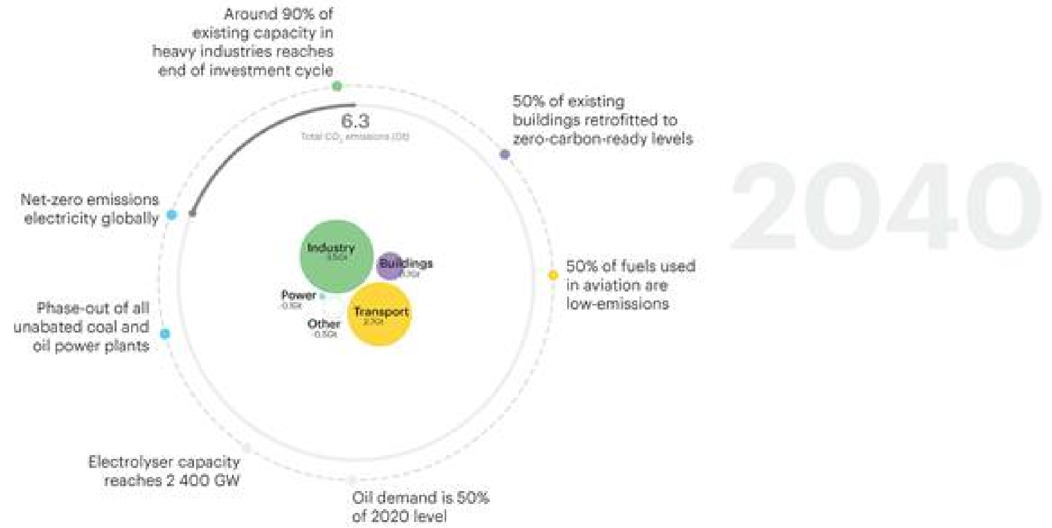
Note: Gt = gigatonnes.

Net Zero Emissions by 2050 Interactive iea.li/nzeroadmap









2040

Around 90% of existing capacity in heavy industries reaches end of investment cycle

50% of existing buildings retrofitted to zero-carbon-ready levels

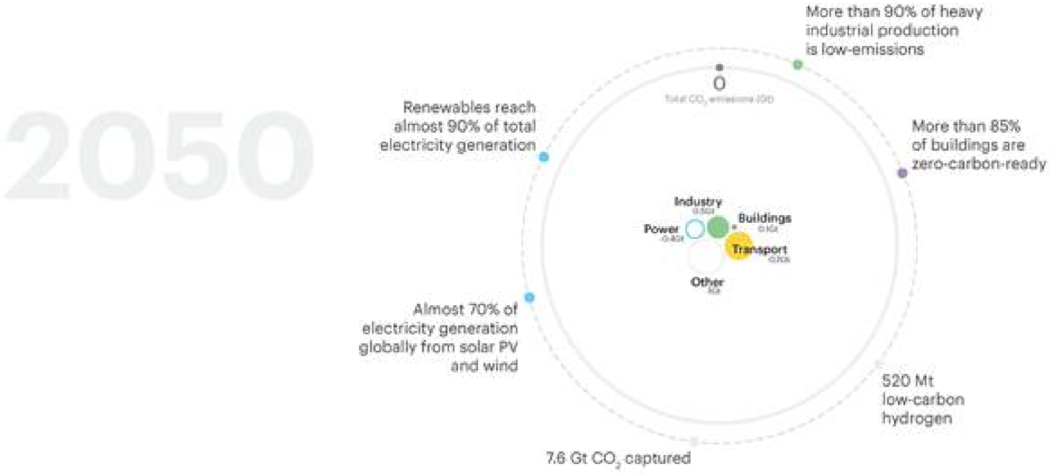
Net-zero emissions electricity globally

50% of fuels used in aviation are low-emissions

Phase-out of all unabated coal and oil power plants

Electrolyser capacity reaches 2 400 GW

Oil demand is 50% of 2020 level



2050

More than 90% of heavy industrial production is low-emissions

Renewables reach almost 90% of total electricity generation

More than 85% of buildings are zero-carbon-ready

Almost 70% of electricity generation globally from solar PV and wind

520 Mt low-carbon hydrogen

7.6 Gt CO_2 captured

Net Zero Emissions by 2050 Interactive iea.li/nzeroadmap

Announced net zero pledges and the energy sector

SUMMARY

- There has been a rapid increase over the last year in the number of governments pledging to reduce greenhouse gas emissions to net zero. Net zero pledges to date cover around 70% of global GDP and CO_2 emissions. However, fewer than a quarter of announced net zero pledges are fixed in domestic legislation and few are yet underpinned by specific measures or policies to deliver them in full and on time.
- The Stated Policies Scenario (STEPS) takes account only of specific policies that are in place or have been announced by governments. Annual energy-related and industrial process CO_2 emissions rise from 34 Gt in 2020 to 36 Gt in 2030 and remain around this level until 2050. If emissions continue on this trajectory, with similar changes in non-energy-related GHG emissions, this would lead to a temperature rise of around 2.7 °C by 2100 (with a 50% probability). Renewables provide almost 55% of global electricity generation in 2050 (up from 29% in 2020), but clean energy transitions lag in other sectors. Global coal use falls by 15% between 2020 and 2050; oil use in 2050 is 15% higher than in 2020; and natural gas use is almost 50% higher.
- The Announced Pledges Case (APC) assumes that all announced national net zero pledges are achieved in full and on time, whether or not they are currently underpinned by specific policies. Global energy-related and industrial process CO_2 emissions fall to 30 Gt in 2030 and 22 Gt in 2050. Extending this trajectory, with similar action on non-energy-related GHG emissions, would lead to a temperature rise in 2100 of around 2.1 °C (with a 50% probability). Global electricity generation nearly doubles to exceed 50 000 TWh in 2050. The share of renewables in electricity generation rises to nearly 70% in 2050. Oil demand does not return to its 2019 peak and falls about 10% from 2020 to 80 mb/d in 2050. Coal use drops by 50% to 2 600 Mtce in 2050, while natural gas use expands by 10% to 4 350 bcm in 2025 and remains about that level to 2050.
- Efficiency, electrification and the replacement of coal by low-emissions sources in electricity generation play a central role in achieving net zero goals in the APC, especially over the period to 2030. The relative contributions of nuclear, hydrogen, bioenergy and CCUS vary across countries, depending on their circumstances.
- The divergence in trends between the APC and the STEPS shows the difference that current net zero pledges could make, while underlining at the same time the need for concrete policies and short-term plans that are consistent with long-term net zero pledges. However, the APC also starkly highlights that existing net zero pledges, even if delivered in full, fall well short of what is necessary to reach global net-zero emissions by 2050.

1.1 Introduction

November 2021 will see the most important UN Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP 26) since the Paris Agreement was signed in 2015. As COP 26 approaches, an increasing number of countries have announced long-term goals to achieve net-zero greenhouse gas (GHG) emissions over the coming decades. On 31 March 2021, the International Energy Agency (IEA) hosted a Net Zero Summit to take stock of the growing list of commitments from countries and companies to reach the goals of the Paris Agreement, and to focus on the actions necessary to start turning those net zero goals into reality.

Achieving those goals will be demanding. The Covid-19 pandemic delivered a major shock to the world economy, resulting in an unprecedented 5.8% decline in CO_2 emissions in 2020. However, our monthly data show that global energy-related CO_2 emissions started to climb again in December 2020, and we estimate that they will rebound to around 33 gigatonnes of carbon dioxide (Gt CO_2) in 2021, only 1.2% below the level in 2019 (IEA, 2021). Sustainable economic recovery packages offered a unique opportunity to make 2019 the definitive peak in global emissions, but the evidence so far points to a rebound in emissions in parallel with renewed economic growth, at least in the near term (IEA, 2020a).

Recent IEA analyses examined the technologies and policies needed for countries and regions to achieve net-zero emissions energy systems. The *World Energy Outlook 2020* examined what would be needed over the period to 2030 to put the world on a path towards net-zero emissions by 2050 in the context of the pandemic-related economic recovery (IEA, 2020b). The Faster Innovation Case in *Energy Technology Perspectives 2020* explored whether net-zero emissions could be achieved globally by 2050 through accelerated energy technology development and deployment alone: it showed that, relative to baseline trends, almost half of the emissions savings needed in 2050 to reach net-zero emissions rely on technologies that are not yet commercially available (IEA, 2020c).

This special report, prepared at the request of the UK President of the COP 26, incorporates the insights and lessons learned from both reports to create a comprehensive and detailed pathway, or roadmap, to achieve net-zero energy-related and industrial process CO_2 emissions globally by 2050. It assesses the costs of achieving this goal, the likely impacts on employment and the economy, and the wider implications for the world. It also highlights the key milestones for technologies, infrastructure, investment and policy that are needed along the road to 2050.

This report is set out in four chapters:

- **Chapter 1** explores the outlook for global CO_2 emissions and energy supply and use based on existing policies and pledges. It sets out projections of global energy use and emissions based on the **Stated Policies Scenario (STEPS)**, which includes only the firm policies that are in place or have been announced by countries, including Nationally

Determined Contributions. It also examines the **Announced Pledges Case (APC)**, a variant of the STEPS that assumes that all of the net zero targets announced by countries around the world to date are met in full.

- **Chapter 2** presents the **Net-Zero Emissions by 2050 Scenario (NZE)**, which describes how energy demand and the energy mix will need to evolve if the world is to achieve net-zero emissions by 2050. It also assesses the corresponding investment needs and explores key uncertainties surrounding technology and consumer behaviour.
- **Chapter 3** examines the implications of the NZE for various sectors, covering fossil fuel supply, the supply of low-emissions fuels (such as hydrogen, ammonia, biofuels, synthetic fuels and biomethane) and the electricity, transport, industry and buildings sectors. It highlights the key changes required to achieve net-zero emissions in the NZE and the major milestones that are needed along the way.
- **Chapter 4** explores the implications of the NZE for the economy, the energy industry, citizens and governments.

1.2 Emissions reduction targets and net zero pledges

1.2.1 Nationally Determined Contributions

Under the Paris Agreement, Parties[1] are required to submit Nationally Determined Contributions (NDCs) to the UNFCCC and to implement policies with the aim of achieving their stated objectives. The process is dynamic; it requires Parties to update their NDCs every five years in a progressive manner to reflect the highest possible ambition. The first round of NDCs, submitted by 191 countries, covers more than 90% of global energy-related and industrial process CO_2 emissions.[2] The first NDCs included some targets that were unconditional and others that were conditional on international support for finance, technology and other means of implementation.

As of 23 April 2021, 80 countries have submitted new or updated NDCs to the UNFCCC, covering just over 40% of global CO_2 emissions (Figure 1.1).[3] Many of the updated NDCs include more stringent targets than in the initial round of NDCs, or targets for a larger number of sectors or for a broader coverage of GHGs. In addition, 27 countries and the European Union have communicated long-term low GHG emissions development strategies to the UNFCCC, as requested by the Paris Agreement. Some of these strategies incorporate a net zero pledge.

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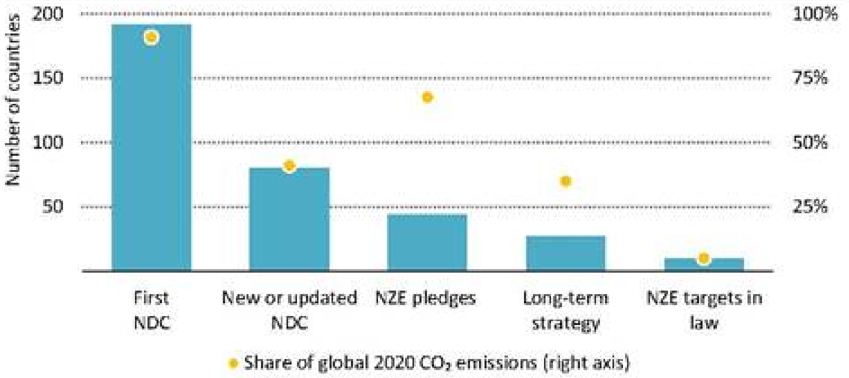
[1] Parties refers to the 197 members of the UNFCCC which includes all United Nations member states, United Nations General Assembly Observer State of Palestine, UN non-member states Niue and the Cook Islands and the European Union.

[2] Unless otherwise stated, CO_2 emissions in this report refer to energy-related and industrial process CO_2 emissions.

[3] Several countries have indicated that they intend to submit new or updated NDCs later in 2021 or in 2022.

Figure 1.1 ▷ Number of countries with NDCs, long-term strategies and net zero pledges, and their shares of 2020 global CO_2 emissions



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Around 40% of countries that have ratified the Paris Agreement have updated their NDCs, but net zero pledges cover around 70% of global CO_2 emissions

1.2.2 Net-zero emissions pledges

There has been a rapid increase in the number of governments making pledges to reduce GHG emissions to net zero (Figure 1.2). In the Paris Agreement, countries agreed to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second-half of the century". The Intergovernmental Panel on Climate Change (IPCC) *Special Report on Global Warming of 1.5 °C* highlighted the importance of reaching net-zero CO_2 emissions globally by mid-century or sooner to avoid the worst impacts of climate change (IPCC, 2018).

Net-zero emissions pledges have been announced by national governments, subnational jurisdictions, coalitions[4] and a large number of corporate entities (see Spotlight). As of 23 April 2021, 44 countries and the European Union have pledged to meet a net-zero emissions target: in total they account for around 70% of global CO_2 emissions and GDP (Figure 1.3). Of these, ten countries have made meeting their net zero target a legal obligation, eight are proposing to make it a legal obligation, and the remainder have made their pledges in official policy documents.

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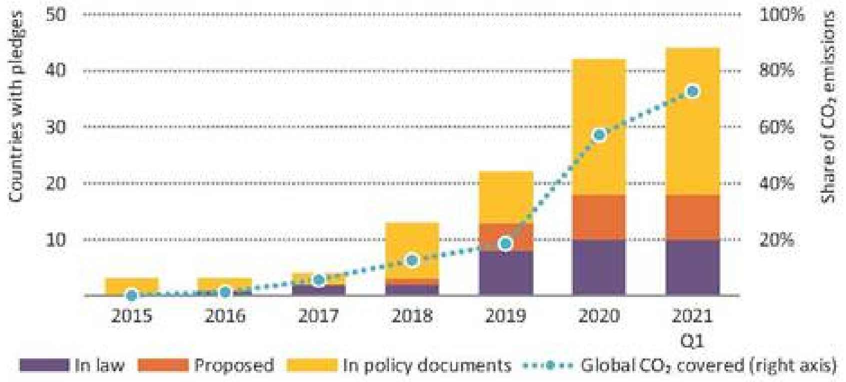
[4] Examples include: the UN-led Climate Ambition Alliance in which signatories signal they are working towards achieving net-zero emissions by 2050; and the Carbon Neutrality Coalition launched at the UN Climate Summit in 2017, in which signatories commit to develop long-term low GHG emissions strategies in line with limiting temperature rises to 1.5 °C.

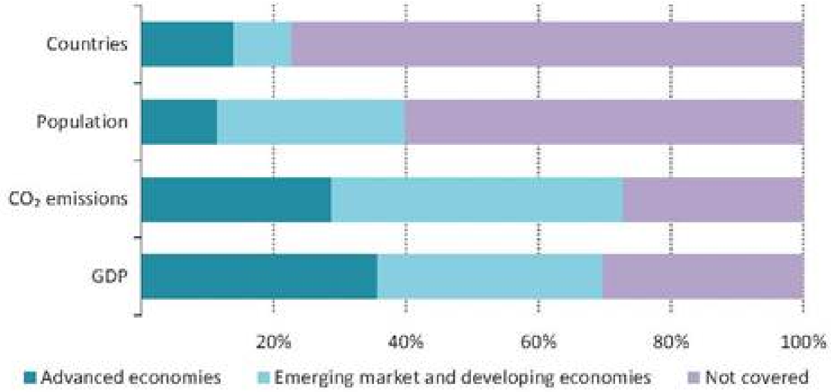
Figure 1.2 ▷ Number of national net zero pledges and share of global CO_2 emissions covered



There has been a significant acceleration in net-zero emissions pledges announced by governments, with an increasing number enshrined in law

Notes: In law = a net zero pledge has been approved by parliament and is legally binding. Proposed = a net zero pledge has been proposed to parliament to be voted into law. In policy document = a net zero pledge has been proposed but does not have legally binding status.

Figure 1.3 ▷ Coverage of announced national net zero pledges



Countries accounting for around 70% of global CO_2 emissions and GDP have set net zero pledges in law, or proposed legislation or in an official policy document

Note: GDP = gross domestic product at purchasing power parity.

In contrast to some of the shorter term commitments contained within NDCs, few net zero pledges are supported by detailed policies and firm routes to implementation. Net-zero emissions pledges also vary considerably in their timescale and scope. Some key differences include:

- **GHG coverage.** Most pledges cover all GHG emissions, but some include exemptions or different rules for certain types of emissions. For example, New Zealand's net zero pledge covers all GHGs except biogenic methane, which has a separate reduction target.
- **Sectoral boundaries.** Some pledges exclude emissions from specific sectors or activities. For example, the Netherlands aims to achieve net-zero GHG emissions only in its electricity sector (as part of an overall aim to reduce total GHG emissions by 95%), and some countries, including France, Portugal and Sweden, exclude international aviation and shipping.
- **Use of carbon dioxide removal (CDR).** Pledges take varying approaches to account for CDR within a country's sovereign territory. CDR options include natural CO_2 sinks, such as forests and soils, as well as technological solutions, such as direct air capture or bioenergy with carbon capture and storage. For example, Uruguay has stated that natural CO_2 sinks will be used to help it reach net-zero emissions, while Switzerland plans to use CDR technologies to balance a part of its residual emissions in 2050.
- **Use of international mitigation transfers.** Some pledges allow GHG mitigation that occurs outside a country's borders to be counted towards the net zero target, such as through the transfer of carbon credits, while others do not. For example, Norway allows the potential use of international transfers, while France explicitly rules them out. Some countries, such as Sweden, allow such transfers but specify an upper limit to their use.
- **Timeframe.** The majority of pledges, covering 35% of global CO_2 emissions in 2020, target net-zero emissions by 2050, but Finland aims to reach that goal by 2035, Austria and Iceland by 2040 and Sweden by 2045. Among others, the People's Republic of China (hereafter China) and Ukraine have set a target date after 2050.

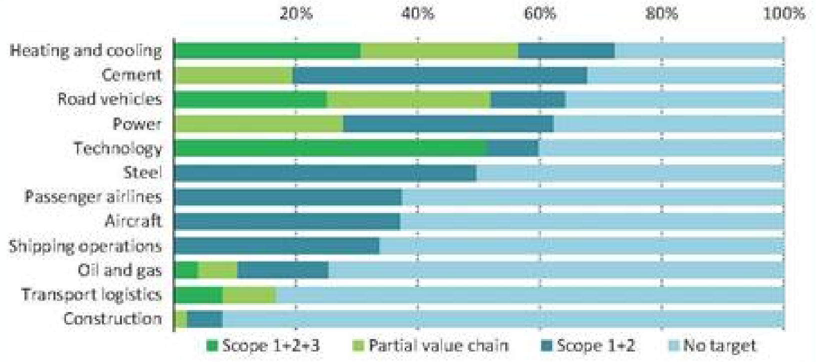
SPOTLIGHT

How are businesses responding to the need to reach net-zero emissions?

There has been a rapid rise in net-zero emissions announcements from companies in recent years: as of February 2021, around 110 companies that consume large amounts of energy directly or produce energy-consuming goods have announced net-zero emissions goals or targets.

Around 60-70% of global production of heating and cooling equipment, road vehicles, electricity and cement is from companies that have announced net-zero emissions targets (Figure 1.4). Nearly 60% of gross revenue in the technology sector is also generated by companies with net-zero emission targets. In other sectors, net zero pledges cover 30-40% of air and shipping operations, 15% of transport logistics and 10% of construction. All these shares are likely to keep growing as more companies make pledges.

Figure 1.4 ▷ **Sectoral activity of large energy-related companies with announced pledges to reach net-zero emissions by 2050**



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Some sectors are more advanced in terms of the extent of net zero targets by companies active in the sector

Notes: Scope 1 = direct emissions from energy and other sources owned or controlled. Scope 2 = indirect emissions from the production of electricity and heat, and fuels purchased and used. Scope 3 = indirect emissions from sources not owned or directly controlled but related to their activities (such as employee travel, extraction, transport and production of purchased materials and fuels, and end-use of fuels, products and services). Partial value chain includes Scope 1 and 2 emissions and Scope 3 emissions in specific geographic locations or sections of a company's value chain.

Source: IEA analysis based on company reports from the largest 10-25 companies within each sector.

Company pledges may not be readily comparable. Most companies account for emissions and set net zero pledges based on the GHG Protocol (WRI, WBCSD, 2004), but the coverage and timeframe of these pledges varies widely. Some cover only their own emissions, for example by shifting to the use of zero-emissions electricity in offices and production facilities, and by eliminating the use of oil in transport or industrial operations, e.g. FedEx, ArcelorMittal and Maersk. Others also cover wider emissions from certain parts of their values chains, e.g. Renault in Europe, or all indirect emissions related to their activities, e.g. Daikin, Toyota, Shell, Eni and Heidelberg. Around 60% of pledges aim to achieve net-zero emissions by 2050, but several companies have set an earlier deadline of 2030 or 2040.

Around 40% of companies that have announced net zero pledges have yet to set out how they aim to achieve them. For those with detailed plans, the main options include direct emissions reductions, use of CO_2 removal technologies, such as afforestation, bioenergy with carbon capture, utilisation and storage (CCUS), or direct air capture with CO_2 storage, and purchasing emissions (credits generated through emissions reductions that occur elsewhere). The use of offsets could be a cost-effective mechanism to eliminate emissions from parts of value chains where emissions reductions are most challenging, provided that schemes to generate emissions credits result in permanent, additional and verified emissions reductions. However, there is likely to be a limited supply of emissions credits consistent with net-zero emissions globally and the use of such credits could divert investment from options that enable direct emissions reductions.

1.3 Outlook for emissions and energy in the STEPS

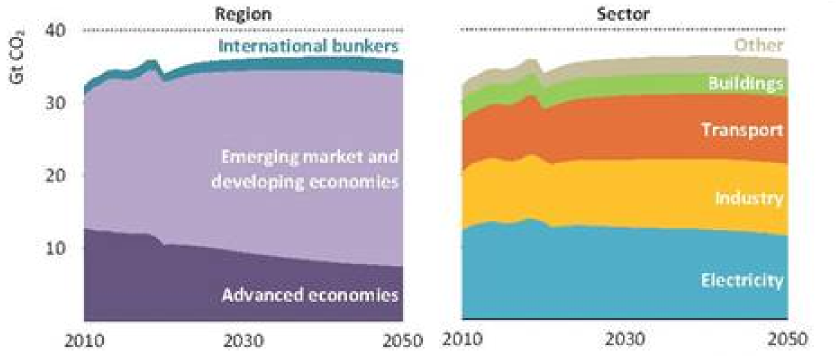
The IEA Stated Policies Scenario (STEPS) illustrates the consequences of existing and stated policies for the energy sector. It draws on the latest information regarding national energy and climate plans and the policies that underpin them. It takes account of all policies that are backed by robust implementing legislation or regulatory measures, including the NDCs that countries have put forward under the Paris Agreement up to September 2020 and the energy components of announced economic stimulus and recovery packages. So far, few net-zero emissions pledges have been backed up by detailed policies, implementation plans or interim targets: most net zero pledges therefore are not included in the STEPS.

1.3.1 CO_2 emissions

Global CO_2 emissions in the STEPS bring about only a marginal overall improvement in recent trends. Switching to renewables leads to an early peak in emissions in the electricity sector, but reductions across all sectors fall far short of what is required for net-zero emissions in 2050. Annual CO_2 emissions rebound quickly from the dip caused by the Covid-19 pandemic in 2020: they increase from 34 Gt in 2020 to 36 Gt in 2030 and then remain around this level until 2050 (Figure 1.5). If emissions trends were to continue along the same trajectory after 2050, and with commensurate changes in other sources of GHG emissions, the global average surface temperature rise would be around 2.7 °C in 2100 (with a 50% probability).

There is strong divergence between the outlook for emissions in advanced economies on one hand and the emerging market and developing economies on the other. In advanced economies, despite a small rebound in the early 2020s, CO_2 emissions decline by about a third between 2020 and 2050, thanks to the impact of policies and technological progress in reducing energy demand and switching to cleaner fuels. In emerging market and developing economies, energy demand continues to grow strongly because of increased population, brisk economic growth, urbanisation and the expansion of infrastructure: these effects outweigh improvements in energy efficiency and the deployment of clean technologies, causing CO_2 emissions to grow by almost 20% by the mid-2040s, before declining marginally to 2050.

Figure 1.5 ▷ Energy-related and industrial process CO_2 emissions by region and sector in the STEPS



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Global CO_2 emissions rebound quickly after 2020 and then plateau, with declines in advanced economies offset by increases elsewhere

Note: Other = agriculture and own use in the energy sector.

1.3.2 Total energy supply, total final consumption and electricity generation

The projected trends in CO_2 emissions in the STEPS result from changes in the amount of energy used and the mix of fuels and technologies. Total energy supply (TES)[5] worldwide rises by just over 30% between 2020 and 2050 in the STEPS (Figure 1.6). Without a projected annual average reduction of 2.2% in energy intensity, i.e. energy use per unit of GDP, TES in 2050 would be around 85% higher. In advanced economies, energy use falls by around 5% to 2050, despite a 75% increase in economic activity over the period. In emerging market and developing economies, energy use increases by 50% to 2050, reflecting a tripling of economic output between 2020 and 2050. Despite the increase in GDP and energy use in emerging market and developing economies, 750 million people still have no access to electricity in 2050, more than 95% of them in sub-Saharan Africa, and 1.5 billion people continue to rely on the traditional use of bioenergy for cooking.

The global fuel mix changes significantly between 2020 and 2050. Coal use, which peaked in 2014, falls by around 15%. Having fallen sharply in 2020 due to the pandemic, oil demand rebounds quickly, returning to the 2019 level of 98 million barrels per day (mb/d) by 2023 and reaching a plateau of around 104 mb/d shortly after 2030. Natural gas demand increases from 3 900 billion cubic metres (bcm) in 2020 to 4 600 bcm in 2030 and 5 700 bcm in 2050. Nuclear energy grows by 15% between 2020 and 2030, mainly reflecting expansions in China.

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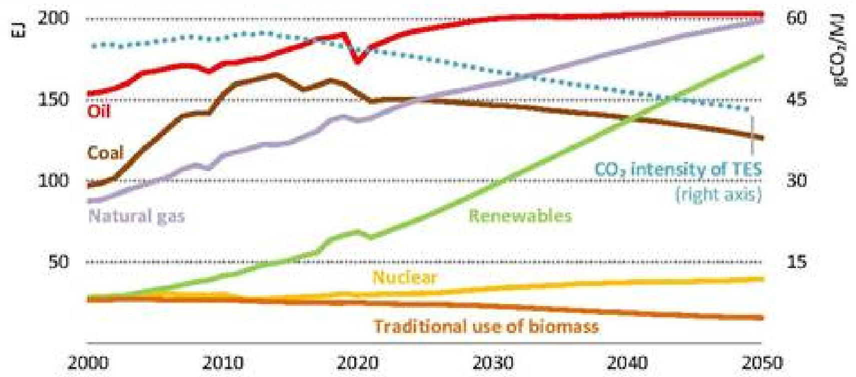
[5] Total primary energy supply (or total primary energy demand) has been renamed total energy supply in accordance with the International Recommendations for Energy Statistics (IEA, 2020d).

Figure 1.6 ▷ Total energy supply and CO_2 emissions intensity in the STEPS



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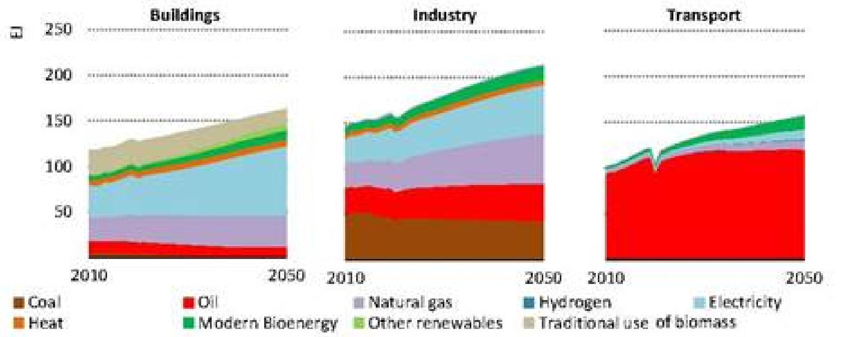
Coal use declines, oil plateaus and renewables and natural gas grow substantially to 2050

Note: EJ = exajoule; MJ = megajoule; TES = total energy supply.

Total final consumption increases in all sectors in the STEPS, led by electricity and natural gas (Figure 1.7). All the growth is in emerging market and developing economies. The biggest change in energy use is in the electricity sector (Figure 1.8). Global electricity demand increases by 80% between 2020 and 2050, around double the overall rate of growth in final energy consumption. More than 85% of the growth in global electricity demand comes from emerging market and developing economies. Coal continues to play an important role in electricity generation in those economies to 2050, despite strong growth in renewables: in advanced economies, the use of coal for electricity generation drops sharply.

Figure 1.7 ▷ Total final consumption by sector and fuel in the STEPS



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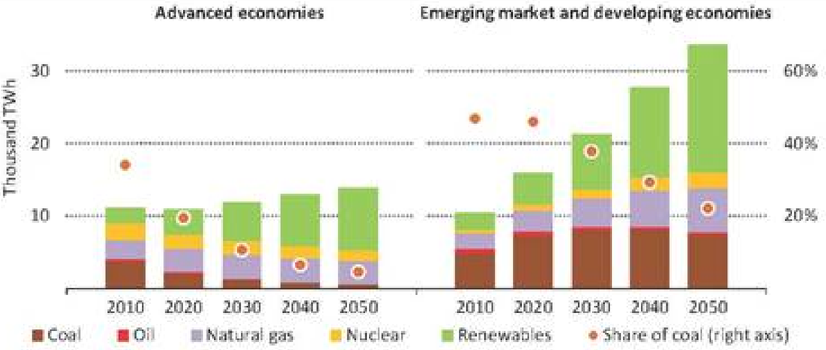
Final energy consumption grows on average by 1% per year between 2020 and 2050, with electricity and natural gas meeting most of the increase

Figure 1.8 ▷ Electricity generation by fuel and share of coal in the STEPS



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Emerging market and developing economies drive most of the increase in global electricity demand, met mainly by renewables and gas, though coal remains important

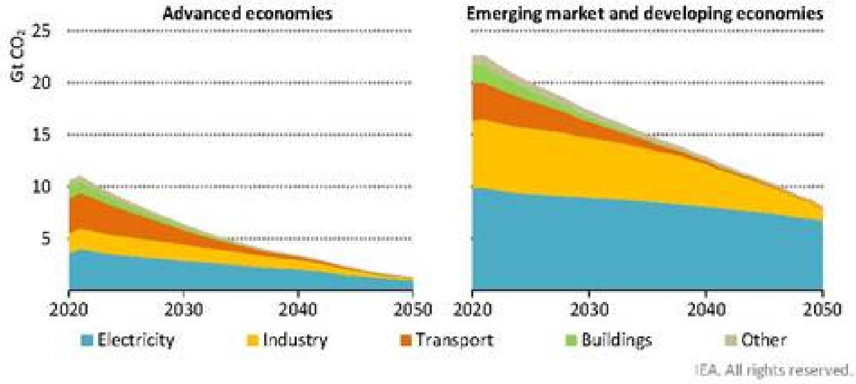
1.3.3 Emissions from existing assets

The energy sector contains a large number of long-lived and capital-intensive assets. Urban infrastructure, pipelines, refineries, coal-fired power plants, heavy industrial facilities, buildings and large hydro power plants can have technical and economic lifetimes of well over 50 years. If today's energy infrastructure was to be operated until the end of the typical lifetime in a manner similar to the past, we estimate that this would lead to cumulative energy-related and industrial process CO_2 emissions between 2020 and 2050 of just under 650 Gt CO_2. This is around 30% more than the remaining total CO_2 budget consistent with limiting global warming to 1.5 °C with a 50% probability (see Chapter 2).

The electricity sector accounts for more than 50% of the total emissions that would come from existing assets; 40% of total emissions would come from coal-fired power plants alone. Industry is the next largest sector, with steel, cement, chemicals and other industry accounting for around 30% total emissions from existing assets. The long lifetime of production facilities in these sub-sectors (typically 30-40 years for a blast furnace or cement kiln) and the relatively young age of the global capital stock explain their large contribution. Transport accounts for just over 10% of emissions from existing assets and the buildings sector accounts for just under 5%. The lifetime of vehicles and equipment in the transport and buildings sectors is generally much shorter than is the case in electricity and industry – passenger cars, for example, are generally assumed to have a lifetime of around 17 years – but associated infrastructure networks such as roads, electricity networks and gas grids have very long lifetimes.

There are some large regional differences in emissions levels from existing assets (Figure 1.9). Advanced economies tend to have much older capital stocks than emerging market and developing economies, particularly in the electricity sector, and existing assets will reach the end of their lifetimes earlier. For example, the average age of coal-fired power plants in China is 13 years and 16 years in the rest of Asia, compared to around 35 years in Europe and 40 years in the United States (IEA, 2020e).

Figure 1.9 ▷ Emissions from existing infrastructure by sector and region



Emerging market and developing economies account for three-quarters of cumulative emissions from existing infrastructure through to 2050

1.4 Announced Pledges Case

The Announced Pledges Case (APC) assumes that all national net-zero emissions pledges are realised in full and on time. It therefore goes beyond the policy commitments incorporated in the STEPS. The aim of the APC is to see how far full implementation of the national net-zero emissions pledges would take the world towards reaching net-zero emissions, and to examine the scale of the transformation of the energy sector that such a path would require.

The way these pledges are assumed to be implemented in the APC has important implications for the energy system. A net zero pledge for all GHG emissions does not necessarily mean that CO_2 emissions from the energy sector need to reach net zero. For example, a country's net zero plans may envisage some remaining energy-related emissions are offset by the absorption of emissions from forestry or land use, or by negative emissions arising from the use of bioenergy or direct capture of CO_2 from the air (DAC) with CCUS.[6] It is not possible to know exactly how net zero pledges will be implemented, but the design of the APC, particularly with respect to the details of the energy system pathway, has been informed by the pathways that a number of national bodies have developed to support net zero pledges (Box 1.1). Policies in countries that have not yet made a net zero pledge are assumed to be the same as in the STEPS. Non policy assumptions, including population and economic growth, are the same as in the STEPS.

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[6] For example, in recent economy-wide net zero mitigation pathways for the European Union, around 140-210 million tonnes CO_2 of emissions from the energy sector remain in 2050, which are offset by CDR from managed land-use sinks, and bioenergy and DAC with CCUS (European Commission, 2018).

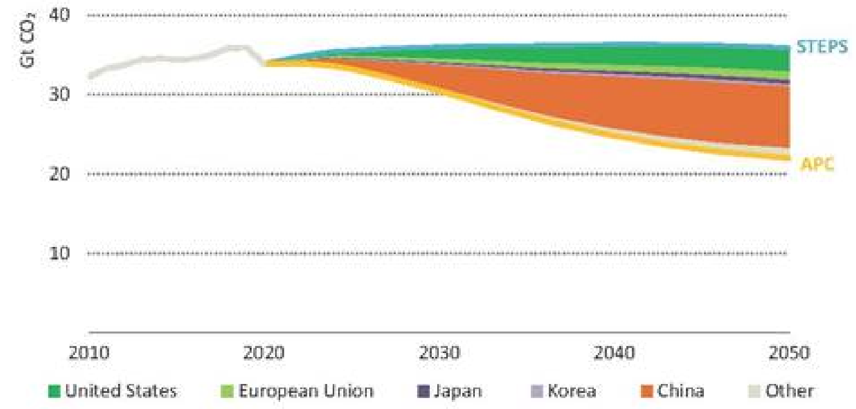
Box 1.1 ▷ **Consultations with national bodies on achieving national net-zero emissions goals**

To help inform its work on net zero pathways, the IEA engaged in extensive consultations with experts in academia and national bodies that have developed pathways to support net zero pledges made by governments. This includes groups that have developed net-zero emissions pathways for several countries including China, European Union, Japan, United Kingdom and United States, as well as the IPCC. These pathways were not used directly as input for the APC, but the discussions informed our modelling of national preferences and constraints within each jurisdiction and to benchmark the overall level of energy-related CO_2 emissions reductions that are commensurate with economy-wide net zero goals.

1.4.1 CO_2 emissions

In the APC, there is a small rebound in emissions to 2023, although this is much smaller than the increase that immediately followed the financial crisis in 2008-09. Emissions never reach the previous peak of 36 Gt CO_2. Global CO_2 emissions fall around 10% to 30 Gt in 2030 and to 22 Gt in 2050. This is around 35% below the level in 2020 and 14 Gt CO_2 lower than in the STEPS (Figure 1.10). If emissions continue this trend after 2050, and with a similar level of changes in non-energy-related GHG emissions, the global average surface temperature rise in 2100 would be around 2.1 °C (with a 50% probability).

Figure 1.10 ▷ **Global energy-related and industrial process CO_2 emissions by scenario and reductions by region, 2010-2050**



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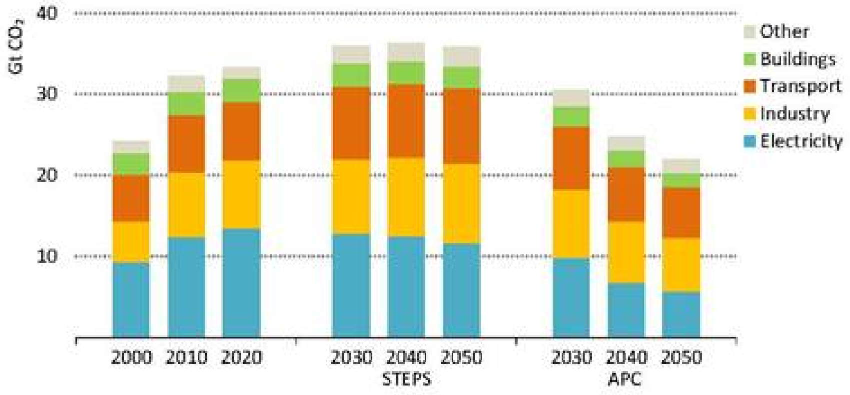
Achieving existing net zero pledges would reduce emissions globally to 22 Gt CO_2 in 2050, a major reduction compared with current policies but still far from net-zero emissions

The net zero pledges that have been made to date therefore make a major difference to the current trajectory for CO_2 emissions. Equally, however, existing net zero pledges fall well short of what is necessary to reach net-zero emissions globally by 2050. This highlights the importance of concrete policies and plans to deliver in full long-term net zero pledges. It also underlines the value of other countries making (and delivering on) net zero pledges: the more countries that do so, and the more ambitious those pledges are, the more the gap will narrow with what is needed to reach net-zero emissions by 2050.

The largest drop in CO_2 emissions is in the APC is in the electricity sector with global emissions falling by nearly 60% between 2020 and 2050. This occurs despite a near-doubling of electricity demand as energy end-uses are increasingly electrified, notably in transport and buildings (Figure 1.11). This compares with a fall in emissions of less than 15% in the STEPS.

Figure 1.11 ▷ Global CO_2 emissions by sector in the STEPS and APC



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Announced net zero pledges would cut emissions in 2050 by 60% in the electricity sector, 40% in buildings, 25% in industry and just over 10% in transport

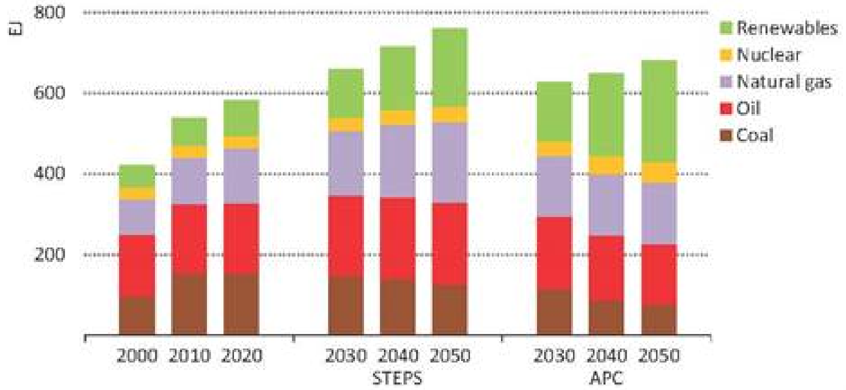
The transport and industry sectors see a less marked fall in CO_2 emissions to 2050 in the APC, with increases in energy demand in regions without net zero pledges partially offsetting emissions reduction efforts in other regions. Emissions from the buildings sector decline by around 40% between 2020 and 2050, compared with around 5% in the STEPS: fossil fuel use in buildings is mostly to provide heating, and countries that have made pledges account for a relatively high proportion of global heating demand.

Even in regions with net zero pledges, there are some residual emissions in 2050, mainly in industry and transport. This reflects the scarcity of commercially available options to eliminate all emissions from heavy-duty trucks, aviation, shipping and heavy industry.

1.4.2 *Total energy supply*

Global total energy supply increases by more than 15% between 2020 and 2050 in the APC, compared with a third in the STEPS (Figure 1.12). Energy intensity falls on average by around 2.6% per year to 2050 compared with 2.2% in the STEPS. There is a substantial increase in energy demand in emerging market and developing economies, where economic and population growth is fastest and where there are fewer net zero pledges, which outweighs the reductions in energy demand in the countries with net zero pledges.

Figure 1.12 ▷ Total energy supply by source in STEPS and APC



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Announced net zero pledges lift renewables in the APC from 12% of total energy supply in 2020 to 35% in 2050, mainly at the expense of coal and oil

The global increase in energy supply in the APC is led by renewables, which increase their share in the energy mix from 12% in 2020 to 35% by 2050 (compared with 25% in 2050 in the STEPS). Solar photovoltaics (PV) and wind in the electricity sector together contribute about 50% of the growth in renewables supply, and bioenergy contributes around 30%. Bioenergy use doubles in industry, triples in electricity generation and grows by a factor of four in transport: it plays an important role in reducing emissions from heat supply and removing CO_2 from the atmosphere when it is combined with CCUS. Nuclear maintains its share of the energy mix, its output rising by a quarter to 2030 (compared with a 15% increase in the STEPS), driven by lifetime extensions at existing plants and new reactors in some countries.

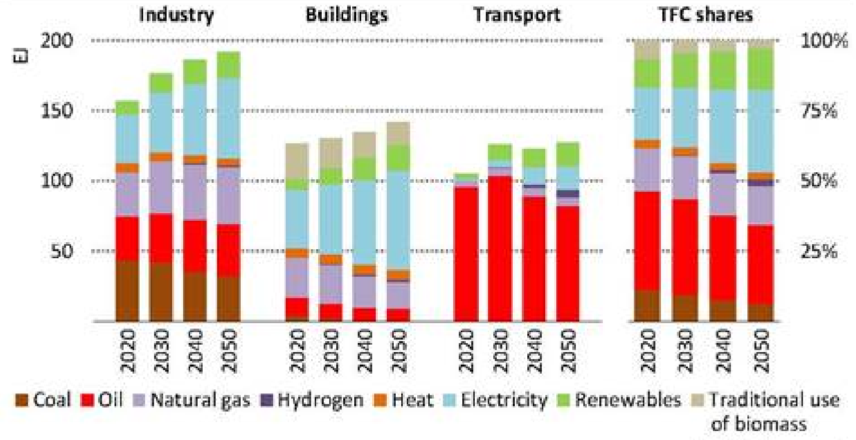
Global coal use falls significantly more rapidly in the APC than in the STEPS. It drops from 5 250 million tonnes of coal equivalent (Mtce) in 2020 to 4 000 Mtce in 2030 and 2 600 Mtce in 2050 (compared with 4 300 Mtce in the STEPS in 2050). Most of this decline is due to reduced coal-fired electricity generation in countries with net zero pledges as plants are repurposed, retrofitted or retired. In advanced economies, unabated coal-fired power plants are generally phased out over the next 10-15 years. China's coal consumption for electricity declines by 85% between 2020 and 2050 on its path towards carbon neutrality in 2060. These declines more than offset continued growth for coal in countries without net zero pledges. Globally, coal use in industry falls by 25% between 2020 and 2050, compared with a 5% decline in the STEPS.

Oil demand recovers slightly in the early 2020s but never again reaches its historic peak in 2019. It declines to 90 mb/d in the early 2030s and to 80 mb/d in 2050, around 25 mb/d lower than in the STEPS, thanks to a strong push to electrify transport and shifts to biofuels and hydrogen, especially in regions with pledges. Natural gas demand increases from about 3 900 bcm in 2020 to around 4 350 bcm in 2025, but is then broadly flat to 2050 (it continues to grow to around 5 700 bcm in the STEPS).

1.4.3 *Total final consumption*

Global energy use continues to grow in all major end-use sectors in the APC, albeit substantially more slowly than in the STEPS (Figure 1.13). Total final consumption (TFC) increases by around 20% in 2020-50, compared with a 35% increase globally in the STEPS. Measures to improve energy efficiency play a major role in the APC in reducing demand growth in countries with net zero pledges. Without those efficiency gains, electricity demand growth would make it much harder for renewables to displace fossil fuels in electricity generation. The biggest reduction in energy demand relative to the STEPS is in transport, thanks to an accelerated shift to electric vehicles (EVs), which are around three-times as energy efficient as conventional internal combustion engine vehicles.

Figure 1.13 ▷ Total final consumption in the APC



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Announced net zero pledges lead to a shift away from fossil fuels globally to electricity, renewables and hydrogen. Electricity's share rises from 20% to 30% in 2050

The fuel mix in final energy use shifts substantially in the APC. By 2050, electricity is the largest single fuel used in all sectors except transport, where oil remains dominant. The persistence of oil in transport stems partly from the extent of its continued use in countries without net zero pledges, and partly from the difficulty of electrifying substantial parts of the transport sector, notably trucking and aviation. Electricity does make inroads into transport, however, and rapid growth in the uptake of EVs puts oil use into decline after 2030, with EVs accounting for around 35% of global passenger car sales by 2030 and nearly 50% in 2050 in the APC (versus around 25% in the STEPS in 2050). Electrification in the buildings sector is also much faster in the APC than in the STEPS.

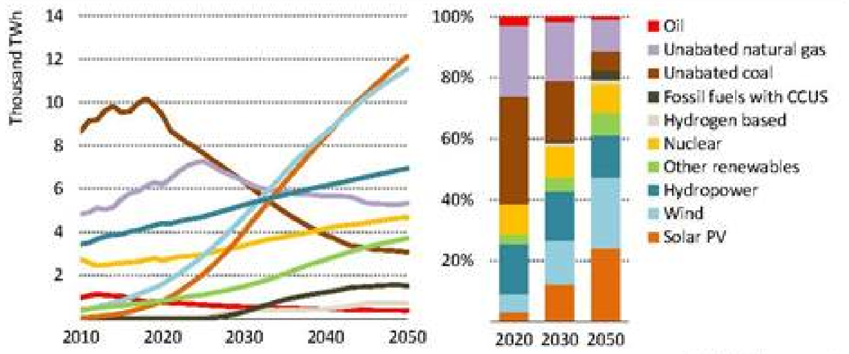
The direct use of renewables expands in all end-use sectors globally through to 2050. Modern bioenergy accounts for the bulk of this growth, predominantly through the blending of biomethane into natural gas networks and liquid biofuels in transport. This occurs mainly in regions with net zero pledges. Hydrogen and hydrogen-based fuels play a larger role in the APC than in the STEPS, reaching almost 15 exajoules (EJ) in 2050, though they still account for only 3% of total final consumption worldwide in 2050. Transport accounts for more than two-thirds of all hydrogen consumption in 2050. In parallel, on-site hydrogen production in the industry and refining sectors gradually shifts towards low-carbon technologies.

1.4.4 Electricity generation

Global electricity generation nearly doubles during the next three decades in the APC, rising from about 26 800 terawatt-hours (TWh) in 2020 to over 50 000 TWh in 2050, some 4 000 TWh higher than in the STEPS. Low-emissions energy sources provide all the increase. The share of renewables in electricity generation rises from 29% in 2020 to nearly 70% in 2050, compared with about 55% in the STEPS, as solar PV and wind race ahead of all other sources of generation (Figure 1.14). By 2050, solar PV and wind together account for almost half of electricity supply. Hydropower also continues to expand, emerging as the third-largest energy source in the electricity mix by 2050. Nuclear power increases steadily too, maintaining its global market share of about 10%, led by increases in China. Natural gas use in electricity increases slightly to the mid-2020s before starting to fall back, while coal's share of electricity generation falls from around 35% in 2020 to below 10% in 2050. At that point, 20% of the remaining coal-fired output comes from plants equipped with CCUS.

Hydrogen and ammonia start to emerge as fuel inputs to electricity generation by around 2030, used largely in combination with natural gas in gas turbines and with coal in coal-fired power plants. This extends the life of existing assets, contributes to electricity system adequacy and reduces the overall costs of transforming the electricity sectors in many countries. Total battery capacity also rises substantially, reaching 1 600 gigawatts (GW) in 2050, 70% more than in the STEPS.

Figure 1.14 ▷ Global electricity generation by source in the APC



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Renewables reach new heights in the APC, rising from just under 30% of electricity supply in 2020 to nearly 70% in 2050, while coal-fired generation steadily declines

Note: Other renewables = geothermal, solar thermal and marine.

A global pathway to net-zero CO_2 emissions in 2050

SUMMARY

- The Net-Zero Emissions by 2050 Scenario (NZE) shows what is needed for the global energy sector to achieve net-zero CO_2 emissions by 2050. Alongside corresponding reductions in GHG emissions from outside the energy sector, this is consistent with limiting the global temperature rise to 1.5 °C without a temperature overshoot (with a 50% probability). Achieving this would require all governments to increase ambitions from current Nationally Determined Contributions and net zero pledges.
- In the NZE, global energy-related and industrial process CO_2 emissions fall by nearly 40% between 2020 and 2030 and to net zero in 2050. Universal access to sustainable energy is achieved by 2030. There is a 75% reduction in methane emissions from fossil fuel use by 2030. These changes take place while the global economy more than doubles through to 2050 and the global population increases by 2 billion.
- Total energy supply falls by 7% between 2020 and 2030 in the NZE and remains at around this level to 2050. Solar PV and wind become the leading sources of electricity globally before 2030 and together they provide nearly 70% of global generation in 2050. The traditional use of bioenergy is phased out by 2030.
- Coal demand declines by 90% to less than 600 Mtce in 2050, oil declines by 75% to 24 mb/d, and natural gas declines by 55% to 1 750 bcm. The fossil fuels that remain in 2050 are used in the production of non-energy goods where the carbon is embodied in the product (like plastics), in plants with carbon capture, utilisation and storage (CCUS), and in sectors where low-emissions technology options are scarce.
- Energy efficiency, wind and solar provide around half of emissions savings to 2030 in the NZE. They continue to deliver emissions reductions beyond 2030, but the period to 2050 sees increasing electrification, hydrogen use and CCUS deployment, for which not all technologies are available on the market today, and these provide more than half of emissions savings between 2030 and 2050. In 2050, there is 1.9 Gt of CO_2 removal in the NZE and 520 million tonnes of low-carbon hydrogen demand. Behavioural changes by citizens and businesses avoid 1.7 Gt CO_2 emissions in 2030, curb energy demand growth, and facilitate clean energy transitions.
- Annual energy sector investment, which averaged USD 2.3 trillion globally in recent years, jumps to USD 5 trillion by 2030 in the NZE. As a share of global GDP, average annual energy investment to 2050 in the NZE is around 1% higher than in recent years.
- The NZE taps into all opportunities to decarbonise the energy sector, across all fuels and all technologies. But the path to 2050 has many uncertainties. If behavioural changes were to be more limited than envisaged in the NZE, or sustainable bioenergy less available, then the energy transition would be more expensive. A failure to develop CCUS for fossil fuels could delay or prevent the development of CCUS for process emissions from cement production and carbon removal technologies, making it much harder to achieve net-zero emissions by 2050.

2.1 Introduction

Achieving a global energy transition that is compatible with the world's climate goals is unquestionably a formidable task. As highlighted in Chapter 1, current pledges by governments to reduce emissions to net zero collectively cover around 70% of today's global economic activity and global CO_2 emissions. The Announced Pledges Case shows that, if all those pledges were met in full, it would narrow the gap between where we are heading and where we need to be to achieve net-zero emissions by 2050 worldwide. But it also shows that the gap would remain large. Meeting all existing net zero pledges in full would still leave 22 gigatonnes (Gt) of energy-related and industrial process CO_2 emissions globally in 2050, consistent with a temperature rise in 2100 of around 2.1 °C (with a 50% probability).

In this chapter, we examine the energy sector transformation which is embodied in our Net-Zero Emissions by 2050 Scenario. First, it provides an overview of the key assumptions and market dynamics underlying the projections, including projected fossil fuel and CO_2 prices. It discusses trends in global CO_2 emissions, energy use and investment, including the key roles played by efficiency measures, behavioural change, electrification, renewables, hydrogen and hydrogen-based fuels, bioenergy, and carbon capture, utilisation and storage (CCUS). Further, it discusses some of the key uncertainties surrounding the global pathway towards net-zero emissions related to behavioural change, the availability of sustainable bioenergy, and the deployment of CCUS for fossil fuels. The transformation of specific energy sectors is assessed and discussed in detail in Chapter 3.

2.2 Scenario design

The Net-Zero Emissions by 2050 Scenario (NZE) is designed to show what is needed across the main sectors by various actors, and by when, for the world to achieve net-zero energy-related and industrial process CO_2 emissions by 2050.[1] It also aims to minimise methane emissions from the energy sector. In recent years, the energy sector was responsible for around three-quarters of global greenhouse gas (GHG) emissions. Achieving net-zero energy-related and industrial process CO_2 emissions by 2050 in the NZE does not rely on action in areas other than the energy sector, but limiting climate change does require such action. We therefore additionally examine the reductions in CO_2 emissions from land use that would be commensurate with the transformation of the energy sector in the NZE, working in co-operation with the International Institute for Applied Systems Analysis (IIASA). In parallel with action on reducing all other sources of GHG emissions, achieving net-zero CO_2 emissions from the energy sector by 2050 is consistent with around a 50% chance of limiting the long-term average global temperature rise to 1.5 °C without a temperature overshoot (IPCC, 2018).

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[1] Unless otherwise stated, carbon dioxide (CO_2) emissions in this chapter refer to energy-related and industrial process CO_2 emissions. Net-zero CO_2 emissions refers to zero CO_2 emissions to the atmosphere, or with any residual CO_2 emissions offset by CO_2 removal from direct air capture or bioenergy with carbon capture and storage.

The NZE aims to ensure that energy-related and industrial process CO_2 emissions to 2030 are in line with reductions in 1.5 °C scenarios with no or low or limited temperature overshoot assessed in the IPCC in its Special Report on Global Warming of 1.5 °C.[2] In addition, the NZE incorporates concrete action on the energy-related United Nations Sustainable Development Goals related to achieving universal energy access by 2030 and delivering a major reduction in air pollution. The projections in the NZE were generated by a hybrid model that combines components of the IEA's World Energy Model (WEM), which is used to produce the projections in the annual *World Energy Outlook,* and the Energy Technology Perspectives (ETP) model.

Box 2.1 ▷ International Energy Agency modelling approach for the NZE

A new, hybrid modelling approach was adopted to develop the NZE and combines the relative strengths of the WEM and the ETP model. The WEM is a large-scale simulation model designed to replicate how competitive energy markets function and to examine the implications of policies on a detailed sector-by-sector and region-by-region basis. The ETP model is a large-scale partial-optimisation model with detailed technology descriptions of more than 800 individual technologies across the energy conversion, industry, transport and buildings sectors.

This is the first time this modelling approach has been implemented. The combination of the two models allows for a unique set of insights on energy markets, investment, technologies, and the level and detail of policies that would be needed to bring about the energy sector transformation in the NZE.

Results from the WEM and ETP model have been coupled with the Greenhouse Gas - Air Pollution Interactions and Synergies (GAINS) model developed by IIASA (Amann et al., 2011). The GAINS model is used to evaluate air pollutant emissions and resultant health impacts linked to air pollution. For the first time, IEA model results have also been coupled with the IIASA's Global Biosphere Management Model (GLOBIOM) to provide data on land use and net emissions impacts of bioenergy demand.

The impacts of changes in investment and spending on global GDP in the NZE have been estimated by the International Monetary Fund (IMF) using the Global Integrated Monetary and Fiscal (GIMF) model. GIMF is a multi-country dynamic stochastic general equilibrium model used by the IMF for policy and risk analysis (Laxton et al., 2010; Anderson et al., 2013). It has been used to produce the IMF's World Economic Outlook scenario analyses since 2008.

There are many possible paths to achieve net-zero CO_2 emissions globally by 2050 and many uncertainties that could affect any of them; the NZE is therefore *a* path, not *the* path to net-zero emissions. Much depends, for example, on the pace of innovation in new and emerging

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[2] The IPCC classifies scenarios as "no or limited temperature overshoot", if temperatures exceed 1.5 °C by less than 0.1 °C but return to less than 1.5 °C in 2100, and as "higher overshoot", if temperatures exceed 1.5 °C by 0.1-0.4 °C but return to less than 1.5 °C in 2100.

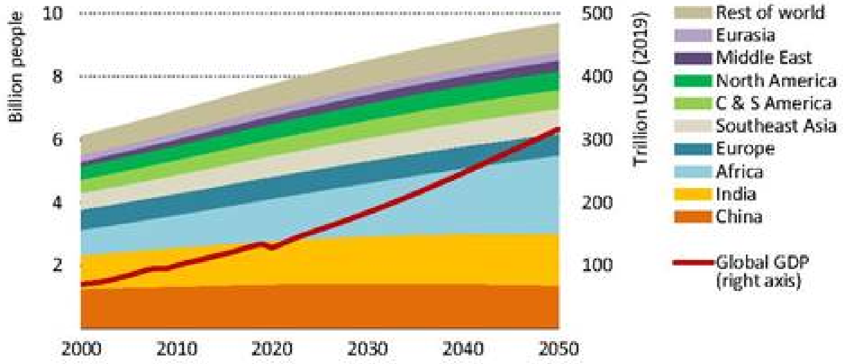
technologies, the extent to which citizens are able or willing to change behaviour, the availability of sustainable bioenergy and the extent and effectiveness of international collaboration. We investigate some of the key alternatives and uncertainties here and in Chapter 3. The Net-Zero Emissions by 2050 Scenario is built on the following principles.

- The uptake of all the available technologies and emissions reduction options is dictated by costs, technology maturity, policy preferences, and market and country conditions.
- All countries co-operate towards achieving net-zero emissions worldwide. This involves all countries participating in efforts to meet the net zero goal, working together in an effective and mutually beneficial way, and recognising the different stages of economic development of countries and regions, and the importance of ensuring a just transition.
- An orderly transition across the energy sector. This includes ensuring the security of fuel and electricity supplies at all times, minimising stranded assets where possible and aiming to avoid volatility in energy markets.

2.2.1 Population and GDP

The energy sector transformation in the NZE occurs against the backdrop of large increases in the world's population and economy (Figure 2.1). In 2020, there were around 7.8 billion people in the world; this is projected to increase by around 750 million by 2030 and by nearly 2 billion people by 2050 in line with the median variant of the United Nations projections (UNDESA, 2019). Nearly all of the population increase is in emerging market and developing economies: the population of Africa alone increases by more than 1.1 billion between 2020 and 2050.

Figure 2.1 ▷ World population by region and global GDP in the NZE



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By 2050, the world's population expands to 9.7 billion people and the global economy is more than twice as large as in 2020

Notes: GDP = gross domestic product in purchasing power parity; C & S America = Central and South America.

Sources: IEA analysis based on UNDESA (2019); Oxford Economics (2020); IMF (2020a, 2020b).

The world's economy is assumed to recover rapidly from the impact of the Covid-19 pandemic. Its size returns to pre-crisis levels in 2021. From 2022, the GDP growth trend is close to the pre-pandemic rate of around 3% per year on average, in line with assessments from the IMF. The response to the pandemic leads to a large increase in government debt, but resumed growth, along with low interest rates in many countries, make this manageable in the long term. By 2030, the world's economy is around 45% larger than in 2020, and by 2050 it is more than twice as large.

2.2.2 Energy and CO_2 prices

Projections of future energy prices are inevitably subject to a high degree of uncertainty. In IEA scenarios, they are designed to maintain an equilibrium between supply and demand. The rapid drop in oil and natural gas demand in the NZE means that no fossil fuel exploration is required and no new oil and natural gas fields are required beyond those that have already been approved for development. No new coal mines or mine extensions are required either. Prices are increasingly set by the operating costs of the marginal project required to meet demand, and this results in significantly lower fossil fuel prices than in recent years. The oil price drops to around USD 35/barrel by 2030 and then drifts down slowly towards USD 25/barrel in 2050.

Table 2.1 ▷ Fossil fuel prices in the NZE

Real terms (USD 2019)	2010	2020	2030	2040	2050
IEA crude oil (USD/barrel)	91	37	35	28	24
Natural gas (USD/MBtu)					
United States	5.1	2.1	1.9	2.0	2.0
European Union	8.7	2.0	3.8	3.8	3.5
China	7.8	5.7	5.2	4.8	4.6
Japan	12.9	5.7	4.4	4.2	4.1
Steam coal (USD/tonne)					
United States	60	45	24	24	22
European Union	108	56	51	48	43
Japan	125	75	57	53	49
Coastal China	135	81	60	54	50

Notes: MBtu = million British thermal units. The IEA crude oil prices are a weighted average import price among IEA member countries. Natural gas prices are weighted averages expressed on a gross calorific-value basis. US natural gas prices reflect the wholesale price prevailing on the domestic market. The European Union and China gas prices reflect a balance of pipeline and liquefied natural gas (LNG) imports, while Japan gas prices solely reflect LNG imports. LNG prices used are those at the customs border, prior to regasification. Steam coal prices are weighted averages adjusted to 6 000 kilocalories per kilogramme. US steam coal prices reflect mine-mouth price plus transport and handling cost. Coastal China steam coal price reflects a balance of imports and domestic sales, while the European Union and Japanese steam coal prices are solely for imports.

In line with the principle of orderly transitions governing the NZE, the trajectory for oil markets and prices avoids excessive volatility. What happens depends to a large degree on the strategies adopted by resource-rich governments and their national oil companies. In the NZE it is assumed that, despite having lower cost resources at their disposal, they restrict investment in new fields. This limits the need for the shutting in and closure of higher cost production. The market share of major resource-rich countries nevertheless still rises in the NZE due to the large size and slow decline rates of their existing fields.

Producer economies could pursue alternative approaches. Faced with rapidly falling oil and gas demand, they could, for example, opt to increase production so as to capture an even larger share of the market. In this event, the combination of falling demand and increased availability of low cost oil would undoubtedly lead to even lower – and probably much more volatile – prices. In practice, the options open to particular producer countries would depend on their resilience to lower oil prices and on the extent to which export markets have developed for low-emissions fuels that could be produced from their natural resources.

Anticipating and mitigating feedbacks from the supply side is a central element of the discussion about orderly energy transitions. A drop in prices usually results in some rebound in demand, and policies and regulations would be essential to avoid this leading to any increase in the unabated use of fossil fuels, which would undermine wider emissions reduction efforts.

As the energy sector transforms, more fuels are traded globally, such as hydrogen-based fuels and biofuels. The prices of these commodities are assumed to be set by the marginal cost of domestic production or imports within each region.

A broad range of energy policies and accompanying measures are introduced across all regions to reduce emissions in the NZE. This includes: renewable fuel mandates; efficiency standards; market reforms; research, development and deployment; and the elimination of inefficient fossil fuel subsidies. Direct emissions reduction regulations are also needed in some cases. In the transport sector, for example, regulations are implemented to reduce sales of internal combustion engine vehicles and increase the use of liquid biofuels and synthetic fuels in aviation and shipping, as well as measures to ensure that low oil prices do not lead to an increase in consumption.

CO_2 prices are introduced across all regions in the NZE (Table 2.2). They are assumed to be introduced in the immediate future across all advanced economies for the electricity generation, industry and energy production sectors, and to rise on average to USD 130 per tonne (tCO_2) by 2030 and to USD 250/tCO_2 by 2050. In a number of other major economies – including China, Brazil, Russia and South Africa – CO_2 prices in these sectors are assumed to rise to around USD 200/tCO_2 in 2050. CO_2 prices are introduced in all other emerging market and developing economies, although it is assumed that they pursue more direct policies to adapt and transform their energy systems and so the level of CO_2 prices is lower than elsewhere.

Table 2.2 ▷ CO$_2$ prices for electricity, industry and energy production in the NZE

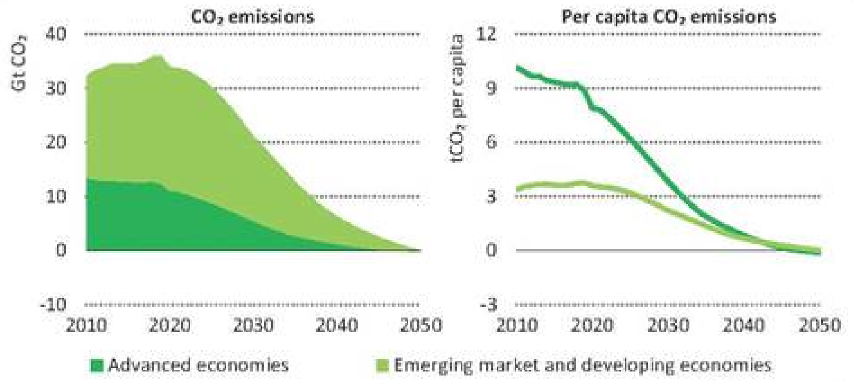
USD (2019) per tonne of CO$_2$	2025	2030	2040	2050
Advanced economies	75	130	205	250
Selected emerging market and developing economies*	45	90	160	200
Other emerging market and developing economies	3	15	35	55

* Includes China, Russia, Brazil and South Africa.

2.3 CO$_2$ emissions

Global energy-related and industrial process CO$_2$ emissions in the NZE fall to around 21 Gt CO$_2$ in 2030 and to net-zero in 2050 (Figure 2.2).[3] CO$_2$ emissions in advanced economies as a whole fall to net zero by around 2045 and these countries collectively remove around 0.2 Gt CO$_2$ from the atmosphere in 2050. Emissions in several individual emerging market and developing economies also fall to net zero well before 2050, but in aggregate there are around 0.2 Gt CO$_2$ of remaining emissions in this group of countries in 2050. These are offset by CO$_2$ removal in advanced economies to provide net-zero CO$_2$ emissions at the global level.

Figure 2.2 ▷ Global net CO$_2$ emissions in the NZE



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CO$_2$ emissions fall to net zero in advanced economies around 2045 and globally by 2050. Per capita emissions globally are similar by the early-2040s.

Note: Includes CO$_2$ emissions from international aviation and shipping.

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[3] In the period to 2030, CO$_2$ emissions in the NZE fall at a broadly similar rate to the P2 illustrative pathway in the IPCC SR 1.5 (IPCC, 2018). The P2 scenario is described as "a scenario with … shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS [bioenergy with carbon capture and storage]". After 2030, emissions in the NZE fall at a much faster pace than in the P2 scenario, which has 5.6 Gt CO$_2$ of residual energy sector and industrial process CO$_2$ emissions remaining in 2050.

Several emerging market and developing economies with a very large potential for producing renewables-based electricity and bioenergy are also a key source of carbon dioxide removal (CDR). This includes making use of renewable electricity sources to produce large quantities of biofuels with CCUS, some of which is exported, and to carry out direct air capture with carbon capture and storage (DACCS).

Per capita CO_2 emissions in advanced economies drop from around 8 tCO_2 per person in 2020 to around 3.5 tCO_2 in 2030, a level close to the average in emerging market and developing economies in 2020. Per capita emissions also fall in emerging market and developing economies, but from a much lower starting point. By the early 2040s, per capita emissions in both regions are broadly similar at around 0.5 tCO_2 per person.

Cumulative global energy-related and industrial process CO_2 emissions between 2020 and 2050 amount to just over 460 Gt in the NZE. Assuming parallel action to address CO_2 emissions from agriculture, forestry and other land use (AFOLU) over the period to 2050 would result in around 40 Gt CO_2 from AFOLU (see section 2.7.2). This means that total CO_2 emissions from all sources – some 500 Gt CO_2 – are in line with the CO_2 budgets included in the IPCC SR1.5, which indicated that the total CO_2 budget from 2020 consistent with providing a 50% chance of limiting warming to 1.5 °C is 500 Gt CO_2 (IPCC, 2018).[4] As well as reducing CO_2 emissions to net-zero, the NZE seeks to reduce non-CO_2 emissions from the energy sector. Methane emissions from fossil fuel production and use, for example, fall from 115 million tonnes (Mt) methane in 2020 (3.5 Gt CO_2-equivalent [CO_2-eq])[5] to 30 Mt in 2030 and 10 Mt in 2050.

The fastest and largest reductions in global emissions in the NZE are initially seen in the electricity sector (Figure 2.3). Electricity generation was the largest source of emissions in 2020, but emissions drop by nearly 60% in the period to 2030, mainly due to major reductions from coal-fired power plants, and the electricity sector becomes a small net negative source of emissions around 2040. Emissions from the buildings sector fall by 40% between 2020 and 2030 thanks to a shift away from the use of fossil fuel boilers, and retrofitting the existing building stock to improve its energy performance. Emissions from industry and transport both fall by around 20% over this period, and their pace of emissions reductions accelerates during the 2030s as the roll-out of low-emissions fuels and other emissions reduction options is scaled up. Nonetheless, there are a number of areas in transport and industry in which it is difficult to eliminate emissions entirely – such as aviation and heavy industry – and both sectors have a small level of residual emissions in 2050. These residual emissions are offset with applications of BECCS and DACCS.

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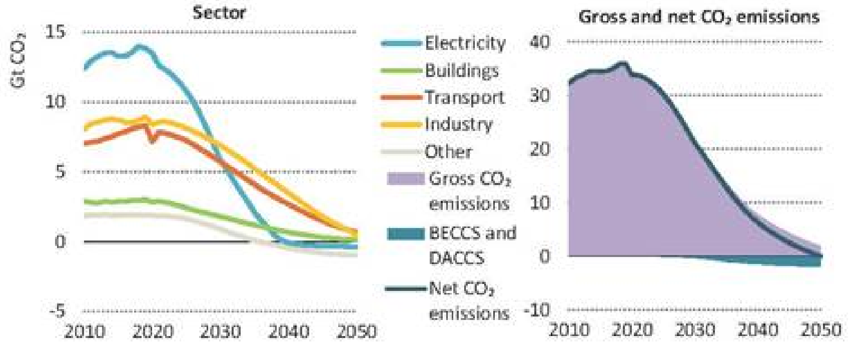
[4] This budget is based on Table 2.2 of the IPCC SR1.5 (IPCC, 2018). It assumes 0.53 °C additional warming from the 2006-2015 period to give a remaining CO_2 budget from 2018 of 580 Gt CO_2. There were around 80 Gt CO_2 emissions emitted from 2018 to 2020.

[5] Non-CO_2 gases are converted to CO_2-equivalents based on the 100-year global warming potentials reported by the IPCC 5th Assessment Report (IPCC, 2014). One tonne of methane is equivalent to 30 tonnes of CO_2.

Figure 2.3 ▷ **Global net-CO_2 emissions by sector, and gross and net CO_2 emissions in the NZE**



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Emissions from electricity fall fastest, with declines in industry and transport accelerating in the 2030s. Around 1.9 Gt CO_2 are removed in 2050 via BECCS and DACCS.

Notes: Other = agriculture, fuel production, transformation and related process emissions, and direct air capture. BECCS = bioenergy with carbon capture and storage; DACCS = direct air capture with carbon capture and storage. BECCS and DACCS includes CO_2 emissions captured and permanently stored.

The NZE includes a systematic preference for all new assets and infrastructure to be as sustainable and efficient as possible, and this accounts for 50% of total emissions reductions in 2050. Tackling emissions from existing infrastructure accounts for another 35% of reductions in 2050, while behavioural changes and avoided demand, including materials efficiency[6] gains and modal shifts in the transport sector, provide the remaining 15% of emissions reductions (see section 2.5.2). A wide range of technologies and measures are deployed in the NZE to reduce emissions from existing infrastructure such as power plants, industrial facilities, buildings, networks, equipment and appliances. The NZE is designed to minimise stranded capital where possible, i.e. cases where the initial investment is not recouped, but in many cases early retirements or lower utilisation lead to stranded value, i.e. a reduction in revenue.

The rapid deployment of more energy-efficient technologies, electrification of end-uses and swift growth of renewables all play a central part in reducing emissions across all sectors in the NZE (Figure 2.4). By 2050, nearly 90% of all electricity generation is from renewables, as is around 25% of non-electric energy use in industry and buildings. There is also a major role for emerging fuels and technologies, notably hydrogen and hydrogen-based fuels, bioenergy and CCUS, especially in sectors where emissions are often most challenging to reduce.

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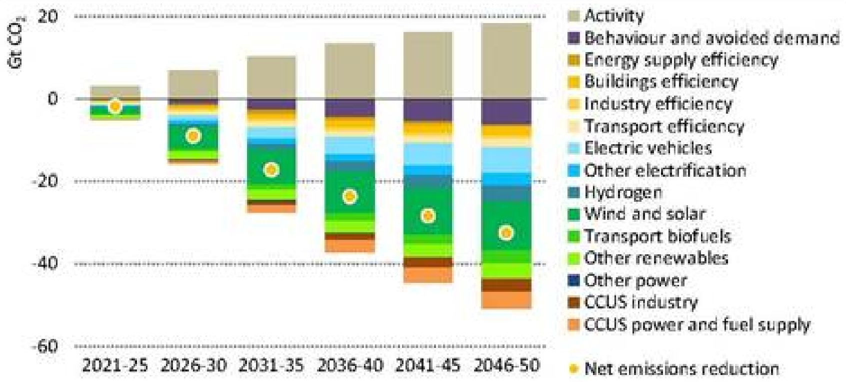
[6] Materials efficiency includes strategies that reduce material demand, or shift to the use of lower emissions materials or lower emissions production routes. Examples include lightweighting and recycling.

Figure 2.4 ▷ Average annual CO_2 reductions from 2020 in the NZE



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Renewables and electrification make the largest contribution to emissions reductions, but a wide range of measures and technologies are needed to achieve net-zero emissions

Notes: Activity = changes in energy service demand from economic and population growth. Behaviour = change in energy service demand from user decisions, e.g. changing heating temperatures. Avoided demand = change in energy service demand from technology developments, e.g. digitalisation.

2.4 Total energy supply and final energy consumption

2.4.1 Total energy supply[7]

Total energy supply falls to 550 exajoules (EJ) in 2030, 7% lower than in 2020 (Figure 2.5). This occurs despite significant increases in the global population and economy because of a fall in energy intensity (the amount of energy used to generate a unit of GDP). Energy intensity falls by 4% on average each year between 2020 and 2030. This is achieved through a combination of electrification, a push to pursue all energy and materials efficiency opportunities, behavioural changes that reduce demand for energy services, and a major shift away from the traditional use of bioenergy.[8] This level of improvement in energy intensity is much greater than has been achieved in recent years: between 2010 and 2020, average annual energy intensity fell by less then 2% each year.

After 2030, continuing electrification of end-use sectors helps to reduce energy intensity further, but the emphasis on maximising energy efficiency improvements in the years up to

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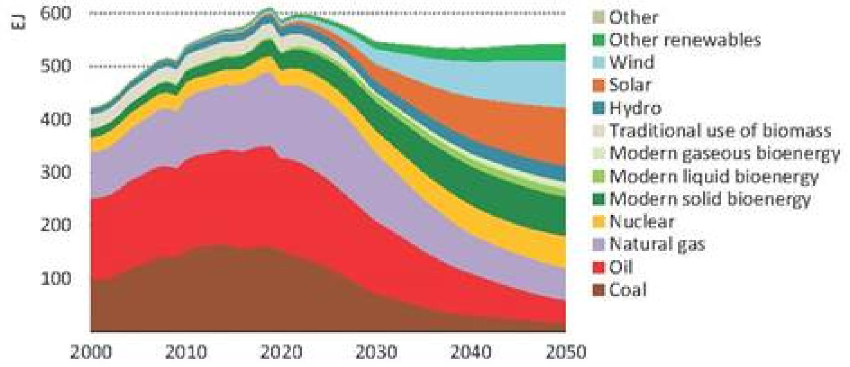
[7] The terms total primary energy supply (TPES) or total primary energy demand (TPED) have been renamed as total energy supply (TES) in accordance with the International Recommendations for Energy Statistics (IEA, 2020a).

[8] Modern forms of cooking require much less energy than the traditional use of biomass in inefficient stoves. For example, cooking with a liquefied petroleum gas stove uses around five-times less energy than the traditional use of biomass.

2030 limits the available opportunities in later years. At the same time, increasing production of new fuels, such as advanced biofuels, hydrogen and synthetic fuels, tends to push up energy use. As a result, the rate of decline in energy intensity between 2030 and 2050 slows to 2.7% per year. With continued economic and population growth, this means that total energy supply falls slightly between 2030 and 2040 but then remains broadly flat to 2050. Total energy supply in 2050 in the NZE is close to the level in 2010, despite a global population that is nearly 3 billion people higher and a global economy that is over three-times larger.

Figure 2.5 ▷ Total energy supply in the NZE



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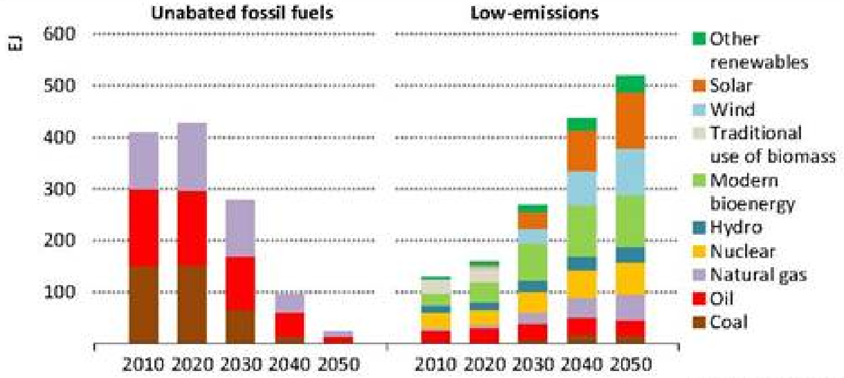
Renewables and nuclear power displace most fossil fuel use in the NZE, and the share of fossil fuels falls from 80% in 2020 to just over 20% in 2050

The energy mix in 2050 in the NZE is much more diverse than today. In 2020, oil provided 30% of total energy supply, while coal supplied 26% and natural gas 23%. In 2050, renewables provide two-thirds of energy use, split between bioenergy, wind, solar, hydroelectricity and geothermal (Figure 2.6). There is also a large increase in energy supply from nuclear power, which nearly doubles between 2020 and 2050.

There are large reductions in the use of fossil fuels in the NZE. As a share of total energy supply, they fall from 80% in 2020 to just over 20% in 2050. However, their use does not fall to zero in 2050: significant amounts are still used in producing non-energy goods, in plants with CCUS, and in sectors where emissions are especially hard to abate such as heavy industry and long-distance transport. All remaining emissions in 2050 are offset by negative emissions elsewhere (Box 2.2). Coal use falls from 5 250 million tonnes of coal equivalent (Mtce) in 2020 to 2 500 Mtce in 2030 and to less than 600 Mtce in 2050 – an average annual decline of 7% each year from 2020 to 2050. Oil demand dropped below 90 million barrels per day (mb/d) in 2020 and demand does not return to its 2019 peak: it falls to 72 mb/d in 2030 and 24 mb/d in 2050 – an annual average decline of more than 4% from 2020 to 2050. Natural gas use dropped to 3 900 billion cubic metres (bcm) in 2020, but exceeds its previous

2019 peak in the mid-2020s before starting to decline as it is phased out in the electricity sector. Natural gas use declines to 3 700 bcm in 2030 and 1 750 bcm in 2050 – an annual average decline of just under 3% from 2020 to 2050.

Figure 2.6 ▷ **Total energy supply of unabated fossil fuels and low-emissions energy sources in the NZE**



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Some fossil fuels are still used in 2050 in the production of non-energy goods, in plants equipped with CCUS, and in sectors where emissions are hard to abate

Note: Low-emissions includes the use of fossil fuels with CCUS and in non-energy uses.

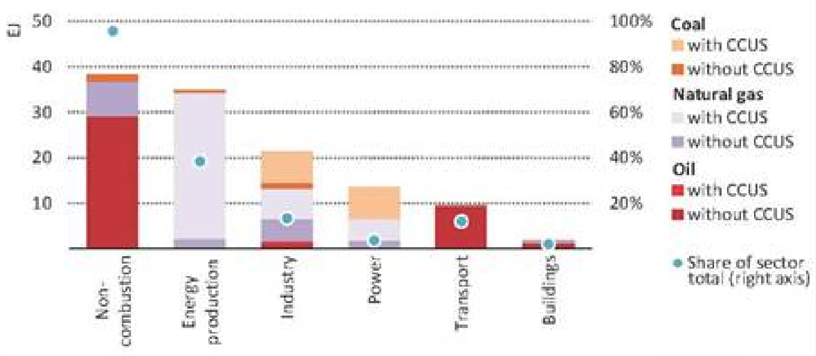
Box 2.2 ▷ Why does fossil fuel use not fall to zero in 2050 in the NZE?

In total, around 120 EJ of fossil fuels is consumed in 2050 in the NZE relative to 460 EJ in 2020. Three main reasons underlie why fossil fuel use does not fall to zero in 2050, even though the energy sector emits no CO_2 on a net basis:

- **Use for non-energy purposes.** More than 30% of total fossil fuel use in 2050 in the NZE – including 70% of oil use – is in applications where the fuels are not combusted and so do not result in any direct CO_2 emissions (Figure 2.7). Examples include use as chemical feedstocks and in lubricants, paraffin waxes and asphalt. There are major efforts to limit fossil fuel use in these applications in the NZE, for instance global plastic collection rates for recycling rising from 15% in 2020 to 55% in 2050, but fossil fuel use in non-energy applications still rises slightly to 2050.
- **Use with CCUS.** Around half of fossil fuel use in 2050 is in plants equipped with CCUS (around 3.5 Gt CO_2 emissions are captured from fossil fuels in 2050). Around 925 bcm of natural gas is converted to hydrogen with CCUS. In addition, around 470 Mtce of coal and 225 bcm of natural gas are used with CCUS in the electricity and industrial sectors, mainly to extend the operations of young facilities and reduce stranded assets.

- **Use in sectors where technology options are scarce.** The remaining 20% of fossil fuel use in 2050 in the NZE is in sectors where the complete elimination of emissions is particularly challenging. Mostly this is oil, as it continues to fuel aviation in particular. A small amount of unabated coal and natural gas are used in industry and in the production of energy. The unabated use of fossil fuel results in around 1.7 Gt CO_2 emissions in 2050, which are fully offset by BECCS and DACCS.

Figure 2.7 ▷ Fossil fuel use and share by sector in 2050 in the NZE



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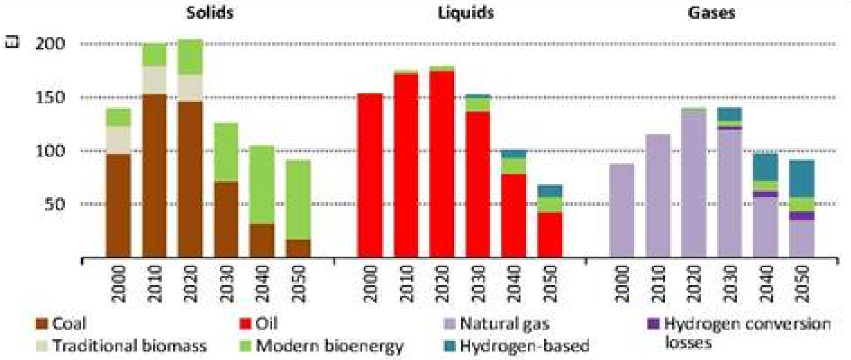
More than 30% of fossil fuel use in 2050 is not combusted and so does not result in direct CO_2 emissions, around 50% is paired with CCUS

Notes: Non-combustion includes use for non-emitting, non-energy purposes such as petrochemical feedstocks, lubricants and asphalt. Energy production includes fuel use for direct air capture.

Solid, liquid and gaseous fuels continue to play an important role in the NZE, which sees large increases in bioenergy and hydrogen (Figure 2.8). Around 40% of bioenergy used today is for the traditional use of biomass in cooking: this is rapidly phased out in the NZE. Modern forms of solid biomass, which can be used to reduce emissions in both the electricity and industry sectors, rise from 32 EJ in 2020 to 55 EJ in 2030 and 75 EJ in 2050, offsetting a large portion of a drop in coal demand. The use of low-emissions liquid fuels, such as ammonia, synthetic fuels and liquid biofuels, increases from 3.5 EJ (1.6 million barrels of oil equivalent per day [mboe/d]) in 2020 to just above 25 EJ (12.5 mboe/d) in 2050. The supply of low-emissions gases, such as hydrogen, synthetic methane, biogas and biomethane rises from 2 EJ in 2020 to 17 EJ in 2030 and 50 EJ in 2050. The increase in gaseous hydrogen production between 2020 and 2030 in the NZE is twice as fast as the fastest ten-year increase in shale gas production in the United States.

Figure 2.8 ▷ Solid, liquid and gaseous fuels in the NZE



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Increases in low-emissions solids, liquids and gases from bioenergy, hydrogen and hydrogen-based fuels offset some of the declines in coal, oil and natural gas

Notes: Hydrogen conversion losses = consumption of natural gas when producing low-carbon merchant hydrogen using steam methane reforming. Hydrogen-based includes hydrogen, ammonia and synthetic fuels.

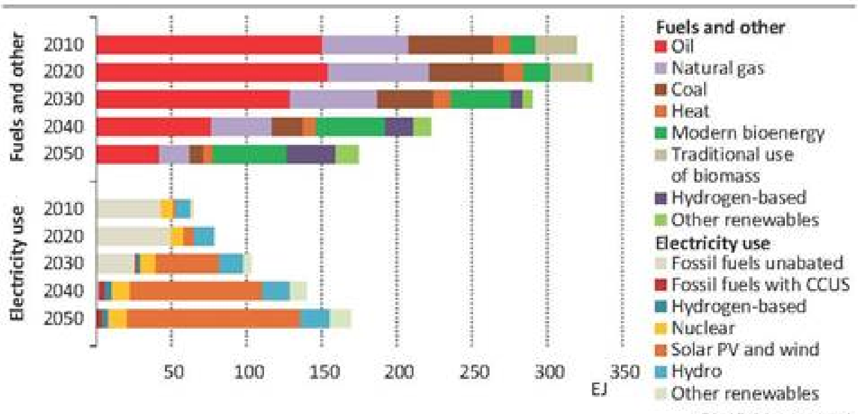
2.4.2 Total final consumption

Total final consumption worldwide rebounds marginally following its 5% drop in 2020, but it never returns to 2019 levels in the NZE (435 EJ). It falls by just under 1% each year on average between 2025 and 2050 to 340 EJ. Energy efficiency measures and electrification are the two main contributing factors, with behavioural changes and materials efficiency also playing a role. Without these improvements, final energy consumption in 2050 would be around 640 EJ, around 90% higher than the level in the NZE. Final consumption of electricity increases by 25% from 2020 to 2030, and by 2050 it is more than double the level in 2020. The increase in electricity consumption from end-uses sectors and from hydrogen production means that overall annual electricity demand growth is equivalent to adding an electricity market the size of India every year in the NZE. The share of electricity in global final energy consumption jumps from 20% in 2020 to 26% in 2030 and to around 50% in 2050 (Figure 2.9). The direct use of renewables in buildings and industry together with low-emissions fuels such as bioenergy and hydrogen-based fuels provide a further 28% of final energy consumption in 2050; fossil fuels comprise the remainder, most of which are used in non-emitting processes or in facilities equipped with CCUS.

In industry, most of the global emissions reductions in the NZE during the period to 2030 are delivered through energy and materials efficiency improvements, electrification of heat, and fuel switching to solar thermal, geothermal and bioenergy. Thereafter, CCUS and hydrogen play an increasingly important role in reducing CO_2 emissions, especially in heavy industries such as steel, cement and chemicals. Electricity consumption in industry more than doubles between 2020 and 2050, providing 45% of total industrial energy needs in 2050 (Figure 2.10).

The demand for merchant hydrogen in industry increases from less than 1 Mt today to around 40 Mt in 2050. A further 10% of industrial energy demand in 2050 is met by fossil fuels used in plants equipped with CCUS.

Figure 2.9 ▷ Global total final consumption by fuel in the NZE



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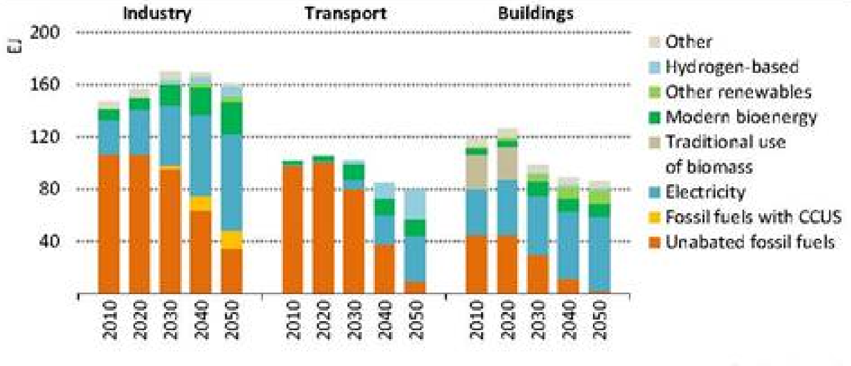
The share of electricity in final energy use jumps from 20% in 2020 to 50% in 2050

Note: Hydrogen-based includes hydrogen, ammonia and synthetic fuels.

In transport, there is a rapid transition away from oil worldwide, which provided more than 90% of fuel use in 2020. In road transport, electricity comes to dominate the sector, providing more than 60% of energy use in 2050, while hydrogen and hydrogen-based fuels play a smaller role, mainly in fuelling long-haul heavy-duty trucks. In shipping, energy efficiency improvements significantly reduce energy needs (especially up to 2030), while advanced biofuels and hydrogen-based fuels, such as ammonia, increasingly displace oil. In aviation, the use of synthetic liquids and advanced biofuels grows rapidly, and their share of total energy demand rises from almost zero today to almost 80% in 2050. Overall, electricity becomes the dominant fuel in the transport sector globally by the early 2040s, and it accounts for around 45% of energy consumption in the sector in 2050 (compared with 1.5% in 2020). Hydrogen and hydrogen-based fuels account for nearly 30% of consumption (almost zero in 2020) and bioenergy for a further 15% (around 4% in 2020).

In buildings, the electrification of end-uses including heating leads to demand for electricity increasing by around 35% between 2020 and 2050: it becomes the dominant fuel, reaching 16 000 terawatt-hours (TWh) in 2050, and accounting for two-thirds of total buildings sector energy consumption. By 2050, two-thirds of residential buildings in advanced economies and around 40% of residential buildings in emerging market and developing economies are fitted with a heat pump. Onsite renewables-based energy systems such as solar water heaters and biomass boilers provide a further quarter of final energy use in the buildings sector in 2050 (up from 6% in 2020). Low-emissions district heating and hydrogen provide only 7% of energy use, but play a significant role in some regions.

Figure 2.10 ▷ Global final energy consumption by sector and fuel in the NZE



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There is a wholesale shift away from unabated fossil fuel use to electricity, renewables, hydrogen and hydrogen-based fuels, modern bioenergy and CCUS in end-use sectors

Note: Hydrogen-based includes hydrogen, ammonia and synthetic fuels.

Buildings energy consumption falls by 25% between 2020 and 2030, largely as a result of a major push to improve efficiency and to phase out the traditional use of solid biomass for cooking: it is replaced by liquefied petroleum gas (LPG), biogas, electric cookers and improved bioenergy stoves. Universal access to electricity is achieved by 2030, and this adds less than 1% to global electricity demand in 2030. Energy consumption in the buildings sector contracts by around 15% between 2030 and 2050 given continued efficiency improvements and electrification. By 2050, energy use in buildings is 35% lower than in 2020. Energy efficiency measures – including improving building envelopes and ensuring that all new appliances brought to market are the most efficient models available – play a key role in limiting the rise in electricity demand in the NZE. Without these measures, electricity demand in buildings would be around 10 000 TWh higher in 2050, or around 70% higher than the level in the NZE.

SPOTLIGHT

How does the NZE compare with similar 1.5 °C scenarios assessed by the IPCC?

The IPCC SR1.5 includes 90 individual scenarios that have at least a 50% chance of limiting warming in 2100 to 1.5 °C (IPCC, 2018).[9] Only 18 of these scenarios have net-zero CO_2 energy sector and industrial process emissions in 2050. In other words, only one-in-five of the 1.5 °C scenarios assessed by the IPCC have the same level of emissions reduction

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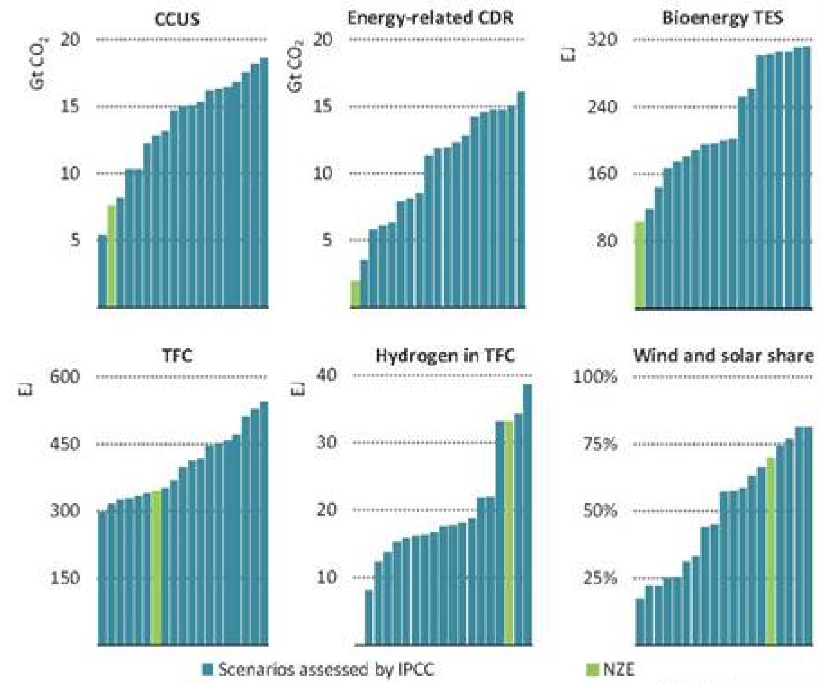
[9] Includes 53 scenarios with no or limited temperature overshoot and 37 scenarios with a higher temperature overshoot.

ambition for the energy and industrial process sectors to 2050 as the NZE.[10] Some comparisons between these 18 scenarios and the NZE in 2050 (Figure 2.11):

Figure 2.11 ▷ Comparison of selected indicators of the IPCC scenarios and the NZE in 2050



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The NZE has the lowest level of energy-related CDR and bioenergy of any scenario that achieves net-zero energy sector and industrial process CO_2 emissions in 2050

Notes: CCUS = carbon capture, utilisation and storage; CDR = carbon direct removal; TES = total energy supply; TFC = total final consumption. Energy-related CDR includes CO_2 captured through bioenergy with CCUS and direct air capture with CCUS and put into permanent storage. Wind and solar share are given as a percentage of total electricity generation. Only 17 of the 18 scenarios assessed by the IPCC report hydrogen use in TFC.

- **Use of CCUS.** The scenarios assessed by the IPCC have a median of around 15 Gt CO_2 captured using CCUS in 2050, more than double the level in the NZE.
- **Use of CDR.** CO_2 emissions captured and stored from BECCS and DACCS in the IPCC scenarios range from 3.5-16 Gt CO_2 in 2050, compared with 1.9 Gt CO_2 in the NZE.

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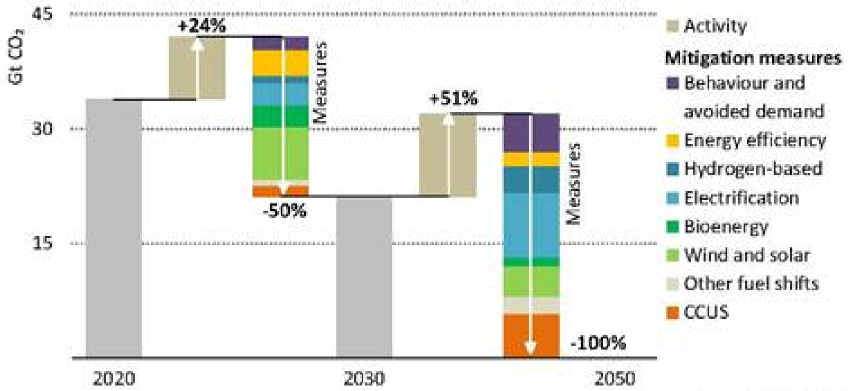
[10] The low-energy demand scenario has around 4.5 Gt CO_2 energy sector and industrial process emissions in 2050 and is not included in this comparison.

- **Bioenergy.** The IPCC scenarios use a median of 200 EJ of primary bioenergy in 2050 (compared with 63 EJ today) and a number use more than 300 EJ. The NZE uses 100 EJ of primary bioenergy in 2050.
- **Energy efficiency.** Total final consumption in the IPCC scenarios range from 300-550 EJ in 2050 (compared with around 410 EJ in 2020). The NZE has final energy consumption of 340 EJ in 2050.
- **Hydrogen.** The IPCC scenarios have a median of 18 EJ hydrogen in total final consumption in 2050, compared with 33 EJ in the NZE.[11]
- **Electricity generation.** The shares of wind and solar in total electricity generation in 2050 in the IPCC scenarios range from around 15-80% with a median value of 50%. In the NZE, wind and solar provide 70% of total generation in 2050.

2.5 Key pillars of decarbonisation

Achieving the rapid reduction in CO_2 emissions over the next 30 years in the NZE requires a broad range of policy approaches and technologies (Figure 2.12). The key pillars of decarbonisation of the global energy system are energy efficiency, behavioural changes, electrification, renewables, hydrogen and hydrogen-based fuels, bioenergy and CCUS.

Figure 2.12 ▹ **Emissions reductions by mitigation measure in the NZE, 2020-2050**



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Solar, wind and energy efficiency deliver around half of emissions reductions to 2030 in the NZE, while electrification, CCUS and hydrogen ramp up thereafter

Notes: Activity = energy service demand changes from economic and population growth. Behaviour = energy service demand changes from user decisions, e.g. changing heating temperatures. Avoided demand = energy service demand changes from technology developments, e.g. digitalisation. Other fuel shifts = switching from coal and oil to natural gas, nuclear, hydropower, geothermal, concentrating solar power or marine.

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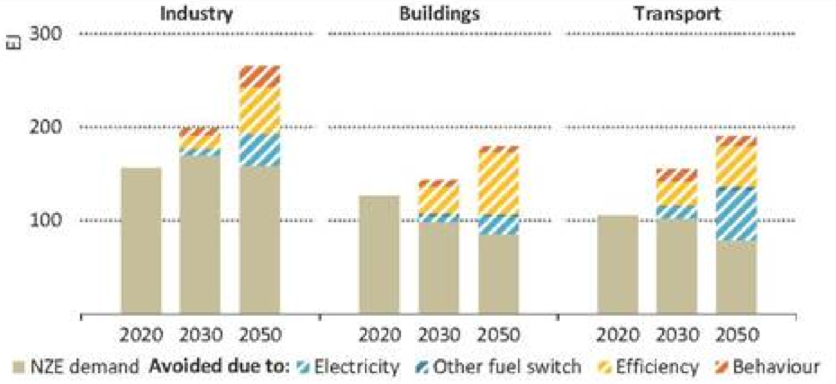
[11] The NZE value for hydrogen includes the total energy content of hydrogen and hydrogen-based fuels consumed in final energy consumption.

2.5.1 Energy efficiency

Minimising energy demand growth through improvements in energy efficiency makes a critical contribution in the NZE. Many efficiency measures in industry, buildings, appliances and transport can be put into effect and scaled up very quickly. As a result, energy efficiency measures are front-loaded in the NZE, and they play their largest role in curbing energy demand and emissions in the period to 2030. Although energy efficiency improves further after 2030, its contribution to overall emissions reductions falls as other mitigation measures play an expanding role. Without the energy efficiency, behavioural changes and electrification measures deployed in the NZE, final energy consumption would be around 300 EJ higher in 2050, almost 90% above the 2050 level in the NZE (Figure 2.13). Efficiency improvements also help reduce the vulnerability of businesses and consumers to potential disruptions to electricity supplies.

Figure 2.13 ▷ Total final consumption and demand avoided by mitigation measure in the NZE



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Energy efficiency plays a key role in reducing energy consumption across end-use sectors

Notes: CCUS = carbon capture utilisation and storage. Other fuel switch includes switching to hydrogen-related fuels, bioenergy, solar thermal, geothermal, or district heat.

In the buildings sector, many efficiency measures yield financial savings as well as reducing energy use and emissions. In the NZE, there are immediate and rapid improvements in energy efficiency in buildings, mainly from large-scale retrofit programmes. Around 2.5% of existing residential buildings in advanced economies are retrofitted each year to 2050 in the NZE to comply with zero-carbon-ready building standards[12] (compared with a current retrofit rate of less than 1%). In emerging market and developing economies, building replacement

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[12] A zero-carbon-ready building is highly energy efficient and uses either renewable energy directly or from an energy supply that will be fully decarbonised by 2050 in the NZE (such as electricity or district heat). A zero-carbon-ready building will become a zero-carbon building by 2050, without further changes to the building or its equipment (see Chapter 3).

rates are higher and the annual rate of retrofits is around 2% through to 2050. By 2050, the vast majority of existing residential buildings are retrofitted to be zero-carbon buildings. Energy-related building codes are introduced in all regions by 2030 to ensure that virtually all new buildings constructed are zero-carbon-ready. Minimum energy performance standards and replacement schemes for low-efficiency appliances are introduced or strengthened in the 2020s in all countries. By the mid-2030s, nearly all household appliances sold worldwide are as efficient as the most efficient models available today.

In the transport sector, stringent fuel-economy standards and ensuring no new passenger cars running on internal combustion engines (ICEs) are sold globally from 2035 result in a rapid shift in vehicle sales toward much more efficient electric vehicles (EVs).[13] The impact on efficiency is seen in the 2030s, as the composition of the vehicle stock changes: electric cars make up 20% of all cars on the road in 2030 and 60% in 2040 (compared with 1% today). Continuous improvements in the fuel economy of heavy road vehicles take place through to 2050 as they switch to electricity or fuel cells, while efficiency in shipping and aviation improves as more efficient planes and ships replace existing stock.

In the industry sector, most manufacturing stock is already quite efficient, but there are still opportunities for energy efficiency improvements. Energy management systems, best-in-class industrial equipment such as electric motors, variable speed drives, heaters and grinders are installed, and process integration options such as waste heat recovery are exploited to their maximum economic potentials in the period to 2030 in the NZE. After 2030, the rate of efficiency improvement slows because many of the technologies needed to reduce emissions in industry in the NZE require more energy than their equivalent conventional technologies. The use of CCUS, for example, increases energy consumption to operate the capture equipment, and producing electrolytic hydrogen on-site requires additional energy than that needed for the main manufacturing process.

Table 2.3 ⊳ **Key global milestones for energy efficiency in the NZE**

Sector	2020	2030	2050
Total energy supply	*2010-20*	*2020-30*	*2030-50*
Annual energy intensity improvement (MJ per USD GDP)	-1.6%	-4.2%	-2.7%
Industry			
Energy intensity of direct reduced iron from natural gas (GJ per tonne)	12	11	10
Process energy intensity of primary chemicals (GJ per tonne)	17	16	15
Transport			
Average fuel consumption of ICE heavy trucks fleet (index 2020=100)	100	81	63
Buildings			
Share of zero-carbon-ready buildings in total stock	<1%	25%	>85%
New buildings: heating & cooling energy consumption (index 2020=100)	100	50	20
Appliances: unit energy consumption (index 2020=100)	100	75	60

Notes: ICE = internal combustion engine; zero-carbon-ready buildings = see description in section 3.7.

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[13] In 2020, the average battery electric car required around 30% of the energy of the average ICE car to provide the same level of activity.

2.5.2 *Behavioural change*

The wholescale transformation of the energy sector demonstrated in the NZE cannot be achieved without the active and willing participation of citizens. It is ultimately people who drive demand for energy-related goods and services, and societal norms and personal choices will play a pivotal role in steering the energy system onto a sustainable path. Just under 40% of emissions reductions in the NZE result from the adoption of low-carbon technologies that require massive policy support and investment but little direct engagement from citizens or consumers, e.g. technologies in electricity generation or steel production. A further 55% of emissions reductions require a mixture of the deployment of low-carbon technologies and the active involvement or engagement of citizens and consumers, e.g. installing a solar water heater or buying an EV. A final 8% of emissions reductions stem from behavioural changes and materials efficiency gains that reduce energy demand, e.g. flying less for business purposes (Figure 2.14). Consumer attitudes can also impact investment decisions by businesses concerned about public image.

In the NZE, behavioural change refers to changes in ongoing or repeated behaviour on the part of consumers which impact energy service demand or the energy intensity of an energy-related activity.[14] Reductions in energy service demand in the NZE also come from advances in technology, but these are not counted as behavioural changes. For example, increased digitalisation and a growing market share of smart appliances, such as smart thermostats or space-differentiated thermal controls reduce the necessity for people to play an active role in energy saving in homes over time in the NZE.

There are three main types of behavioural change included in the NZE. A wide range of government interventions could be used to motivate these changes (see section 2.7.1).

- **Reducing excessive or wasteful energy use.** This includes reducing energy use in buildings and on roads, e.g. by reducing indoor temperature settings, adopting energy saving practices in homes and limiting driving speeds on motorways to 100 kilometres per hour.
- **Transport mode switching.** This includes a shift to cycling, walking, ridesharing or taking buses for trips in cities that would otherwise be made by car, as well as replacing regional air travel by high-speed rail in regions where this is feasible. Many of these types of behavioural changes would represent a break in familiar or habitual ways of life and as such would require a degree of public acceptance and even enthusiasm. Many would also require new infrastructure, such as cycle lanes and high-speed rail networks, clear policy support and high quality urban planning.
- **Materials efficiency gains.** This includes reduced demand for materials, e.g. higher rates of recycling, and improved design and construction of buildings and vehicles. The scope for gains to some extent reflects societal preferences. For instance, in some places there

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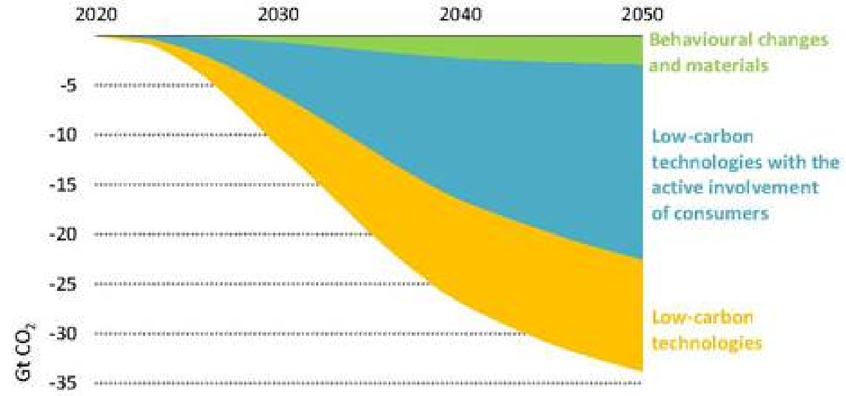
[14] This means, for example, that purchasing an electric heat pump instead of a gas boiler is not considered as a behavioural change, as it is both an infrequent event and does not necessarily impact energy service demand.

has been a shift away from the use of single-use plastics in recent years, a trend that accelerates in the NZE. Gains in materials efficiency depend on a mixture of technical innovation in manufacturing and buildings construction, standards and regulations to support best-practice and ensure universal adoption of these innovations, and increased recycling in society at large.

Figure 2.14 ▷ Role of technology and behavioural change in emissions reductions in the NZE



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Around 8% of emissions reductions stem from behavioural changes and materials efficiency

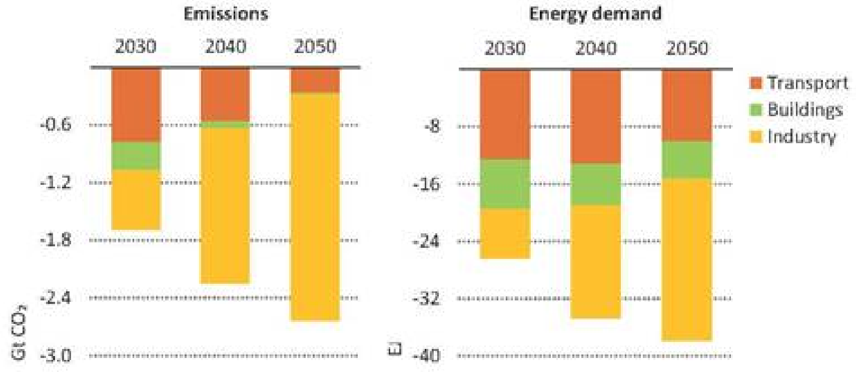
Notes: Low-carbon technologies include low-carbon electricity generation, low-carbon gases in end-uses and biofuels. Low-carbon technologies with the active involvement of citizens includes fuel switching, electrification and efficiency gains in end-uses. Behavioural changes and materials efficiency includes transport mode switching, curbing excessive or wasteful energy use, and materials efficiency measures.

Three-quarters of the emissions reductions from behavioural changes in the NZE are achieved through targeted government policies supported by infrastructure development, e.g. a shift to rail travel supported by high-speed railways. The remainder come from adopting voluntary changes in energy saving habits, mainly in homes. Even in this case, public awareness campaigns can help shape day-to-day choices about how consumers use energy. (Details of what governments can do to help bring about behavioural changes are discussed in Chapter 4).

Behavioural changes reduce energy-related activity by around 10-15% on average over the period to 2050 in the NZE, reducing overall global energy demand by over 37 EJ in 2050 (Figure 2.15). In 2030, around 1.7 Gt CO_2 emissions are avoided, 45% of which come from transport, notably through measures to phase out car use in cities and to improve fuel economy. For example, reducing speed limits on motorways to 100 km/h reduces emissions from road transport by 3% or 140 Mt CO_2 in 2030. A shift away from single occupancy car use towards ridesharing or cycling and walking in large cities saves a further 185 Mt CO_2. Around

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**



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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.

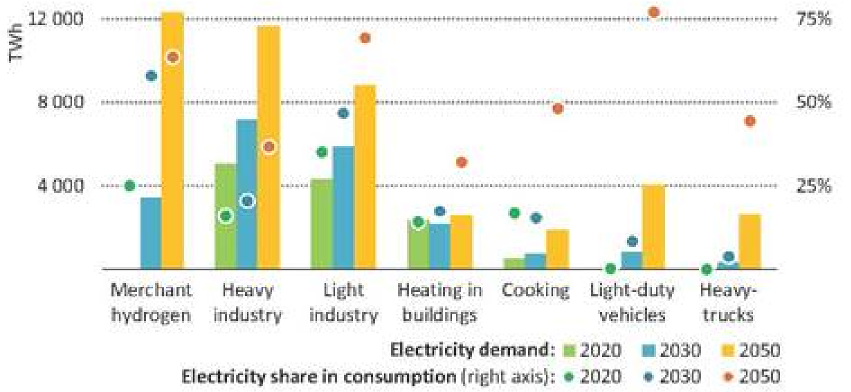
Note: Eco-driving involves pre-emptive stopping and starting; ICE = internal combustion engine.

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**



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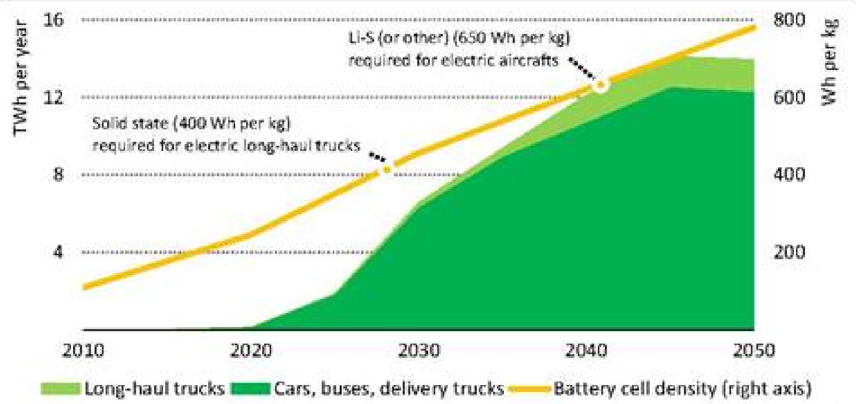
Global electricity demand more than doubles in the period to 2050, with the largest rises to produce hydrogen and in industry

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



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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.

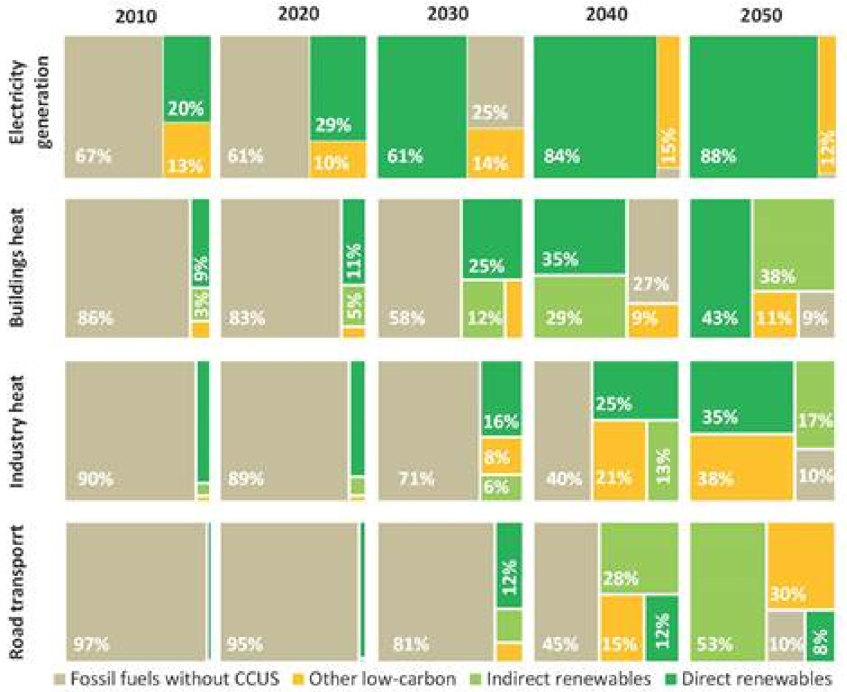
Table 2.5 ▷ Key global milestones for electrification in the NZE

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%

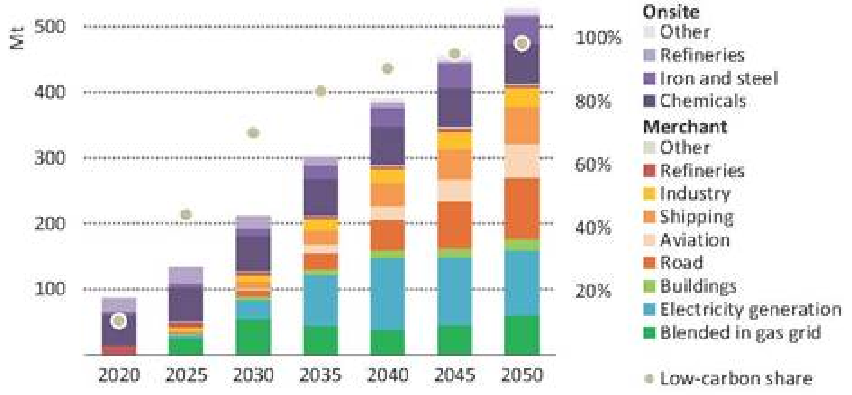
Note: TFC = total final consumption.

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



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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

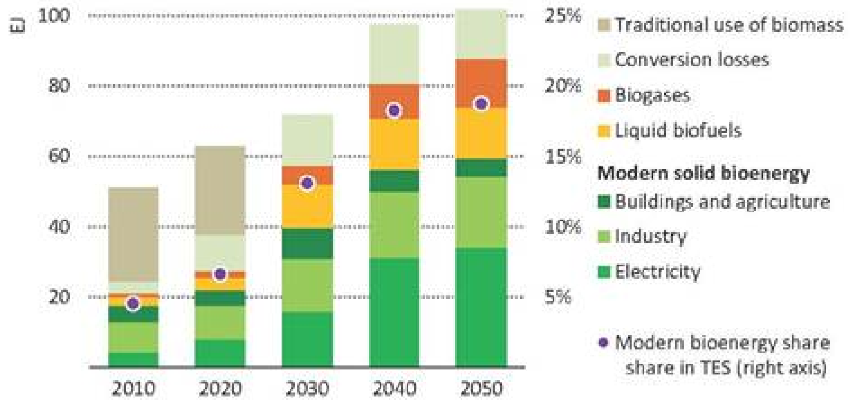
Sector	2020	2030	2050
Total production hydrogen-based fuels (Mt)	**87**	**212**	**528**
Low-carbon hydrogen production	9	150	520
share of fossil-based with CCUS	*95%*	*46%*	*38%*
share of electrolysis-based	*5%*	*54%*	*62%*
Merchant production	15	127	414
Onsite production	73	85	114
Total consumption 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



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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

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[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.

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[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).

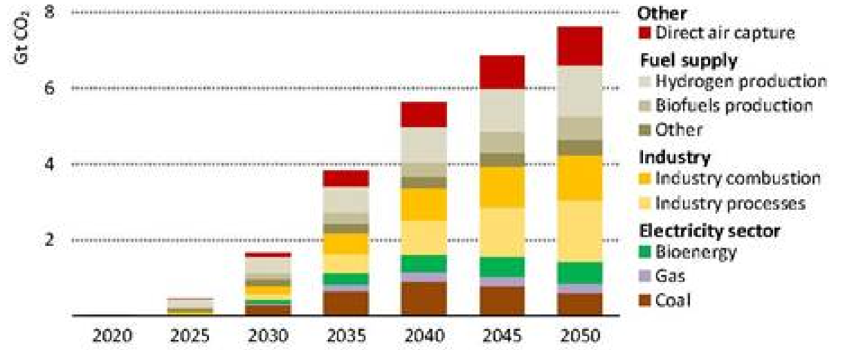
2.5.7 Carbon capture, utilisation and storage

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



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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.

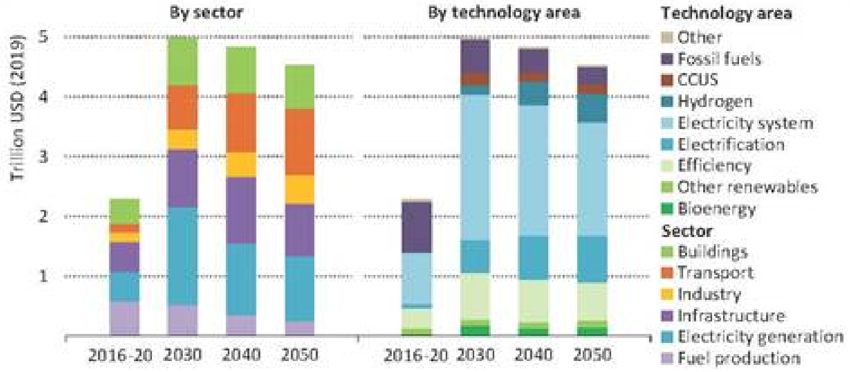
Table 2.9 ▷ Key global milestones for CCUS

	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



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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

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[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).

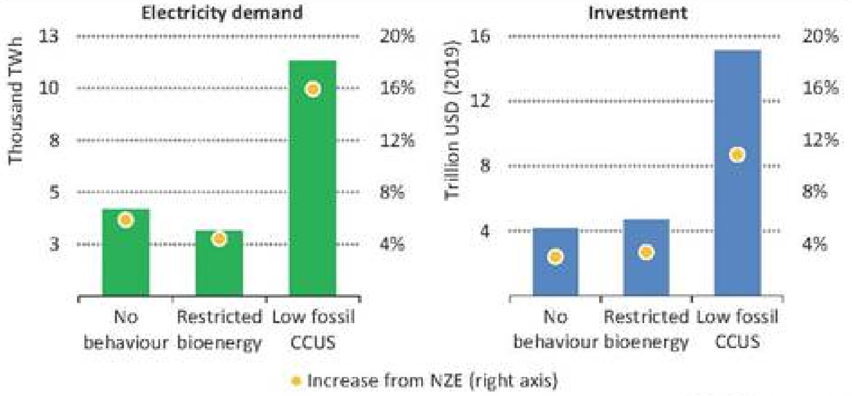
Financing the investment needed in the NZE involves redirecting existing capital towards clean energy technologies and substantially increasing the overall level of investment in energy. Most of this increase in investment comes from private sources, mobilised by public policies that create incentives, 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



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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.

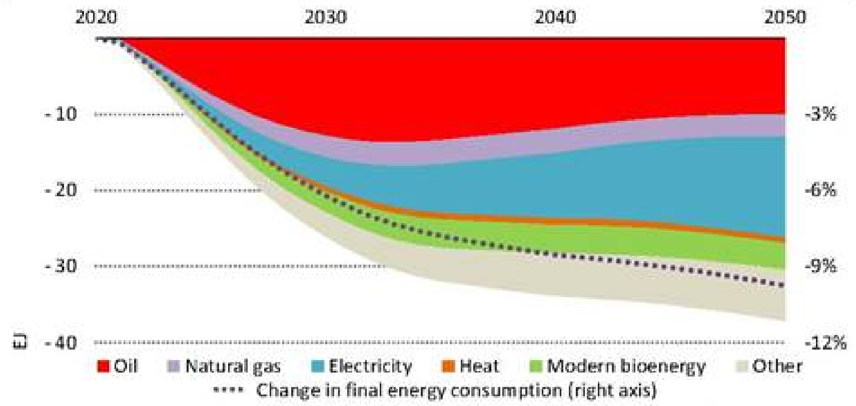
- Bioenergy use grows by 60% between 2020 and 2050 in the NZE and land use for its propagation increases by around 25%. Bioenergy use in 2050 in the NZE is well below current best estimates of global sustainable bioenergy potential, but there is a high degree of uncertainty concerning this level. If 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



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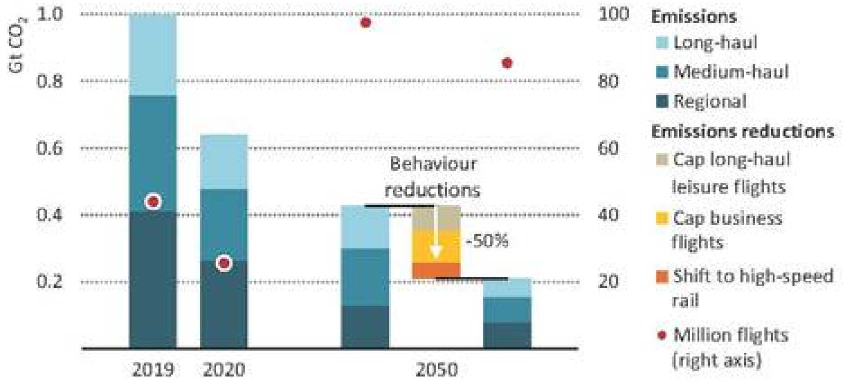
The impact of behaviour changes and materials efficiency on final energy consumption increases over time

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



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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.

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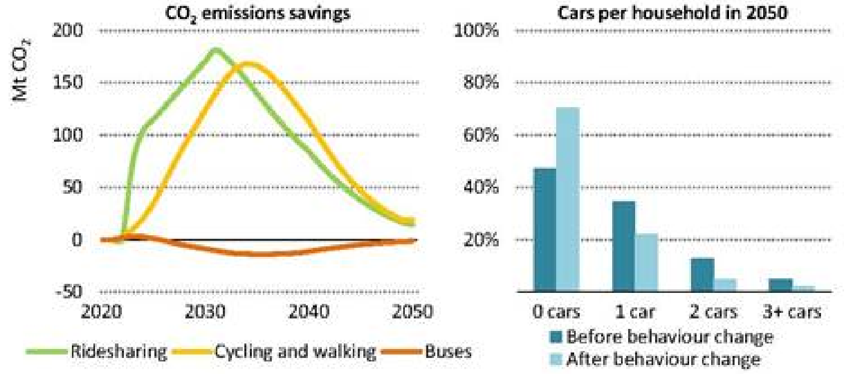
[18] This assumes that: new rail routes avoid water bodies and tunnelling through elevated terrain; travel times are similar to aviation; and centres of demand are sufficiently large to ensure that high-speed rail is economically viable.

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

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[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

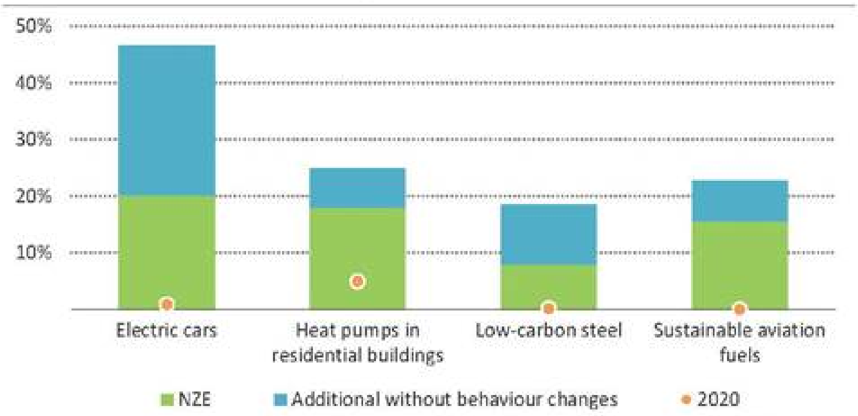
Notes: Large cities = cities over 1 million inhabitants. ICE = internal combustion engine. CO_2 emissions impact = cumulative reductions 2020-2050. Eco-driving = early upshifting as well as avoiding sudden acceleration, stops or idling. The number of jobs that can be done at home varies considerably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



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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.

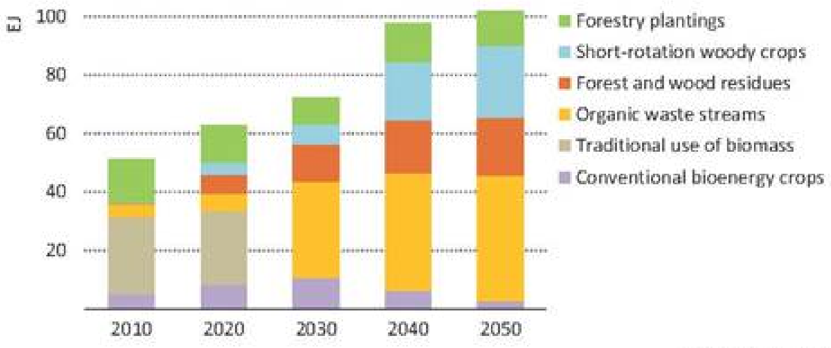
The level of bioenergy use in the NZE takes account of these constraints: bioenergy demand in 2050 is around 100 EJ. The global sustainable bioenergy potential in 2050 has been assessed to be at least 100 EJ (Creutzig, 2015) and recent assessments estimate a potential between 150-170 EJ when integrating 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.

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[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.

Total land use for bioenergy in the NZE is well below estimated ranges of potential land availability that take full account of sustainability constraints, including the need to protect biodiversity hotspots and to meet the UN Sustainable Development Goal 15 on biodiversity and land use. The certification of bioenergy products and strict control of what land can be converted to expand forestry plantations and woody energy crops nevertheless is critical to avoid land-use conflict issues. Certification is also critical to ensure the integrity of CO_2 offsets (see Chapter 1), the use of which should be carefully managed and restricted to sectors that lack alternative mitigation options. A related land-use issue is how to tackle emissions that arise from outside the energy sector (Box 2.3).

Box 2.3 ▷ Balancing emissions from land use, agriculture and forestry

To limit the global temperature rise, all sources of GHG emissions need to decline to close to zero or to be offset with CDR. The energy sector accounted for around three quarters of total GHG emissions in recent years. The largest source of GHG emissions other than the energy sector is agriculture, forestry and other land use (AFOLU), which produced between 10-12 Gt CO_2-eq net GHG emissions in recent years.[24] CO_2 emissions from AFOLU were around 5-6 Gt CO_2, and nitrous oxide and methane emissions were around 5-6 Gt CO_2-eq (IPCC, 2019).

Options to reduce emissions from AFOLU and enhance removals include: halting deforestation; improving forest management practices; instituting farming practices that increase soil carbon levels; and afforestation. A number of companies have recently expressed interest in these sorts of nature-based solutions to offset emissions from their operations (see Chapter 1). For afforestation, converting around 170 Mha (roughly half the size of India) to forests would sequester around 1 Gt CO_2 annually by 2050.

Achieving net-zero energy-related and industrial process CO_2 emissions by 2050 in the NZE does not rely on any offsets from outside the energy sector. But commensurate action on AFOLU would help limit climate change. The energy-sector transformation in the NZE would reduce CO_2 emissions from AFLOU in 2050 by around 150 Mt CO_2 given the switch away from conventional crops and the increase in short rotation advanced-bioenergy crop production on marginal lands and pasture land. To reduce emissions from AFOLU further would require reducing deforestation by two-thirds by 2050, instituting improved forest management practices and planting around 250 Mha of new forests. The combined impact of these changes would reduce CO_2 emissions from AFOLU to zero by 2040 and absorb 1.3 Gt CO_2 annually by 2050. In this case, cumulative AFOLU CO_2 emissions between 2020 and 2050 would be around 40 Gt CO_2.

Non-CO_2 emissions from livestock, as well as other agricultural emissions, may be more difficult to mitigate given the link between livestock production and nitrous oxide and methane emissions. Changes to farming practices and technology improvements,

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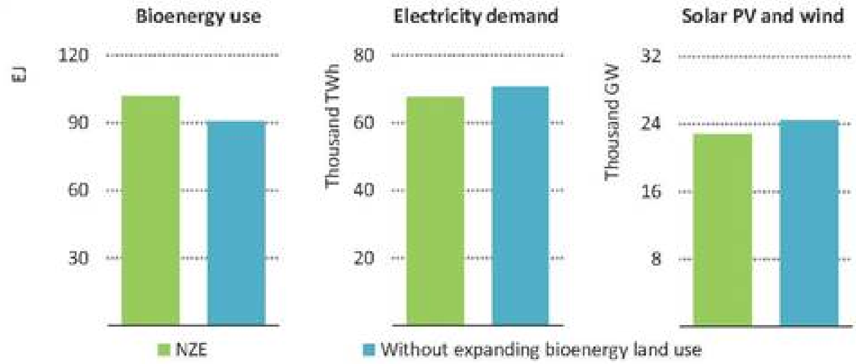
[24] AFOLU emissions are emissions from anthropogenic activities and do not include CO_2 emissions removal from the atmosphere by natural land sinks.

including changes to animal feed, could help to reduce these emissions, but it may be necessary to use afforestation to offset these emissions entirely. An alternative could be to reduce these emissions by reducing the demand for livestock products. For example, we estimate that reducing meat consumption in households with the highest levels of per capita consumption today to the global average level would reduce GHG emissions by more than 1 Gt CO_2-eq in 2050. Lower demand for livestock products would reduce the pasture needed globally for livestock by close to 200 Mha and the cropland that is used to grow feed for livestock by a further 80 Mha.

Are net-zero emissions by 2050 possible without expanding land use for bioenergy?

Estimates of the global sustainable bioenergy potential are subject to a high degree of uncertainty, in particular over the extent to which new land area could sustainably be converted to bioenergy production. As a result, the NZE takes a cautious approach to bioenergy use, with consumption in 2050 (100 EJ) well below the latest estimates that integrate relevant SDGs, which suggest a potential between 150-170 EJ. But it is possible that the land available to provide sustainable bioenergy is even more limited. Here we explore the implications for emissions of restricting land use for dedicated bioenergy crops and forestry plantations to around 330 Mha, which is what is used today.

Figure 2.29 ▷ Impact on electricity demand and ability to achieve net-zero emissions by 2050 without expanded bioenergy land use



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Achieving net-zero emissions without expanding bioenergy land use would require a further 3 200 TWh from solar PV and wind, increasing capacity in the NZE by nearly 10%

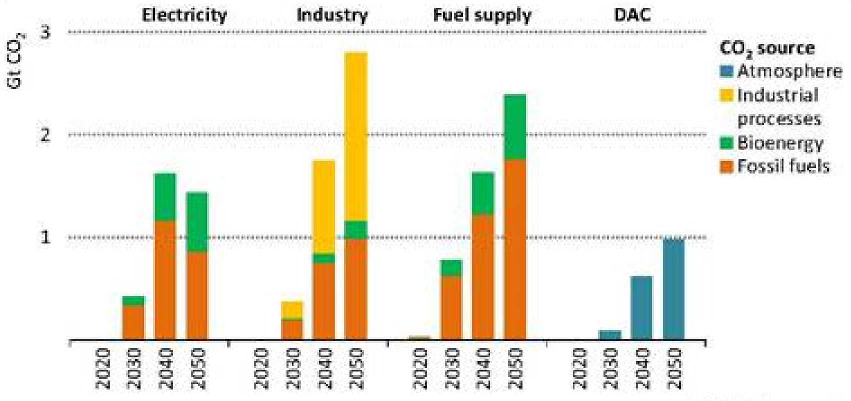
Limiting land use to 330 Mha would reduce available bioenergy supply in 2050 by more than 10 EJ. This would mostly take the form of a reduction in the availability of short-rotation woody energy crops, which are mainly used in the NZE in place of fossil fuels to provide high temperature heat for industrial processes and for electricity generation. Without bioenergy, it is likely that hydrogen and synthetic methane would be used instead, and their production would require around 70 Mt of hydrogen in 2050 (15% more than in the NZE). If this were to be produced through the use of electrolysis it would require around 750 GW of electrolyser capacity and increase electricity demand in 2050 by around 3 200 TWh (Figure 2.29).

The additional electricity that would be needed could be produced using renewables, which would require an additional 1 700 GW of wind and solar PV capacity and almost 350 GW of additional battery capacity in 2050. Annual capacity additions during the 2030s would need to be 160 GW higher than in the NZE. The additional wind, solar, battery and electrolyser capacity, together with the electricity networks and storage needed to support this higher level of deployment would cost more than USD 5 trillion by 2050. This is USD 4.5 trillion more than would be needed if the use of bioenergy were to be expanded as envisaged in the NZE, and would increase the total investment needed in the NZE by 3%. While it might therefore be possible still to achieve net-zero emissions in 2050 without expanding land use for bioenergy, this would make the energy transition significantly more expensive.

2.7.3 CCUS applied to emissions from fossil fuels

A total of 7.6 Gt CO_2 is captured in 2050 in the NZE, almost 50% of which is from fossil fuel combustion, 20% is from industrial processes, and around 30% is from bioenergy use with CO_2 capture and DAC (Figure 2.30). The use of CCUS with fossil fuels provides almost 70% of the total growth in CCUS to 2030 in the NZE. Yet the prospects for the rapid scaling up of CCUS are very uncertain for economic, political and technical reasons. Here we look at the implications for reaching net-zero emissions in 2050 if fossil fuel CCUS does not expand beyond existing and planned projects.

Figure 2.30 ▷ **CCUS by sector and emissions source in the NZE**



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Fossil fuel emissions account for almost 70% of total CO_2 capture in 2030 and almost 50% in 2050

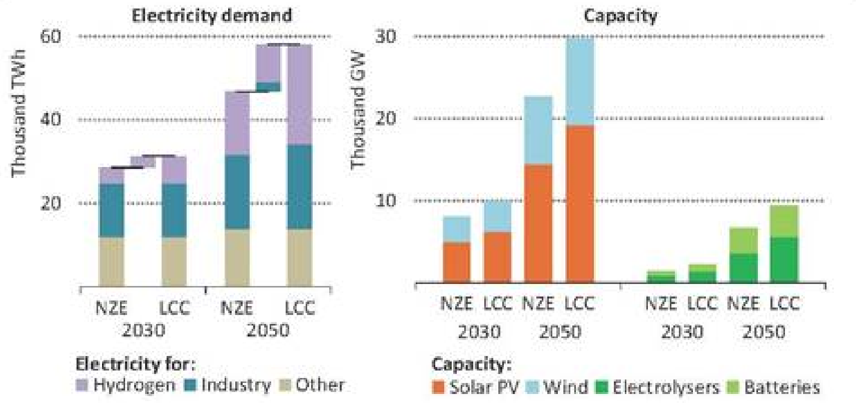
Note: DAC = direct air capture.

Are net-zero emissions by 2050 possible without fossil fuel-based CCUS?

Fossil fuel-based CCUS applications comprise most of the CCUS projects added to 2030 in the NZE. These projects help to reduce risks for other non-fossil fuel CCUS applications that are essential to reach net zero. In view of the challenges that fossil fuel-based CCUS projects face, we have constructed a *Low CCUS Case (LCC)* in which no new fossil fuel CCUS projects are developed beyond those already under construction or approved for development. In the LCC, CO_2 emissions captured from fossil fuels are only around 150 Mt in 2050, compared with 3 600 Mt in 2050 in the NZE.

In industry, the lack of new fossil fuel CCUS projects leads in the LCC to 1.2 Gt of additional CO_2 emissions compared with the NZE in 2050. It would be necessary to use alternative technologies to eliminate these emissions in order to achieve net zero by 2050. A number of technologies that are at the prototype stage of development would be needed, such as electric cement kilns or electric steam crackers for high-value chemicals production (see Box 2.4). Assuming that these technologies could be demonstrated and deployed at scale, this would increase electricity demand by around 2 400 TWh and hydrogen demand in industry by around 45 Mt in 2050. It would also be necessary to replace the 145 Mt of hydrogen that is produced in the NZE from fossil fuels equipped with CCUS. Provision of this 190 Mt of hydrogen through electrolysis would require an additional 2 000 GW capacity of electrolysers in 2050 (almost 60% more than in the NZE) and an additional 9 000 TWh of electricity (Figure 2.31).

Figure 2.31 ▷ Impacts of achieving net-zero emissions by 2050 without expanded fossil fuel-based CCUS



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Failure to deploy fossil fuel-based CCUS would significantly increase electricity demand and require much more solar, wind and electrolyser capacity

Note: LCC = Low CCUS Case where CCUS applied to fossil fuels is restricted to projects under construction or approved for development today.

Box 2.4 ▷ Technology innovation in the NZE

Innovation is key to developing new clean energy technologies and advancing existing ones. The importance of innovation increases as we get closer to 2050 because existing technologies will not be able to get us all the way along the path to net-zero emissions. Almost 50% of the emissions reductions needed in 2050 in the NZE depend on technologies that are at the prototype or demonstration stage, i.e. are not yet available on the market (see Chapter 4).

After a new idea makes its way from the drawing board to the laboratory and out into the world, there are four key stages in the clean energy innovation pipeline (IEA, 2020d). But the pathway to maturity can be long and success is not guaranteed.

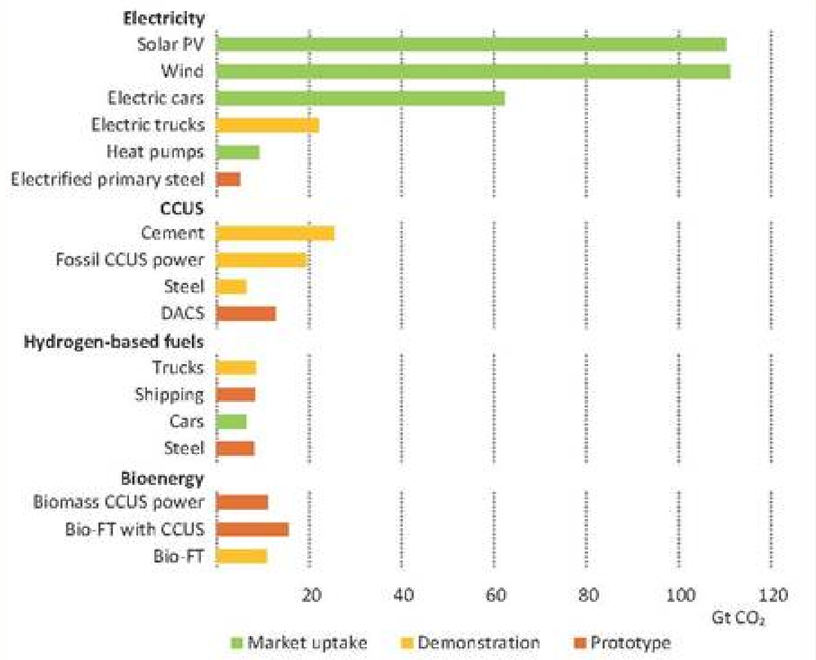
- **Prototype.** A concept is developed into a design and then into a prototype for a new device, e.g. a furnace that produces steel with pure hydrogen instead of coal.
- **Demonstration.** The first examples of a new technology are introduced at the size of a full-scale commercial unit, e.g. a system that captures CO_2 emissions from cement plants.
- **Market uptake.** The technology is being deployed in a number of markets. However, it either has a cost and performance gap with established technologies (e.g. electrolysers for hydrogen production) or it is competitive but there are still barriers, such as integration with existing infrastructure or consumer preferences, to reaching its full market potential (e.g. heat pumps). Policy attention is needed in both cases to stimulate wider diffusion to reduce costs and to overcome existing barriers, with more of the costs and risks being borne gradually by the private sector.
- **Maturity.** The technology has reached market stability, and new purchases or installations are constant or even declining in some environments as newer technologies start to compete with the stock of existing assets, e.g. hydropower turbines.

Innovation is critical in the NZE to bring new technologies to market and to improve emerging technologies, including for electrification, CCUS, hydrogen and sustainable bioenergy. The degree of reliance on innovation in the NZE varies across sectors and along the various steps of the value chains involved (Figure 2.32).

- **Electrification.** Almost 30% of the 170 Gt CO_2 cumulative emissions reductions from the use of low-emissions electricity in the NZE comes from technologies that are currently at prototype or demonstration stage, such as electricity-based primary steel production or electric trucks.
- **Hydrogen.** Not all steps of the low-carbon hydrogen value chain are available on the market today. The majority of demand technologies, such as hydrogen-based steel production, are only at the demonstration or prototype stage. These deliver more than 75% of the cumulative emissions reductions in the NZE related to hydrogen.

- **CCUS.** Around 55% of the cumulative emissions reductions that come from CCUS in the NZE are from technologies that are at the demonstration or prototype stage today. While CO_2 capture has been in use for decades in certain industrial and fuel transformation processes, such as ammonia production and natural gas processing, it is still being demonstrated at a large scale in many of the other possible applications.
- **Bioenergy.** Around 45% of the cumulative emissions reductions in the NZE related to sustainable bioenergy come from technologies that are at the demonstration or prototype stage today, mainly for the production of biofuels.

Figure 2.32 ▷ **Cumulative CO_2 emissions reductions for selected technologies by maturity category in the NZE**



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CCUS, hydrogen and bioenergy technologies are less mature than electrification. Most technologies for heavy industry and trucks are at early stages of development.

Notes: Bio-FT = Biomass gasification with Fischer-Tropsch synthesis. Maturity levels are the technology design at the most advanced stage.

In the electricity sector, it would be necessary to produce an additional 11 300 TWh of electricity for industry and fuel transformation and to replace virtually all of the electricity generated from fossil fuel powered plants equipped with CCUS in 2050 in the NZE. Using renewables, this would require an additional 7 000 GW of wind and solar PV capacity in 2050. This is around 30% more than in the NZE, and would mean that annual capacity additions of solar PV and wind during the 2030s would need to reach 1 300 GW (300 GW more than in the NZE). To accommodate this additional level of variable renewables and to provide the flexibility that is available from fossil fuel CCUS equipped plants in the NZE, around 660 GW more battery capacity would be needed in 2050 (20% more than in the NZE in in 2050), together with additional 110 GW of other dispatchable capacity.

Reducing the rate of adding CCUS at existing coal- and gas-fired generation plants in the LCC would also raise the risk of stranded assets. We estimate that up to USD 90 billion of existing coal- and gas-fired capacity could be stranded in 2030 and up to USD 400 billion by 2050. Investment in fossil fuel-based CCUS in the NZE to 2050 is around USD 650 billion, which would be avoided in the LCC. But additional investment is required in the LCC for extra wind, solar and electrolyser capacity, for electricity-based routes in heavy industry, and for expanded electricity networks and storage to support this higher level of deployment. As a result, the additional cumulative investment to reach net-zero emissions in 2050 in the LCC is USD 15 trillion higher than in the NZE.

Failure to develop CCUS for fossil fuels would also be likely to delay or prevent the development of other CCUS applications. Without fossil fuel-based CCUS, the number of users and the volumes of the CO_2 transport and storage infrastructure deployed around industrial clusters would be reduced. Fewer actors and more limited pools of capital would be available to incur the high upfront costs of infrastructure, as well as other risks associated with the initial roll-out of CCUS infrastructure clusters. In addition, there would be fewer spill-over learning and cost-reduction benefits from developing fossil fuel-based CCUS, making the successful demonstration and scale up of more nascent CCUS technologies much less likely. A delay in the development of other CCUS technologies would have a major impact on the prospect of getting to net-zero emissions in 2050. For example, CCUS is the only scalable low-emissions option to remove CO_2 from the atmosphere and to almost eliminate emissions from cement production. If progress in these technologies were delayed and could not be deployed at scale, then achieving net-zero emissions by 2050 would be vastly more difficult.

Sectoral pathways to net-zero emissions by 2050

SUMMARY

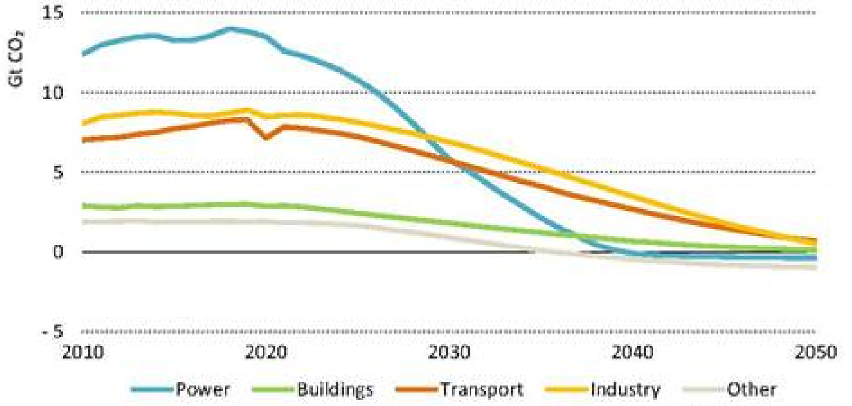
- Fossil fuel use falls drastically in the Net-Zero Emissions Scenario (NZE) by 2050, and no new oil and natural gas fields are required beyond those that have already been approved for development. No new coal mines or mine extensions are required. Low-emissions fuels – biogases, hydrogen and hydrogen-based fuels – see rapid growth. They account for almost 20% of global final energy in 2050, compared with 1% in 2020. More than 500 Mt of low-carbon hydrogen is produced in 2050, of which about 60% is produced using electrolysis that accounts for 20% of global electricity generation in 2050. Liquid biofuels provide 45% of global aviation fuel in 2050.
- Electricity demand grows rapidly in the NZE, rising 40% from today to 2030 and more than two-and-a-half-times to 2050, while emissions from generation fall to net-zero in aggregate in advanced economies by 2035 and globally by 2040. Renewables drive the transformation, up from 29% of generation in 2020 to 60% in 2030 and nearly 90% in 2050. From 2030 to 2050, 600 GW of solar PV and 340 GW of wind are added each year. The least-efficient coal plants are phased out by 2030 and all unabated coal by 2040. Investment in electricity grids triples to 2030 and remains elevated to 2050.
- In industry, emissions drop by 20% to 2030 and 90% to 2050. Around 60% of heavy industry emissions reductions in 2050 in the NZE come from technologies that are not ready for market today: many of these use hydrogen or CCUS. From 2030, all new industry capacity additions are near-zero emissions. Each month from 2030, the world equips 10 new and existing heavy industry plants with CCUS, adds 3 new hydrogen-based industrial plants and adds 2 GW of electrolyser capacity at industrial sites.
- In transport, emissions drop by 20% to 2030 and 90% to 2050. The initial focus is on increasing the operational and technical efficiency of transport systems, modal shifts, and the electrification of road transport. By 2030, electric cars account for over 60% of car sales (4.6% in 2020) and fuel cell or electric vehicles are 30% of heavy truck sales (less than 0.1% in 2020). By 2035, nearly all cars sold globally are electric, and by 2050 nearly all heavy trucks sold are fuel cell or electric. Low-emissions fuels and behavioural changes help to reduce emissions in long-distance transport, but aviation and shipping remain challenging and account for 330 Mt CO_2 emissions in 2050.
- In buildings, emissions drop by 40% to 2030 and more than 95% to 2050. By 2030, around 20% of the existing building stock worldwide is retrofitted and all new buildings comply with zero-carbon-ready building standards. Over 80% of the appliances sold are the most efficient models available by 2025 in advanced economies and by the mid-2030s worldwide. There are no new fossil fuel boilers sold from 2025, except where they are compatible with hydrogen, and sales of heat pumps soar. By 2050, electricity provides 66% of energy use in buildings (33% in 2020). Natural gas use for heating drops by 98% in the period to 2050.

Z

3.1 Introduction

The Net-Zero Emissions by 2050 Scenario (NZE) involves a global energy system transformation that is unparalleled in its speed and scope. This chapter looks at how the main sectors are transformed, as well as the specific challenges and opportunities this involves (Figure 3.1). It covers the supply of fossil and low-emissions fuels, electricity generation and the three main end-use sectors – industry, transport and buildings. For each sector, we set out some key technology and infrastructure milestones on which the NZE depends for its successful delivery. Further we discuss what key policy decisions are needed, and by when, to achieve these milestones. Recognising that there is no single pathway to achieve net-zero emissions by 2050 and that there are many uncertainties related to clean energy transitions, in this chapter we also explore the implications of choosing not to rely on certain fuels, technologies or emissions reduction options across the transformation and end-use sectors.

Figure 3.1 ▷ CO_2 emissions by sector in the NZE



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Emissions fall fastest in the power sector, with transport, buildings and industry seeing steady declines to 2050. Reductions are aided by the increased availability of low-emissions fuels

Note: Other = agriculture, fuel production, transformation and related process emissions, and direct air capture.

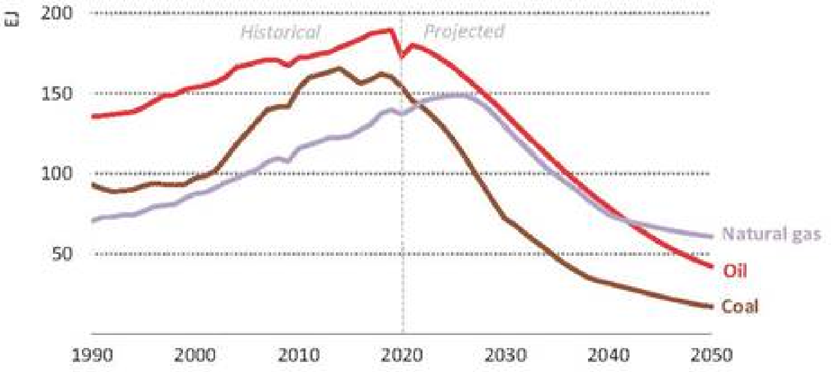
3.2 Fossil fuel supply

3.2.1 Energy trends in the Net-Zero Emissions Scenario

Coal use declines from 5 250 million tonnes of coal equivalent (Mtce) in 2020 to 2 500 Mtce in 2030 and to less than 600 Mtce in 2050. Even with increasing deployment of carbon capture, utilisation and storage (CCUS), coal use in 2050 is 90% lower than in 2020

(Figure 3.2). Oil demand never returns to its 2019 peak and it declines from 88 million barrels per day (mb/d) in 2020 to 72 mb/d in 2030 and to 24 mb/d in 2050, a fall of almost 75% between 2020 and 2050. Natural gas quickly rebounds from the dip in demand in 2020 and rises through to the mid-2020s, reaching a peak of around 4 300 billion cubic metres (bcm), before dropping to 3 700 bcm in 2030 and to 1 750 bcm in 2050. By 2050, natural gas use is 55% lower than in 2020.

Figure 3.2 ▷ Coal, oil and natural gas production in the NZE



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Between 2020 and 2050, demand for coal falls by 90%, oil by 75%, and natural gas by 55%

Oil

The trajectory of oil demand in the NZE means that no exploration for new resources is required and, other than fields already approved for development, no new oil fields are necessary. However, continued investment in existing sources of oil production are needed. On average oil demand in the NZE falls by more than 4% per year between 2020 and 2050. If all capital investment in producing oil fields were to cease immediately, this would lead to a loss of over 8% of supply each year. If investment were to continue in producing fields but no new fields were developed, then the average annual loss of supply would be around 4.5% (Figure 3.3). The difference is made up by fields that are already approved for development.

These dynamics are reflected in the oil price in the NZE, which drops to around USD 35/barrel in 2030 and USD 25/barrel in 2050. This price trajectory is largely determined by the operating costs for fields currently in operation, and only a very small volume of existing production would need to be shut in. However, income from oil production in all countries is much lower in the NZE than in recent years,[1] and the NZE projects significant stranded

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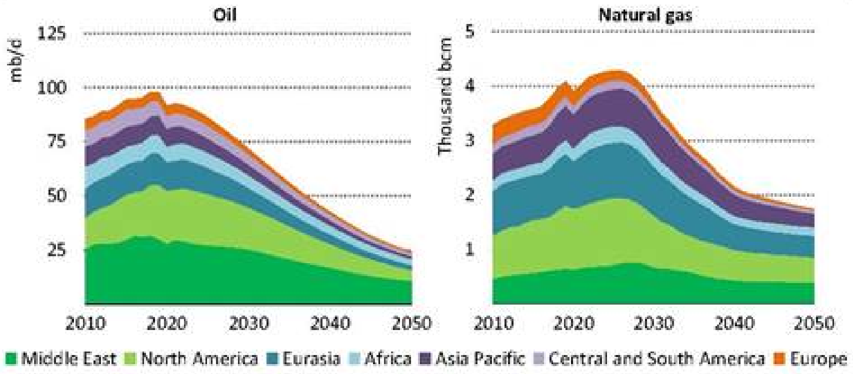
[1] Governments may also reduce or eliminate upstream taxes to ensure that production costs are below the oil price to maintain domestic production.

capital and stranded value.[2] The oil price in the NZE would be sufficient in principle to cover the cost of developing new fields for the lowest cost producers, including those in the Middle East, but it is assumed that major resource holders do not proceed with investment in new fields because doing so would create significant additional downward pressure on prices.

The refining sector also faces major challenges in the NZE. Refinery throughput drops considerably and there are significant changes in product demand. With rapid electrification of the vehicle fleet, there is a major drop in demand for traditional refined products such as gasoline and diesel, while demand for non-combusted products such as petrochemicals increases. In recent years, around 55% of oil demand was for gasoline and diesel, but this drops to less than 15% in 2050, while the share of ethane, naphtha and liquefied petroleum gas (LPG) rises from 20% in recent years to almost 60% in 2050. This shift accentuates the drop in oil demand for refiners, and refinery runs fall by 85% between 2020 and 2050. Refiners are used to coping with changing demand patterns, but the scale of the changes in the NZE would inevitably lead to refinery closures, especially for refineries not able to concentrate primarily on petrochemical operations or the production of biofuels.

Figure 3.3 ▷ Oil and natural gas production in the NZE



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No new oil and natural gas fields are required beyond those already approved for development. Supply is increasingly concentrated in a few major producing countries

Natural gas

No new natural gas fields are needed in the NZE beyond those already under development. Also not needed are many of the liquefied natural gas (LNG) liquefaction facilities currently under construction or at the planning stage. Between 2020 and 2050, natural gas traded as

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[2] Stranded capital is capital investment in fossil fuel infrastructure that is not recovered over the operating lifetime of the asset because of reduced demand or reduced prices resulting from climate policies. Stranded value is a reduction in the future revenue generated by an asset or asset owner assessed at a given point in time because of reduced demand or reduced prices resulting from climate policies (IEA, 2020a).

LNG falls by 60% and trade by pipeline falls by 65%. During the 2030s, global natural gas demand declines by more than 5% per year on average, meaning that some fields may be closed prematurely or shut in temporarily. Declines in natural gas demand slow after 2040, and more than half of natural gas use globally in 2050 is to produce hydrogen in facilities with CCUS. The large level of hydrogen, also produced using electrolysis, and biomethane in the NZE, means that the decline in total gaseous fuels is more muted than the decline in natural gas. This has important implications for the future of the gas industry (see Chapter 4).

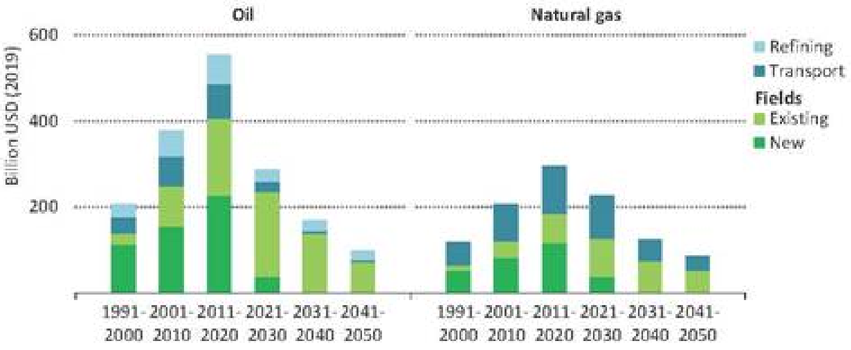
Coal

No new coal mines or extensions of existing ones are needed in the NZE as coal demand declines precipitously. Demand for coking coal falls at a slightly slower rate than for steam coal, but existing sources of production are sufficient to cover demand through to 2050. Such a decline in coal demand would have major consequences for employment in coal mining regions (see Chapter 4). There is a slowdown in the rate of decline in the 2040s as coal production facilities are increasingly equipped with CCUS: in the NZE, around 80% of coal produced in 2050 applies CCUS.

3.2.2 Investment in oil and gas

Upstream oil and gas investment averages about USD 350 billion each year from 2021 to 2030 in the NZE (Figure 3.4). This is similar to the level in 2020, but around 30% lower than average levels during the previous five years. Once fields under development start production, all of the upstream investment in the NZE is to support operations in existing fields; after 2030, total annual upstream investment is around USD 170 billion each year.

Figure 3.4 ▷ **Investment in oil and natural gas supply in the NZE**



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Once fields under development start production, all upstream oil and gas investment is spent on maintaining production at existing fields

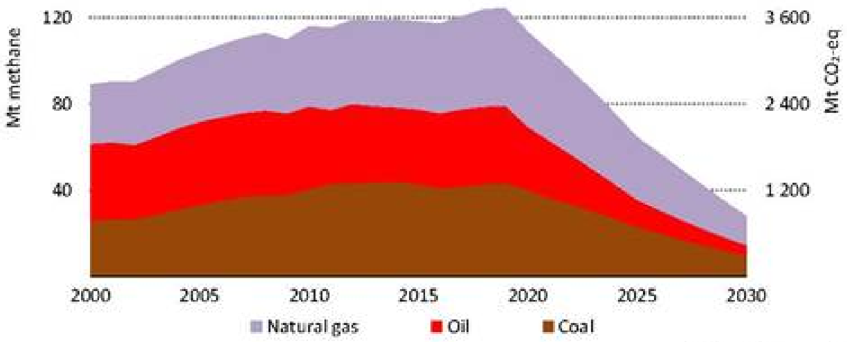
Note: Investment in new fields in the 2021-2030 period is for projects that are already under construction or have been approved.

3.2.3 *Emissions from fossil fuel production*

Emissions from the supply chains of coal, oil and natural gas fall dramatically in the NZE. The global average greenhouse gas (GHG) emissions intensity of oil production today is just under 100 kilogrammes of carbon-dioxide equivalent (kg CO_2-eq) per barrel. Without changes, a large proportion of global production would become uneconomic, as CO_2 prices are applied to the full value chains of fossil fuels. For example, by 2030 the CO_2 price in advanced economies in the NZE is USD 100 per tonne of CO_2 (tCO_2), which would add USD 10 to the cost of producing each barrel at today's average level of emissions intensity.

Methane constitutes about 60% of emissions from the coal and natural gas supply chains and about 35% of emissions from the oil supply chain. In the NZE, total methane emissions from fossil fuels fall by around 75% between 2020 and 2030, equivalent to a 2.5 gigatonne of carbon-dioxide equivalent (Gt CO_2-eq) reduction in GHG emissions (Figure 3.5). Around one-third of this decline is a result of an overall reduction in fossil fuel consumption, but the larger share comes from a huge increase in the deployment of emissions reduction measures and technologies, which leads to the elimination of all technically avoidable methane emissions by 2030 (IEA, 2020a).

Figure 3.5 ▷ Methane emissions from coal, oil and natural gas in the NZE



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Methane emissions from fossil fuels fall by 75% between 2020 and 2030 as result of a concerted global effort to deploy all available reduction measures and technologies

Note: Mt = million tonnes.

Actions to reduce the emissions intensity of existing oil and gas operations in the NZE leads to: the end of all flaring; the use of CCUS with centralised sources of emissions (including to capture natural sources of CO_2 that are often extracted with natural gas); and significant electrification of upstream operations (often making use of off-grid renewable energy sources).

The NZE inevitably brings significant challenges for fossil fuel industries and those who work in them, but it also brings opportunities. Coal mining declines dramatically in the NZE, but the mining of minerals needed for clean energy transitions increases very rapidly, and mining expertise is likely to be highly valued in this context. The oil and gas industry could play a key role in helping to develop at scale a number of clean energy technologies such as CCUS, low-carbon hydrogen, biofuels and offshore wind. Scaling up these technologies and bringing down their costs will rely on large-scale engineering and project management capabilities, qualities that are a good match to those of large oil and gas companies. These issues, including the question of how to help those affected by the major changes implied by the NZE, are discussed in more detail in Chapter 4.

3.3 Low-emissions fuel supply

3.3.1 Energy trends in the Net-Zero Emissions Scenario

Reaching net-zero emissions will require low-emissions fuels[3] where energy needs cannot easily or economically be met by electricity (Figure 3.6). This is likely to be the case for some modes of long-distance transport (trucks, aviation and shipping) and of heat and feedstock supply in heavy industry. Some low-emissions fuels are effectively drop-in, i.e. they are compatible with the existing fossil fuel distribution infrastructure and end-use technologies, and require few if any modifications to equipment or vehicles.

Low-emissions fuels today account for just 1% of global final energy demand, a share that increases to 20% in 2050 in the NZE. Liquid biofuels meet 14% of global transport energy demand in 2050, up from 4% in 2020; hydrogen-based fuels meet a further 28% of transport energy needs by 2050. Low-carbon gases (biomethane, synthetic methane and hydrogen) meet 35% of global demand for gas supplied through networks in 2050, up from almost zero today. The combined share of low-carbon hydrogen and hydrogen-based fuels in total final energy use worldwide reaches 13% in 2050. Hydrogen and ammonia also provide important low-emissions sources of power system flexibility and contribute 2% of overall electricity generation in 2050, which is enough to make the electricity sector an important driver of hydrogen demand.

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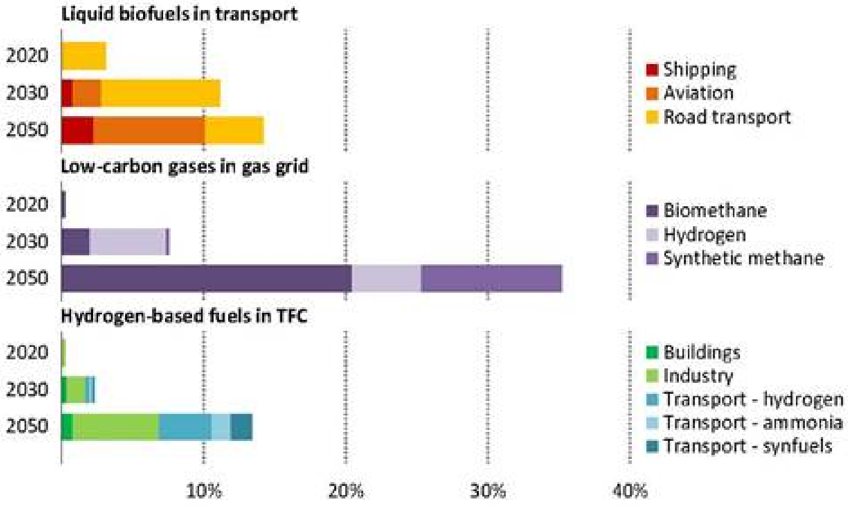
[3] Low-emissions fuels refer to liquid biofuels, biogas and biomethane, and hydrogen-based fuels (hydrogen, ammonia and synthetic hydrocarbon fuels) that do not emit CO_2 from fossil fuels directly when used and also emit very little when being produced. For example, hydrogen produced from natural gas with CCUS and high capture rates (90% or higher) is considered a low-emissions fuel, but not if produced without CCUS.

Figure 3.6 ▷ Global supply of low-emissions fuels by sector in the NZE



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Low-emissions fuels in the form of liquid biofuels, biomethane, hydrogen-based fuels help to decarbonise sectors where direct electrification is challenging

Notes: TFC = total final consumption. Low-carbon gases in the gas grid refers to the blending of biomethane, hydrogen and synthetic methane with natural gas in a gas network for use in buildings, industry, transport and electricity generation. Synfuels refer to synthetic hydrocarbon fuels produced from hydrogen and CO_2. Final energy consumption of hydrogen includes, in addition to the final energy consumption of hydrogen, ammonia and synthetic hydrocarbon fuels, the on-site hydrogen production in the industry sector.

3.3.2 Biofuels[4]

Around 10% of the global primary supply of modern bioenergy (biomass excluding traditional uses for cooking) was consumed as liquid biofuels for road transport and 6% was consumed as biogases (biogas and biomethane) to provide power and heat in 2020, with the rest directly used for electricity generation and heating in the residential sector. Supply accelerates sharply in the NZE with liquid biofuels expanding by a factor of almost four and biogases increasing by a factor of six by 2050.

All but about 7% of liquid biofuels for transport are currently produced from conventional crops such as sugarcane, corn and soybeans. Such crops directly compete with arable land that can be used for food production, which limits the scope for expanding output. So most of the growth in biofuels in the NZE comes from advanced feedstocks such as wastes and residues and woody energy crops grown on marginal lands and cropland not suitable for food

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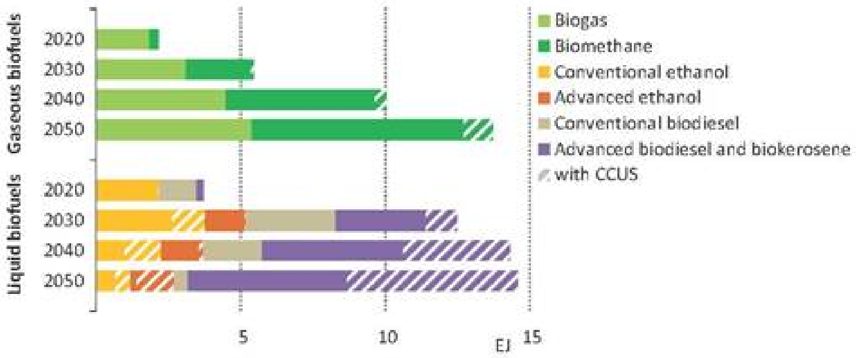
[4] Liquids and gases produced from bioenergy.

production (see section 2.7.2). Advanced liquid biofuel production technology using woody feedstock expands rapidly over the next decade in the NZE, and its contribution to liquid biofuels jumps from less than 1% in 2020 to almost 45% in 2030 and 90% in 2050 (Figure 3.7). By 2030, production reaches 2.7 million barrels of oil equivalent per day (mboe/d) by 2030, underpinned by biomass gasification using the Fischer-Tropsch process (bio-FT) and cellulosic ethanol, mostly to produce drop-in substitutes for diesel and jet kerosene. Advanced liquid biofuel production increases by an additional 130% to more than 6 mboe/d in 2050, the bulk of which is biokerosene.

Figure 3.7 ▷ **Global biofuels production by type and technology in the NZE**



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Liquid biofuel production quadruples while that of biogases expands sixfold between 2020 and 2050, underpinned by the development of sustainable biomass supply chains

Notes: EJ = exajoules; CCUS = carbon capture, utilisation and storage. Conventional ethanol refers to production using food energy crops. Advanced ethanol refers to production using wastes and residues and non-food energy crops grown on marginal and non-arable land. Conventional biodiesel includes fatty acid and methyl esters (FAME) route using food energy crops. Advanced biodiesel includes biomass-based Fischer-Tropsch and HEFA routes using wastes, residues and non-food energy crops grown on marginal and non-arable land. Biomethane includes biogas upgrading and biomass gasification-based routes.

Production using these feedstocks is mostly under development today. Current output capacity, principally cellulosic ethanol, is about 2.5 thousand barrels of oil equivalent per day (kboe/d). The NZE assumes that projects currently in the pipeline in Japan, the United Kingdom and the United States will bring these technologies to the market within the next few years. The scale up required for all advanced liquid biofuels (including from waste oils) over the next decade is equivalent to building one 55 kboe/d biorefinery every ten weeks (the world's largest biorefinery has capacity of 28 kboe/d).

The supply of these biofuels after 2030 shifts rapidly in the NZE from passenger vehicles and light trucks, where electrification is increasingly the order of the day, to heavy road freight, shipping and aviation. Ammonia makes inroads into shipping. Advanced liquid biofuels increase their share of the global aviation fuel market from 15% in 2030 to 45% in 2050.

Advanced biofuels such as hydrogenated esters and fatty acids (HEFA) and bio-FT are able to adjust their product slates (up to a point) from renewable diesel to biokerosene, and existing ethanol plants, especially those that can be retrofitted with CCUS or integrated with cellulosic feedstock, also make a contribution.

The supply of biogases increases even more than liquid biofuels. Injection into gas networks expands from under 1% of total gas volume in 2020 to almost 20% in 2050, reducing the emissions intensity of the network-based gas. Biomethane is mostly produced by upgrading biogas produced from anaerobic digestion of feedstocks such as agricultural residues like manure and biogenic municipal solid waste, thereby avoiding methane emissions that would otherwise be released. Due to the dispersed nature of these feedstocks, this assumes the construction of thousands of injection sites and associated distribution lines every year. Biogas and biomethane are also used as clean cooking fuels and in electricity generation in the NZE.

The production of biofuels can be combined with CCUS at a relatively low cost in some biofuel production routes (ethanol, bio-FT, biogas upgrading) because the processes involved release very pure streams of CO_2. In the NZE, the use of biofuels with CCUS results in annual carbon dioxide removal (CDR) of 0.6 Gt CO_2 in 2050, which offset residual emissions in transport and industry.

3.3.3 Hydrogen and hydrogen-based fuels

Hydrogen use in the energy sector today is largely confined to oil refining and the production of ammonia and methanol in the chemicals industry. Global hydrogen demand was around 90 million tonnes (Mt) in 2020, mainly produced from fossil fuels (mostly natural gas) and emitting close to 900 Mt CO_2. Both the amount needed and the production route of hydrogen change radically in the NZE. Demand increases almost sixfold to 530 Mt in 2050, of which half is used in heavy industry (mainly steel and chemicals production) and in the transport sector; 30% is converted into other hydrogen-based fuels, mainly ammonia for shipping and electricity generation, synthetic kerosene for aviation and synthetic methane blended into gas networks; and 17% is used in gas-fired power plants to balance increasing electricity generation from solar PV and wind and to provide seasonal storage. Overall, hydrogen-based fuels[5] account for 13% of global final energy demand in 2050 (Figure 3.8).

Ammonia is used today as feedstock in the chemical industry, but in the NZE it is also used as fuel in various energy applications, benefitting from its lower transport cost and higher energy density than hydrogen. Ammonia accounts for around 45% of global energy demand for shipping in 2050 in the NZE. Co-firing with ammonia is also a potential early option to reduce CO_2 emissions in existing coal-fired power plants. The toxicity of ammonia means that its handling is likely to be limited to professionally trained operators, which could restrict its potential.

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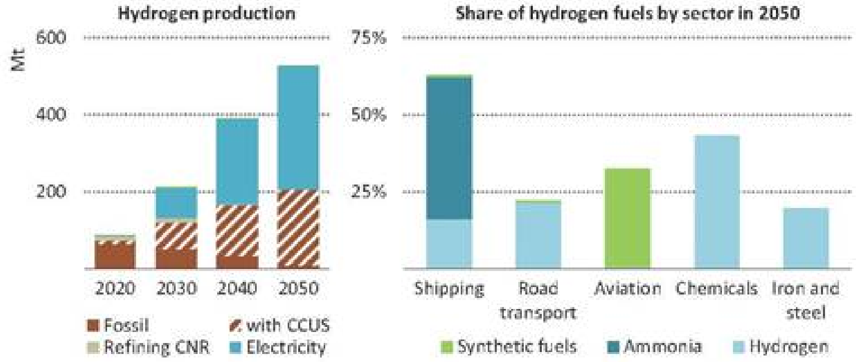
[5] Hydrogen-based fuels are defined as hydrogen, ammonia as well as synthetic hydrocarbon fuels produced from hydrogen and CO_2.

Figure 3.8 ▷ Global production of hydrogen by fuel and hydrogen demand by sector in the NZE



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Hydrogen production jumps sixfold by 2050, driven by water electrolysis and natural gas with CCUS, to meet rising demand in shipping, road transport and heavy industry

Note: Refining CNR = hydrogen by-product from catalytic naphtha reforming at refineries.

Synthetic kerosene meets around one-third of global aviation fuel demand in 2050 in the NZE. Its manufacture at bioenergy-fired power or biofuel production plants requires CO_2 captured from the atmosphere. CO_2 from these sources can be considered carbon neutral, as it results in no net emissions when the fuel is used. There is scope for the co-production of advanced liquid biofuels and synthetic liquid fuels from hydrogen and CO_2, with the integration of the two processes reducing the overall liquid fuel production costs. Alongside synthetic liquid fuels, enough synthetic methane is produced from hydrogen and CO_2 in 2050 to meet 10% of demand for network supplied gas in the buildings, industry and transport sectors.

By 2050, hydrogen production in the NZE is almost entirely based on low-carbon technologies: water electrolysis accounts for more than 60% of global production, and natural gas in combination with CCUS for almost 40%. Global electrolyser capacity reaches 850 gigawatts (GW) by 2030 and 3 600 GW by 2050, up from around 0.3 GW today. Electrolysis absorbs close to 15 000 terawatt-hours (TWh), or 20% of global electricity supply in 2050, largely from renewable resources (95%), but also from nuclear power (3%) and fossil fuels with CCUS (2%). Natural gas use for hydrogen production with CCUS is 925 bcm in 2050, or around 50% of global natural gas demand, with 1.8 Gt CO_2 being captured.

Scaling up deployment of technologies and related manufacturing capacity will be critical to reducing costs. Water electrolysers are available on the market today and hydrogen production from natural gas with CCUS has been demonstrated at a commercial scale (there are seven plants in operation around the world). The choice between the two depends on economic factors, mainly the cost of natural gas and electricity, and on whether CO_2 storage is available. For natural gas with CCUS, production costs in the NZE are around USD 1-2 per kilogramme (kg) of hydrogen in 2050, with gas costs typically accounting for 15-55% of total production costs. For water electrolysis, learning effects and economies of scale result in CAPEX cost reductions of 60% in the NZE by 2030 compared to 2020. Production cost reductions hinge on lowering the cost of low-carbon electricity, as electricity accounts for 50-85% of total production costs, depending on the electricity source and region. The average cost of producing hydrogen from renewables drops in the NZE from USD 3.5-7.5/kg today to around USD 1.5-3.5/kg in 2030 and USD 1-2.5/kg in 2050 – essentially about the same as the cost of producing with natural gas with CCUS.

Converting hydrogen into other energy carriers, such as ammonia or synthetic hydrocarbon fuels, involves even higher costs. But it results in fuels that can be more easily transported and stored, and which are also often compatible with existing infrastructure or end-use technologies (as in the case of ammonia for shipping or synthetic kerosene for aviation). For ammonia, the additional synthesis step increases the production costs by around 15% compared with hydrogen (mainly due to additional conversion losses and equipment costs).

The relatively high cost of synthetic hydrocarbon fuels explains why their use is largely restricted to aviation in the NZE, where alternative low-carbon options are limited. Synthetic kerosene costs were USD 300-700/barrel in 2020: although these costs fall to USD 130-300/barrel by 2050 in the NZE as the costs of electricity from renewables and CO_2 feedstocks decline, the cost of synthetic kerosene remains far higher than the projected USD 25/barrel cost of conventional kerosene in 2050 in the NZE. The supply of CO_2, captured from bioenergy equipped with CCUS or direct air capture (DAC), needed to make these fuels is a relevant cost factor, accounting for USD 15-70/barrel of the cost of synthetic hydrocarbon fuels in 2050. Closing these cost gaps implies penalties for fossil kerosene or support measures for synthetic kerosene corresponding to a CO_2 price of USD 250-400/tonne.

Increasing global demand for low-carbon hydrogen in the NZE provides a means for countries to export renewable electricity resources that could not otherwise be exploited. For example, Chile and Australia announced ambitions to become major exporters in their national hydrogen strategies. With declining demand for natural gas in the NZE, gas-producing countries could join this market by exporting hydrogen produced from natural gas with CCUS. Long-distance transport of hydrogen, however, is difficult and costly because of its low energy density, and can add around USD 1-3/kg of hydrogen to its price. This means that, depending on each country's own circumstances, producing hydrogen domestically may be cheaper than importing it, even if domestic production costs from low-carbon electricity or natural gas with CCUS are relatively high. International trade nevertheless becomes increasingly important in the NZE: around half of global ammonia and a third of synthetic liquid fuels are traded in 2050.

3.3.4 Key milestones and decision points

Table 3.1 ▷ Key milestones in transforming low-emissions fuels

Sector	2020	2030	2050
Bioenergy			
Share of modern biofuels in modern bioenergy (excluding conversion losses)	20%	45%	48%
Advanced liquid biofuels (mboe/d)	0.1	2.7	6.2
Share of biomethane in total gas networks	<1%	2%	20%
CO_2 captured and stored from biofuels production (Mt CO_2)	1	150	625
Hydrogen			
Production (Mt H_2)	87	212	528
of which: low-carbon (Mt H_2)	9	150	520
Electrolyser capacity (GW)	<1	850	3 585
Electricity demand for hydrogen-related production (TWh)	1	3 850	14 500
CO_2 captured from hydrogen production (Mt CO_2)	135	680	1 800
Number of export terminals at ports for hydrogen and ammonia trade	0	60	150

Note: mboe/d = million barrels of oil equivalent per day; Mt = million tonnes; H_2 = hydrogen.

Biofuels

Several sustainability frameworks considering net lifecycle GHG emissions and other sustainability indicators exist in different regions, e.g. the Renewable Energy Directive II in the European Union, RenovaBio in Brazil and the Low-C Fuel Standards in California. However, the scope, methodology and sustainability metrics of these frameworks differ. Global consensus on a sustainability framework and indicators within the next few years would help stimulate investment; this should be a priority. Such a framework should cover all forms of bioenergy (liquid, gaseous and solid) and other low-emissions fuels, and should strive for continuous environmental performance improvement. Certification schemes ideally should be developed in parallel.

Another early priority is for governments to assess national sustainable biomass feedstock potential as soon as possible to establish the quantities and types of wastes, residues and marginal lands suitable for energy crops. Assessments should provide the basis for national roadmaps for all liquid and gaseous biofuels, and strategies for low-emissions fuels. Early decisions will be needed in this context about how to support the sustainable collection of wastes and residues from the forestry, agriculture, animal and food industries and from advanced municipal solid waste sorting systems: in the NZE, support measures are in place by 2025. Measures might usefully include low-emissions fuels standards that incentivise the use of biofuels as feedstock. International knowledge-sharing would help with the design of such measures and assist efficient dissemination of best practices from regions with existing collection systems, e.g. for forestry residues in Nordic countries and used cooking oil collection in Europe, China and Southeast Asia countries.

Governments will also need to decide how best to support biogas installations and distribution in order to move away from traditional uses of biomass for cooking and heating by 2030. Such practices remain widespread in some developing countries. They are best tackled as part of broader programmes to promote clean cooking alongside improving access to electricity and LPG.

Decisions will be needed by 2025 on how best to create markets for sustainable biofuels and close the cost gap between biofuels and fossil fuels. Measures will need to incentivise the rapid development and deployment of advanced liquid biofuel technologies in end-use sectors (particularly heavy-duty trucking, shipping and aviation), using mechanisms such as low-carbon fuel standards, biofuel mandates and CO_2 removal credits. Measures that could boost the scaling up of advanced biofuels production in the next four years include: incentives for co-processing bio-oil in existing oil refineries or fully converting oil refineries to biorefineries; retrofitting ethanol plants with CCUS; and integrating cellulosic ethanol production with existing ethanol plants.

New infrastructure will be needed to provide for the injection of more biomethane into gas networks and to transport and store the CO_2 captured from ethanol and bio-FT biofuel plants. Governments should prioritise the co-development of biogas upgrading facilities and biomethane injection sites by 2030, ensuring that particular attention is paid to minimising fugitive biomethane emissions from the supply chain. Where biomass availability allows, governments may see value in encouraging the deployment of biofuel plants with CCUS near existing industrial hubs where integrated CCUS projects are planned, such as the Humber region in the United Kingdom.

Hydrogen-based fuels

An immediate priority should be for governments to assess the opportunities and challenges of developing a low-carbon hydrogen industry as part of national hydrogen strategies or roadmaps. Decisions will be needed on whether to produce hydrogen domestically from low-carbon electricity via water electrolysis or from gas with CCUS or a combination of both, or whether to rely on imported hydrogen-based fuels. Building technology leadership along the hydrogen supply chain could help create jobs and stimulate economic growth.

Decisions will be needed during the next decade on how best to bring down the costs of low-carbon hydrogen production. Switching existing hydrogen production in industry and oil refining from unabated fossil fuels to low-carbon hydrogen is one possible way to ramp up low-carbon hydrogen production in applications that have large demand already available. Financial support instruments, such as contracts for differences, could help to reduce the current cost gap of low-carbon hydrogen production compared to existing unabated production from fossil fuels.

Decisions will also be needed on how best to scale up hydrogen. Industrial ports could be a good starting point, since they may provide access to low-carbon hydrogen supply in the form of offshore wind or CO_2 storage. They also offer scope to promote new port-related uses for hydrogen, e.g. shipping and delivery trucks, and they could become the first nodes of an international hydrogen trade network. The establishment of hydrogen trade will require the development of methodologies to determine the carbon footprint of the different hydrogen production routes and the adoption of guarantees of origin and certification schemes for low-carbon hydrogen (and hydrogen-based fuels).

Blending hydrogen into existing gas networks offers another early avenue to scale up low-carbon hydrogen production and trigger cost reductions. International harmonisation of safety standards and national regulations on allowed concentrations of hydrogen in gas grids would help with this, as would the adoption of blending quotas or low-emissions fuel standards.

Repurposing existing gas pipelines, where technically feasible, with declining natural gas demand and connecting large hydrogen demand hubs to transport hydrogen could result in low cost and low regret opportunities to kick-start the development of new hydrogen infrastructure. Developing the infrastructure for hydrogen at the pace required in the NZE would involve considerable investment risks along the value chain of production, transport and demand ranging from hydrogen production technologies through to low-emissions electricity generation and CO_2 transport and storage. Governments and local authorities could play an important role by co-ordinating the planning processes among the various stakeholders; direct public investment or public-private partnerships could help to develop necessary shared infrastructure for hydrogen; and international co-operation and cross-border initiatives could help to share investment burdens and risks and so facilitate large-scale deployments, as in the EU Important Projects of Common European Interest.

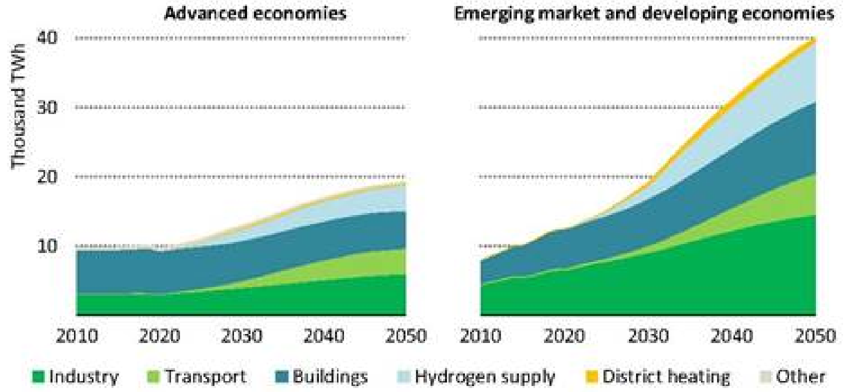
3.4 Electricity sector

3.4.1 Energy and emissions trends in the Net-Zero Emissions Scenario

The NZE involves both a significant increase in electricity needs – the result of an increase in economic activity, rapid electrification of end-uses and expansion of hydrogen production by electrolysis – and a radical transformation in the way electricity is generated. Global electricity demand was 23 230 TWh in 2020 with an average growth rate of 2.3% per year over the previous decade. It climbs to 60 000 TWh in 2050 in the NZE, an average increase of 3.2% per year.

Emerging market and developing economies account for 75% of the projected global increase in electricity demand to 2050 (Figure 3.9). Their demand increases by half by 2030 and triples by 2050, driven by expanding population and rising incomes and living standards, as well new sources of demand linked to decarbonisation. In advanced economies, electricity demand returns to growth after a decade-long lull, nearly doubling between 2020 and 2050, driven mostly by end-use electrification and hydrogen production.

Figure 3.9 ▷ Electricity demand by sector and regional grouping in the NZE



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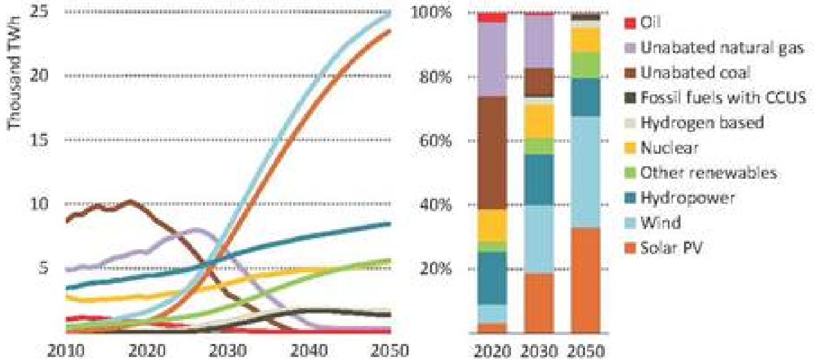
Electrification of end-uses and hydrogen production raise electricity demand worldwide, with a further boost to expand services in emerging market and developing economies

The transformation of the electricity sector is central to achieving net-zero emissions in 2050. Electricity generation is the single largest source of energy-related CO_2 emissions today, accounting for 36% of total energy-related emissions. CO_2 emissions from electricity generation worldwide totalled 12.3 Gt in 2020, of which 9.1 Gt was from coal-fired generation, 2.7 Gt from gas-fired plants and 0.6 Gt from oil-fired plants. In the NZE, CO_2 emissions from electricity generation fall to zero in aggregate in advanced economies in the 2030s. They fall to zero in emerging market and developing economies around 2040.

Renewables contribute most to decarbonising electricity in the NZE: global generation from renewables nearly triples by 2030 and grows eightfold by 2050 (Figure 3.10). This raises the share of renewables in total output from 29% in 2020 to over 60% in 2030 and nearly 90% in 2050. Solar PV and wind race ahead, becoming the leading sources of electricity globally before 2030: each generates over 23 000 TWh by 2050, equivalent to about 90% of all electricity produced in the world in 2020. Pairing battery storage systems with solar PV and wind to improve power system flexibility and maintain electricity security becomes commonplace in the late 2020s, complemented by demand response for short duration flexibility and hydropower or hydrogen for flexibility across days or even seasons. Hydropower is the largest low-carbon source of electricity today and steadily grows in the NZE, doubling by 2050. Generation using bioenergy – in dedicated plants and as biomethane delivered through gas networks – doubles to 2030 and increases nearly fivefold by 2050.

Figure 3.10 ▷ Global electricity generation by source in the NZE



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Solar and wind power race ahead, raising the share of renewables in total generation from 29% in 2020 to nearly 90% in 2050, complemented by nuclear, hydrogen and CCUS

Nuclear power also makes a significant contribution in the NZE, its output rising steadily by 40% to 2030 and doubling by 2050, though its overall share of generation is below 10% in 2050. At its peak in the early 2030s, global nuclear capacity additions reach 30 GW per year, five-times the rate of the past decade. In advanced economies, lifetime extensions for existing reactors are pursued in many countries as they are one of the most cost-effective sources of low-carbon electricity (IEA, 2019), while new construction expands to about 4.5 GW per year on average from 2021 to 2035, with an increasing emphasis on small modular reactors. Despite these efforts, the nuclear share of total generation in advanced economies falls from 18% in 2020 to 10% in 2050. Two-thirds of new nuclear power capacity in the NZE is built in emerging market and developing economies mainly in the form of large-scale reactors, where the fleet of reactors quadruples to 2050. This raises the share of nuclear in electricity generation in those countries from 5% in 2020 to 7% in 2050 (as well as nuclear meeting 4% of commercial heat demand in 2050).

Nuclear power technologies have advanced in recent years, with several first-of-a-kind large-scale reactors completed that include enhanced safety features. While projects have been completed on schedule in China, Russia and the United Arab Emirates, there have been substantial delays and cost overruns in Europe and the United States. Small modular reactors and other advanced reactor designs are moving towards full-scale demonstration, with scalable designs, lower upfront costs and the potential to improve the flexibility of nuclear power in terms of both operations and outputs, e.g. electricity, heat or hydrogen.

Retrofitting coal- and gas-fired capacity with CCUS or co-firing with hydrogen-based fuels enables existing assets to contribute to the transition while cutting emissions and supporting electricity security. The best opportunities for CCUS are at large, young facilities with available space to add capture equipment and in locations with CO_2 storage options or demand for use. Opportunities are concentrated in China for coal-fired power plants and the United States for gas-fired capacity. While they provide just 2% of total generation from 2030 to 2050 in the NZE, retrofitted plants capture a total of 15 Gt CO_2 emissions over the period.

Carbon capture technologies remain at an early stage of commercialisation. Two commercial power plants have been equipped with CCUS over the past five years, and there are currently 18 CCUS power projects in development worldwide. Completing these projects in a timely manner and driving down costs through learning-by-doing will be critical to further expansion. An alternative would be to retrofit existing coal- and gas-fired power plants to co-fire high shares of hydrogen-based fuels. In the NZE, hydrogen-based fuels generate 900 TWh of electricity in 2030 and 1 700 TWh in 2050 in this way (about 2.5% of global generation in both years). A large-scale (1 GW) demonstration project to co-fire with 20% ammonia is underway in 2021, with aims to move towards ammonia-only combustion. Manufacturers have signalled that future gas turbine designs will be capable of co-firing high shares of hydrogen. While the investment needed to co-fire hydrogen-based fuels looks to be modest, relatively high fuel costs point to targeted applications to support power system stability and flexibility rather than bulk power.

The global use of unabated fossil fuels in electricity generation is sharply reduced in the NZE. Unabated coal-fired generation is cut by 70% by 2030, including the phase-out of unabated coal in advanced economies, and phased out in all other regions by 2040. Large-scale oil-fired generation is phased out in the 2030s. Generation using natural gas without carbon capture rises in the near term, replacing coal, but starts falling by 2030 and is 90% lower by 2040 compared with 2020.

The electricity sector is the first to achieve net-zero emissions mainly because of the low costs, widespread policy support and maturity of an array of renewable energy technologies. Solar PV is first among them: it is the cheapest new source of electricity in most markets and has policy support in more than 130 countries. Onshore wind is also a market-ready low cost technology that is widely supported and can be scaled up quickly, rivalling the low costs of solar PV where conditions are good, though it faces public opposition and extensive permitting and licensing processes in several markets. Offshore wind technology has been maturing rapidly in recent years; its deployment is poised to accelerate in the near term. The current focus is on fixed-bottom installations, but floating offshore wind starts to make a major contribution from around 2030 in the NZE, helping to unlock the enormous potential that exists around the world. Hydropower, bioenergy and geothermal technologies are well established, mature and flexible renewable energy sources. As dispatchable generating options, they will be critical to electricity security, complemented by batteries, which have seen sharp cost reductions, have proven their ability to provide high-value grid services and can be built in a matter of months in most locations. Concentrating solar and marine power are less mature technologies, but innovation could see them make important contributions in the long term.

3.4.2 Key milestones and decision points

Table 3.2 ▷ Key milestones in transforming global electricity generation

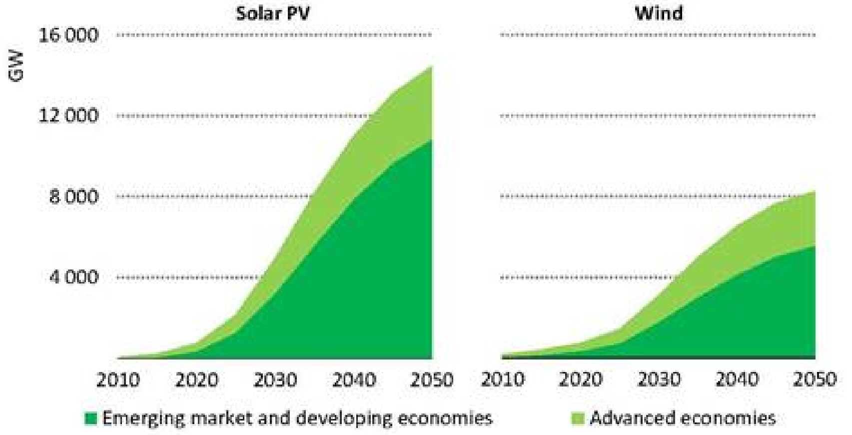
Category	
Decarbonisation of electricity sector	• Advanced economies in aggregate: 2035. • Emerging market and developing economies: 2040.
Hydrogen-based fuels	• Start retrofitting coal-fired power plants to co-fire with ammonia and gas turbines to co-fire with hydrogen by 2025.
Unabated fossil fuel	• Phase out all subcritical coal-fired power plants by 2030 (870 GW existing plants and 14 GW under construction). • Phase out all unabated coal-fired plants by 2040. • Phase out large oil-fired power plants in the 2030s. • Unabated natural gas-fired generation peaks by 2030 and is 90% lower by 2040.

Category	2020	2030	2050
Total electricity generation (TWh)	26 800	37 300	71 200
Renewables			
Installed capacity (GW)	2 990	10 300	26 600
Share in total generation	29%	61%	88%
Share of solar PV and wind in total generation	9%	40%	68%
Carbon capture, utilisation and storage (CCUS) generation (TWh)			
Coal and gas plants equipped with CCUS	4	460	1 330
Bioenergy plants with CCUS	0	130	840
Hydrogen and ammonia			
Average blending in global coal-fired generation (without CCUS)	0%	3%	100%
Average blending in global gas-fired generation (without CCUS)	0%	9%	85%
Unabated fossil fuels			
Share of unabated coal in total electricity generation	35%	8%	0.0%
Share of unabated natural gas in total electricity generation	23%	17%	0.4%
Nuclear power	*2016-20*	*2021-30*	*2031-50*
Average annual capacity additions (GW)	7	17	24
Infrastructure			
Electricity networks investment in USD billion (2019)	260	820	800
Substations capacity (GVA)	55 900	113 000	290 400
Battery storage (GW)	18	590	3 100
Public EV charging (GW)	46	1 780	12 400

Note: GW = gigawatts; GVA = gigavolt amperes.

Transforming the electricity sector in the way envisioned in the NZE involves large capacity additions for all low-emissions fuels and technologies. Global renewables capacity more than triples to 2030 and increases ninefold to 2050. From 2030 to 2050, this means adding more than 600 GW of solar PV capacity per year on average and 340 GW of wind capacity per year including replacements (Figure 3.11), while offshore wind becomes increasingly important over time (over 20% of total wind additions from 2021 to 2050, compared with 7% in 2020). The annual deployment of battery capacity in the electricity sector needs to scale up in parallel, from 3 GW in 2019 to 120 GW in 2030 and over 240 GW in 2040. Retrofitting existing coal- and gas-fired power plants also needs to get underway.

Figure 3.11 ▷ Solar PV and wind installed capacity in the NZE



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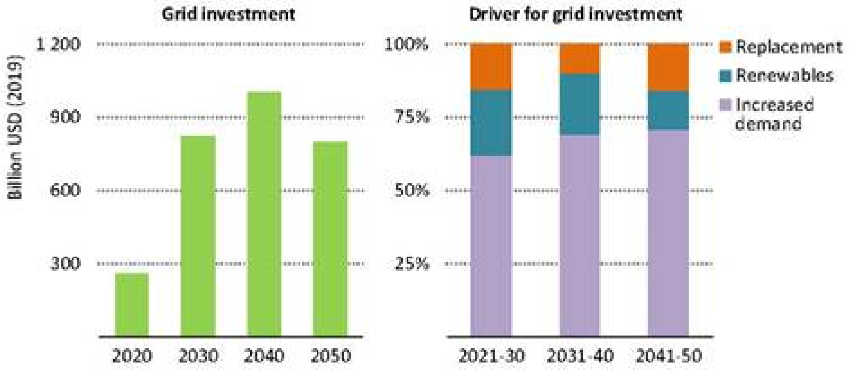
Solar PV and wind need to scale up rapidly to decarbonise electricity, with total solar PV capacity growing 20-fold and wind 11-fold by 2050

Figure 3.12 ▷ Global investment in electricity networks in the NZE



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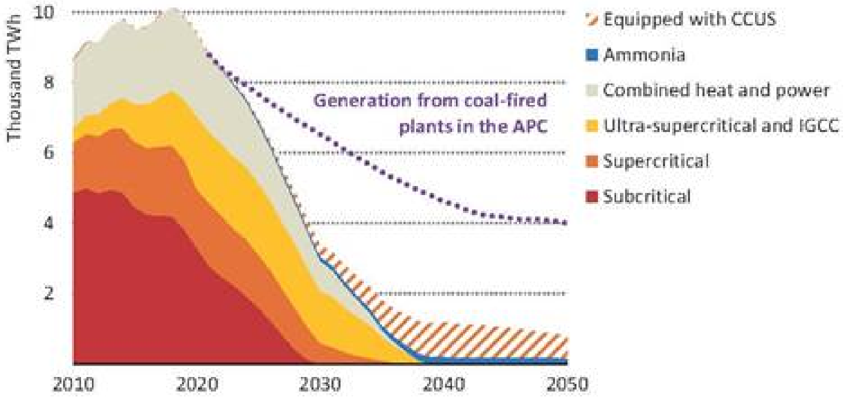
Electricity network investment triples to 2030 and remains elevated to 2050, meeting new demand, replacing ageing infrastructure and integrating more renewables

Investment in electricity networks will be crucial to achieving this transformation. Global electricity networks that took over 130 years to build need to more than double in total length by 2040 and increase by another 25% by 2050. Total grid investment needs to rise to USD 820 billion by 2030, and USD 1 trillion in 2040, before falling back after electricity is fully decarbonised and the growth of renewables slows to match demand growth (Figure 3.12). Replacing ageing infrastructure is an important part of network investment through to 2050 in the NZE.

Governments face several key decisions in the electricity sector if they are to follow the pathway to net-zero emissions by 2050 envisioned in the NZE particularly about how to best use existing power plants. For retrofits of coal- or gas-fired capacity, either with carbon capture or co-firing with hydrogen-based fuels (or full conversion), decisions are needed to support first-of-a-kind projects before 2030 before widespread retirement of unabated plants becomes necessary. For other fossil fuel power stations, decisions about phase outs are needed. Coal-fired power plants should be phased out completely by 2040 unless retrofitted, starting with the least-efficient designs by 2030 (Figure 3.13). This would require shutting 870 GW of existing subcritical coal capacity globally (11% of all power capacity) and international collaboration to facilitate substitutes. By 2040, all large-scale oil-fired power plants should be phased out. Natural gas-fired generation remains an important part of electricity supply through to 2050, but strong government support will be needed to ensure that CCUS is deployed soon and on a large scale.

Figure 3.13 ▷ Coal-fired electricity generation by technology in the NZE



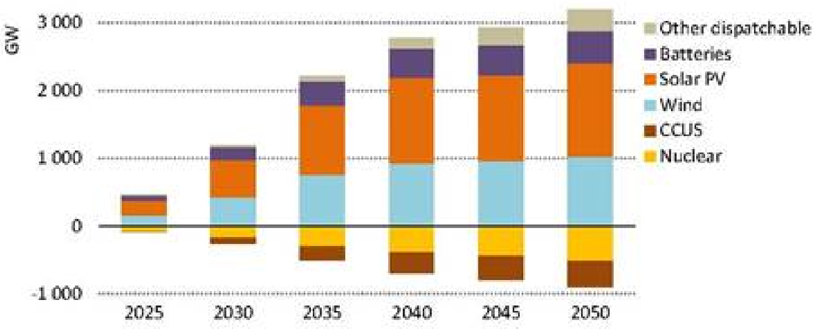
Coal-fired power accounted for 27% of global energy CO_2 emissions in 2020, and in the NZE, all subcritical plants are phased out by 2030 and all plants without CCUS by 2040

Notes: APC = Announced Pledges Case; IGCC = integrated gasification combined-cycle. Ammonia includes co-firing and full conversion of coal plants.

The path to net-zero emissions could be facilitated by early government action to help move several technologies that provide power system flexibility through the demonstration phases and bring them to market. Expanding the set of energy storage technologies to complement batteries and addressing emerging needs for longer duration seasonal storage would be of particular value. Technical solutions to support the stability of power grids with high shares of solar and wind would also benefit from research and development (R&D) support.

There are three important sets of decisions to be made concerning nuclear power: lifetime extensions; pace of new construction; and advances in nuclear power technology. In advanced economies, decisions need to be made about new construction and the large number of nuclear power plants that may be retired over the next decade absent action to extend their lifetimes and make the required investment. Without further lifetime extensions and new projects beyond those already under construction, nuclear power output in advanced economies will decline by two-thirds over the next two decades (IEA, 2019). In emerging market and developing economies, there are decisions to be made about the pace of new nuclear power construction. From 2011 to 2020, an average of 6 GW of new nuclear capacity came online each year. By 2030, the rate of new construction increases to 24 GW per year in the NZE. The third set of decisions concerns the extent of government support for advanced nuclear technologies, particularly those related to small modular reactors and high-temperature gas reactors, both of which can expand markets for nuclear power beyond electricity.

Figure 3.14 ▷ Additional global alternative capacity needed in a Low Nuclear and CCUS Case



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Sharply reducing the roles of nuclear power and carbon capture would require even faster growth in solar PV and wind, making achieving the net zero goal more costly and less likely

Note: The Low Nuclear and CCUS Case assumes that global nuclear power output is about 60% lower in 2050 than in the NZE due to no additional lifetime extensions or new nuclear projects in advanced economies and no expansion of the current pace of construction in emerging market and developing economies, and that the amount of coal- and gas-fired capacity equipped with CCUS is 99% lower than in the NZE.

Failing to take timely decisions on nuclear power and CCUS would raise the costs of a net-zero emissions pathway and add to the risk of not meeting the goal by placing an additional burden on wind and solar to scale up even more quickly than in the NZE (Figure 3.14). In a *Low Nuclear and CCUS Case*, we assume that global nuclear power output is 60% lower in 2050 than in the NZE as a result of no additional nuclear lifetime extensions or new projects in advanced economies and no expansion of the current pace of construction in emerging market and developing economies, and that only the announced CCUS projects are completed (representing 1% of the CCUS capacity added in the NZE).

Our analysis indicates that the burden of replacing those sources of low-carbon generation would fall mainly on solar PV and wind power, calling for 2 400 GW more capacity than in the NZE – an amount far exceeding their combined global capacity in operation in 2020 (Figure 3.14). There would also be a need for about 480 GW of battery capacity above and beyond the 3 100 GW deployed in the NZE, plus more than 300 GW of other dispatchable capacity to meet demand in all seasons and ensure system adequacy. This would call for an additional USD 2 trillion investment in power plants and related grid assets (net of lower investment in nuclear and CCUS). Taking account of avoided fuel costs, the estimated total additional cost of electricity to consumers between 2021 and 2050 is USD 260 billion.

3.5 Industry

3.5.1 Energy and emission trends in the Net-Zero Emissions Scenario

As the second-largest global source of energy sector CO_2 emissions, industry has a vital contribution to make in achieving the net zero goal. Industrial CO_2 emissions[6] (including from energy use and production processes) totalled about 8.4 Gt in 2020. Advanced economies accounted for around 20% and emerging market and developing economies for around 80%, although complex global supply chains for the production of materials and manufacturing mean that advanced economies generally consume far more finished goods than they produce.

Three heavy industries – chemicals, steel and cement – account for nearly 60% of all industrial energy consumption and around 70% of CO_2 emissions from the industry sector. Production is highly concentrated in emerging market and developing economies, which account for 70-90% of the combined output of these commodities (Figure 3.15). China alone was responsible for almost 60% of both steel and cement production in 2020. These bulk materials are essential inputs to our modern way of life, with few cost-competitive substitutes; the challenge is to carry on producing these materials without emitting CO_2.

The outlook for global materials demand in the NZE is one of plateaus and small increases. This is in stark contrast with the growth seen during the last two decades when global steel

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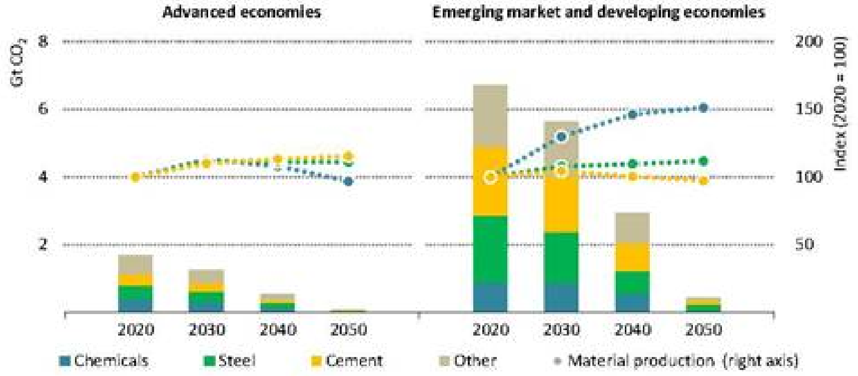
[6] All CO_2 emissions in this section refer to direct CO_2 emissions from the industry sector unless otherwise specified.

demand rose by 2.1-times, cement by 2.4-times and plastics (a key group of material outputs from the chemical sector) by 1.9-times in response to global economic and population expansion. When economies are developing, per capita material demand tends to rise rapidly to build up stocks of goods and infrastructure. As economies mature, future demand stems primarily from the need to refurbish and replace these stocks, the levels of which tend to saturate. In the NZE, flattening or even declining demand in many countries around the world leads to slower global demand growth. Some countries such as India see higher growth in steel and cement production, while production in China declines considerably following its industrial boom period after the turn of the millennium.

Figure 3.15 ▷ **Global CO_2 emissions from industry by sub-sector in the NZE**



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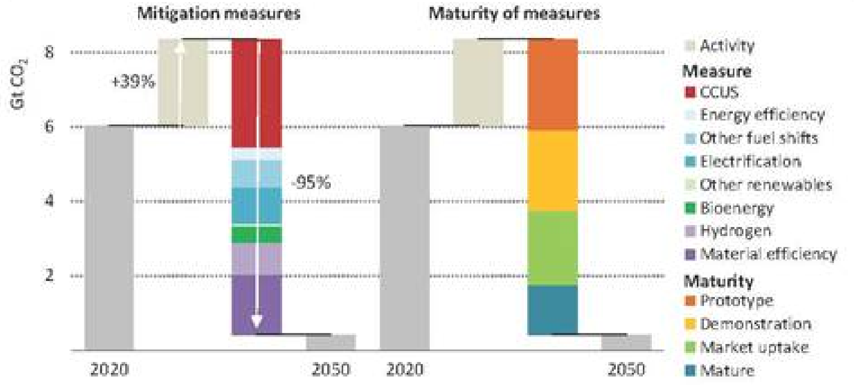
The majority of residual emissions in industry in 2050 come from heavy industries in emerging market and developing economies

Note: Other includes the production of aluminium, paper, other non-metallic minerals and other non-ferrous metals, and a series of light industries.

Certain segments of material demand increase rapidly to support the required expansion of energy-related infrastructure in the NZE, notably renewable electricity generation and transport infrastructure. The additional infrastructure required for these two segments by 2050 relative to today alone contributes roughly 10% of steel demand in 2050. But co-ordinated cross-sectoral strategies, including modal shifts in transport and building renovation, as well as other changes in design, manufacturing methods, construction practices and consumer behaviour, more than offset this increase. Overall, global demand for steel in 2050 is 12% higher than today, primary chemicals is 30% higher and cement demand is broadly flat.

CO_2 emissions from heavy industry decline by 20% by 2030 and 93% by 2050 in the NZE. Optimising the operational efficiency of equipment, adopting the best available technologies for new capacity additions and measures to improve material efficiency play an important part in this. However, there are limits to how much emissions can be reduced by these measures. Almost 60% of emissions reductions in 2050 in the NZE are achieved using technologies that are under development today (large prototype or demonstration scale) (Figure 3.16).

Figure 3.16 ▷ Global CO_2 emissions in heavy industry and reductions by mitigation measure and technology maturity category in the NZE



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An array of measures reduces emissions in heavy industry, with innovative technologies like CCUS and hydrogen playing a critical role

Hydrogen and CCUS technologies together contribute around 50% of the emissions reductions in heavy industry in 2050 in the NZE. These technologies enable the provision of large amounts of high-temperature heat, which in many cases cannot be easily provided by electricity with current technologies, and help to reduce process emissions from the chemical reactions inherent in some industrial production. Bioenergy also makes a contribution in a wide array of industrial applications.

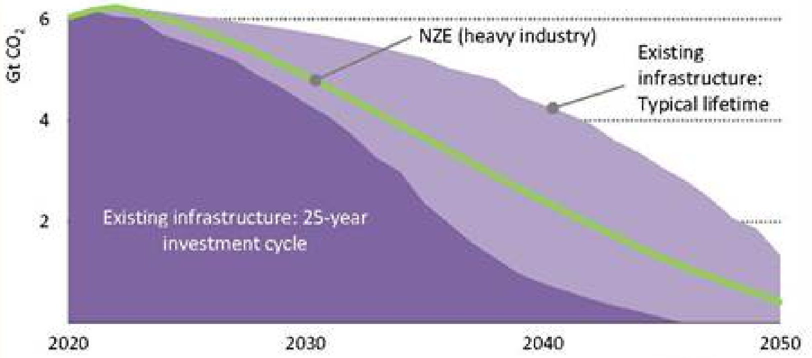
Aside from the need for high-temperature heat and process emissions, two factors explain the slower pace of emissions reductions in heavy industries relative to other areas of the energy system. First, the ease with which many industrial materials and products can be traded globally means that markets are competitive and margins are low. This leaves little room to absorb additional costs stemming from the adoption of more expensive production pathways. It will take time to develop robust global co-operation and technology transfer frameworks or domestic solutions to enable a level playing field for these technologies. Second, heavy industries use capital-intensive and long-lived equipment, which slows the deployment of innovative low-emission technologies. Capacity additions in the period to 2030 – before a large-scale roll-out of innovative processes can take place – largely explain the persistence of industrial emissions in 2050, more than 80% of which are in emerging market and developing economies. Strategically timed investment in low-carbon technologies could help minimise early retirements (Box 3.1).

Box 3.1 ⊳ Investment cycles in heavy industry

For heavy industry, the year 2050 is just one investment cycle away. Average lifetimes of emissions-intensive assets such as blast furnaces and cement kilns are around 40 years. After about 25 years of operation, however, plants often undergo a major refurbishment to extend their lifetimes.

The challenge is to ensure that innovative near-zero emissions industrial technologies that are at large prototype and demonstration stage today reach markets within the next decade, when around 30% of existing assets will have reached 25 years of age and thus face an investment decision. If these innovative technologies are not ready, or not used even if ready, this would have a major negative impact on the pace of emissions reductions or risk an increase in stranded assets (Figure 3.17). Conversely, if they are ready, and if existing plants are retrofit or replaced with them at the 25-year investment decision point, this could reduce projected cumulative emissions to 2050 from existing heavy industry assets by around 40%. The critical window of opportunity from now to 2030 should not be missed.

Figure 3.17 ⊳ CO_2 emissions from existing heavy industrial assets in the NZE



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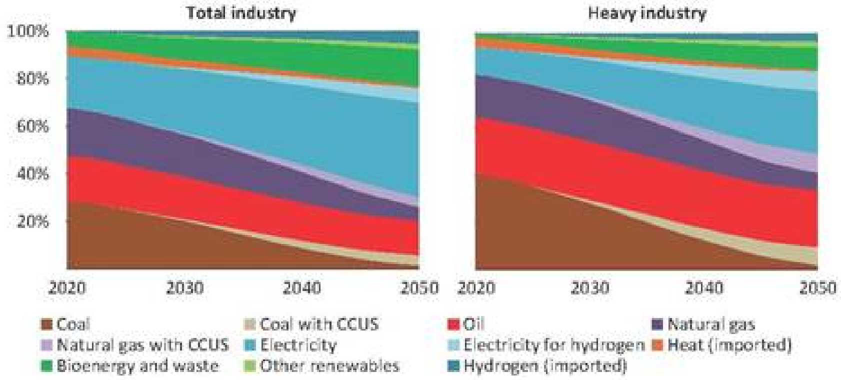
Intervening at the end of the next 25-year investment cycle could help unlock 60 Gt CO_2, around 40% of projected emissions from existing heavy industry assets

The energy mix in industry changes radically in the NZE. The share of fossil fuels in total energy use declines from around 70% today to 30% in 2050. The vast majority of fossil fuels still being used then are in heavy industries, mainly as chemical feedstock (50%) or in plants equipped with CCUS (around 30%). Electricity is the dominant fuel in industrial energy demand growth, with its share of total industrial energy consumption rising from 20% in 2020 to 45% in 2050. Some 15% of this electricity is used to produce hydrogen. Bioenergy plays an important role, contributing 15% of total energy use in 2050, but sustainable supplies are limited, and it is also in high demand in the power and transport sectors. Renewable solar and geothermal technologies to provide heat make a small but fast growing contribution (Figure 3.18).

Figure 3.18 ▷ Global final industrial energy demand by fuel in the NZE



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Fossil fuel use in industry is halved by 2050, replaced primarily by electricity and bioenergy

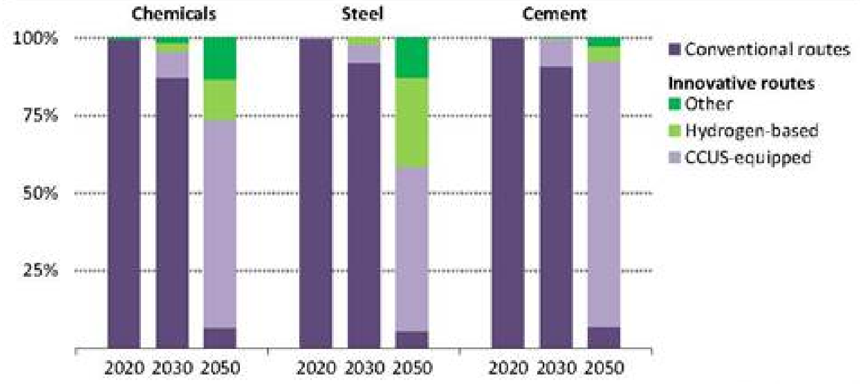
Notes: Industrial energy consumption includes chemical feedstock and energy consumed in blast furnaces and coke ovens. Hydrogen refers to imported hydrogen and excludes captive hydrogen generation. Electricity for hydrogen refers to electricity used in the production of captive hydrogen via electrolysis.

Chemicals production

In the NZE, emissions from the chemicals sub-sector fall from 1.3 Gt in 2020 to 1.2 Gt in 2030 and around 65 Mt in 2050. The share of fossil fuels in total energy use falls from 83% in 2020 (mostly oil and natural gas), to 76% in 2030 and 61% in 2050. Oil remains the largest fuel used in primary chemicals production by 2050 in the NZE, along with smaller quantities of gas and coal.

Technologies that are currently available on the market account for almost 80% of the emissions savings achieved globally in the chemical industry by 2030 in the NZE relative to today. They include recycling and re-use of plastics and more efficient use of nitrogen fertilisers, which reduce the demand for primary chemicals, and measures to increase energy efficiency. Beyond 2030, the bulk of emissions reductions result from the use of technologies whose integration in chemical processes is under development today, including certain CCUS applications and electrolytic hydrogen generated directly from variable renewable electricity (Figure 3.19). CCUS-equipped conventional routes and pyrolysis technologies are most competitive in regions with access to low cost natural gas, while electrolysis is the favoured option in regions where the deployment of CCUS is impeded by a lack of infrastructure or public acceptance.

Figure 3.19 ▷ Global industrial production of bulk materials by production route in the NZE



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Near-zero emissions routes dominate cement, primary steel and chemicals production by 2050, with key roles for CCUS and hydrogen-based technologies

Notes: CCUS = carbon capture, utilisation and storage. Chemicals refers to the production of primary chemicals (ethylene, propylene, benzene, toluene, mixed xylenes, ammonia and methanol). Steel refers to primary steel production. Other includes innovative processes that utilise bioenergy and directly electrify production. Hydrogen-based refers to electrolytic hydrogen. Fossil fuel-based hydrogen with CCUS is included in the CCUS-equipped category.

Iron and steel production

In the NZE, global CO_2 emissions from the iron and steel sub-sector fall from 2.4 Gt in 2020 to 1.8 Gt in 2030 and 0.2 Gt in 2050, as the unabated use of fossil fuels falls sharply. Their share of the overall fuel mix drops from 85% today to just over 30% in 2050. The steel industry remains one of the last sectors using significant amounts of coal in 2050, primarily due to its importance as a chemical reduction agent, albeit mostly in conjunction with CCUS.

The NZE sees a radical technological transformation of the iron and steel sub-sector based largely on a major shift from coal to electricity. By 2050, electricity and other non-fossil fuels account for nearly 70% of final energy demand in the sector, up from just 15% in 2020. This shift is driven by technologies such as scrap-based electric arc furnaces (EAF), hydrogen-based direct reduced iron (DRI) facilities, iron ore electrolysis and the electrification of ancillary equipment. The share of coal in total energy use drops from 75% in 2020 to 22% by 2050 in the NZE, of which 90% is used in conjunction with CCUS.

Technologies that are currently on the market deliver around 85% of emissions savings in steel production to 2030. They include material and energy efficiency measures and a major increase in scrap-based production – which requires only around one-tenth of the energy of primary steel production – driven primarily by increased scrap availability as more products reach their end-of-life. Partial hydrogen injection into commercial blast furnaces and DRI furnaces gain pace in the mid-2020s, building on pilot projects testing the practice today. After 2030, the bulk of emission reductions come from the use of technologies that are under development, including hydrogen-based DRI and iron ore electrolysis. Several CCUS-equipped process technologies are deployed in parallel, including innovative smelting reduction, natural gas-based DRI production (particularly in regions with low natural gas prices) and innovative blast furnace retrofit arrangements in regions with relatively young plants.

Cement production

Producing a tonne of cement today generates around 0.6 tonnes CO_2 on average, two-thirds of which are process emissions generated from carbon released from the raw materials used. Fossil fuels – mostly coal plus some petroleum coke – account for 90% of thermal energy needs.

Increased blending of alternative materials into cement to replace a portion of clinker (the active and most emissions-intensive ingredient), lower demand for cement and energy efficiency measures deliver around 40% of the emissions savings in 2030 compared with 2020. Through use of blended cements, the global clinker-to-cement ratio declines from 0.71 in 2020 to 0.65 in 2030. The ratio continues to decline after 2030, but more slowly, reaching 0.57 in 2050 (blended cements could reach a clinker-to-cement ratio as low as 0.5, but market application potential depends on regional contexts). Limestone and calcined clay are the main alternative materials used in blended cements by 2050. Since 0.5 is the lowest technically achievable clinker-to-cement ratio, other measures are needed to achieve deeper emission reductions.

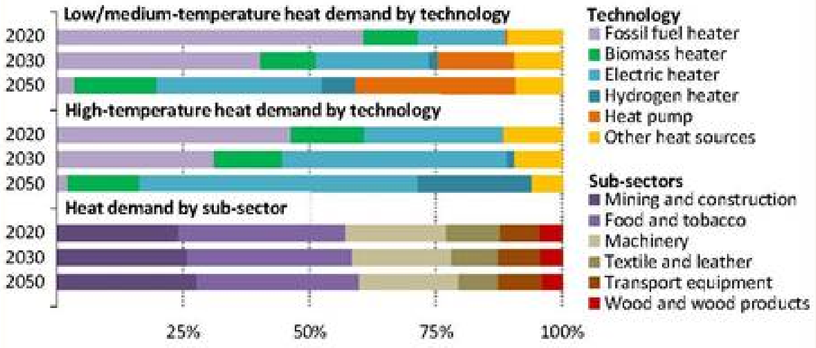
After 2030 in the NZE, the bulk of emissions reductions come from the use of technologies that are under development today. CCUS is the most important, accounting for 55% of reductions in 2050 relative to today. In many cases, it is more cost-effective in the NZE to apply CCUS to fossil fuel combustion emissions than to switch to zero-emissions energy sources. Coal use is eliminated from cement production by 2050, when natural gas accounts for about 40% of thermal energy (up from 15% today), biomass and renewable waste for a further 35% (up from less than 5% today), hydrogen and direct electrification for just about 15%, and oil products and non-renewable waste for the remainder. Constraints on the availability of sustainable biomass supplies prevent it from claiming a higher share. Direct electrification of cement kilns is at the small prototype stage today, and so only starts to be deployed after 2040 on a small scale. From the 2040s, hydrogen provides around 10% of thermal energy needs in cement kilns, although blending of small amounts begins earlier. Innovative types of cement based on alternative binding materials that limit or avoid the generation of process emissions, and even enable CO_2 capture during the curing process, are either still at much earlier stages of development relative to other options like CCUS, or have limited applicability.

Box 3.2 ▷ What about other industry sub-sectors?

Steel, cement and chemicals are not the only outputs from the industry sector. It also includes other energy-intensive sub-sectors such as aluminium, paper, other non-metallic minerals and non-ferrous metals, as well as light industries that produce vehicles, machinery, food, timber, textiles and other consumer goods, together with the energy consumed in construction and mining operations.

Emissions from the light industries decline by around 30% by 2030 and around 95% by 2050 in the NZE. In contrast to the heavy industries, most of the technologies required for deep emission reductions in these sub-sectors are available on the market and ready to deploy. This is in part because more than 90% of total heat demand is low/medium-temperature, which can be more readily and efficiently electrified.

Figure 3.20 ▷ Share of heating technology by temperature level in light industries in the NZE



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The share of electricty in satisfying heat demand for light industries rises from less than 20% today to around 40% in 2030 and about 65% in 2050

Notes: Light industries excludes non-specified industrial energy consumption. Low/medium-temperature heat corresponds to 0-400 °C and high-temperature heat to >400 °C. Other heat sources includes solar thermal and geothermal heaters, as well as imported heat from the power and fuel transformation sector.

Electricity accounts for around 40% of heat demand by 2030 and about 65% by 2050. For low- (<100 °C) and some medium- (100-400 °C) temperature heat, electrification includes an important role for heat pumps (accounting for about 30% of total heat demand in 2050). In the NZE, around 500 MW of heat pumps need to be installed every month over the next 30 years. Along with electrification, there are smaller roles for hydrogen and bioenergy for high-temperature heat (>400 °C), accounting for around 20% and around 15% respectively of total energy demand in 2050 (Figure 3.20). The rate of electrolyser capacity deployment is much lower than heavy industries, but the unit sizes will also be much smaller. About 5% of heat demand is satisfied by direct use of renewables, including solar thermal and geothermal heating technologies.

Energy efficiency also plays a critical role in these manufacturing industries, notably through increased efficiency in electric motors (conveyers, pumps and other driven systems). By 2030, 90% of the motor sales in other industries are Class 3 or above.

3.5.2 Key milestones and decision points

Table 3.3 ▷ Key milestones in transforming global heavy industry sub-sectors

Category	
Heavy industry	• 2035: virtually, all capacity additions are innovative low-emissions routes.
Industrial motors	• 2035: all electric motors sales are best in class.

Category	2020	2030	2050
Total industry			
Share of electricity in total final consumption	21%	28%	46%
Hydrogen demand (Mt H_2)	51	93	187
CO_2 captured (Mt CO_2)	3	375	2 800
Chemicals			
Share of recycling: reuse in plastics collection	17%	27%	54%
reuse in secondary production	8%	14%	35%
Hydrogen demand (Mt H_2)	46	63	83
with on-site electrolyser capacity (GW)	0	38	210
Share of production via innovative routes	1%	13%	93%
CO_2 captured (Mt CO_2)	2	70	540
Steel			
Recycling, re-use: scrap as share of input	32%	38%	46%
Hydrogen demand (Mt H_2)	5	19	54
with on-site electrolyser capacity (GW)	0	36	295
Share of primary steel production: hydrogen-based DRI-EAF	0%	2%	29%
iron ore electrolysis-EAF	0%	0%	13%
CCUS-equipped processes	0%	6%	53%
CO_2 captured	1	70	670
Cement			
Clinker to cement ratio	0.71	0.65	0.57
Hydrogen demand (Mt H_2)	0	2	12
Share of production via innovative routes	0%	9%	93%
CO_2 captured (Mt CO_2)	0	215	1 355

Note: DRI = direct reduced iron; EAF = electric arc furnace.

From 2030 onwards, all new capacity additions in industry in the NZE feature near-zero emissions technologies. Much of the heavy industry capacity that will be added and replaced in the coming years is in emerging market and developing economies; they may expect financial support from advanced economies. Each month from 2030 to 2050, the NZE implies an additional 10 industrial plants equipped with CCUS, three additional fully hydrogen-based industrial plants and 2 GW of extra electrolyser capacity at industrial sites. While challenging, this is achievable. For comparison, about 12 heavy industrial facilities were built from scratch on average per month in China alone from 2000 to 2015. By 2050, nearly all production in heavy industry is with near-zero emissions technologies.

Decisive action from governments is imperative to achieve clean energy transitions in heavy industry at the scale and pace envisioned in the NZE. Within the next two years, governments in advanced economies will need to take decisions about funding for R&D for critical near-zero emissions industrial technologies and for mitigating the investment risks associated with demonstrating them at scale. This should lead to at least two or three commercial demonstration projects for each technology in different regions, and to market deployment by the mid-2020s. International co-ordination and co-operation would facilitate better use of resources and help prevent gaps in funding.

Governments also need to take early decisions on large-scale deployment of near-zero emissions technologies. By 2024 in advanced economies and 2026 in emerging market and developing economies, governments should have in place a strategy for incorporating near-zero emissions technologies into the next series of capacity additions and replacements for steel and chemical plants, which should include decisions about whether to pursue CCUS, hydrogen or a combination of both. If they are to succeed, those strategies need to include concrete plans for developing and financing the necessary infrastructure for CCUS and/or hydrogen, together with clean electricity generation for hydrogen production. The construction of the required infrastructure should begin as soon as possible given the long lead-times involved.

Within a similar timeframe, governments of countries that produce cement should decide how to develop the necessary CCUS infrastructure for that sub-sector, including the necessary legal and regulatory frameworks. Importing countries should make plans to move progressively to exclusive use of low-emissions cement, which may involve the need to support the development of CCUS-equipped facilities elsewhere in order to ensure supplies and to avoid a disproportionate burden being placed on other countries.

Strategies must be underpinned by specific policies. By 2025, all countries should have a long-term CO_2 emissions reduction policy framework in place to provide certainty that the next wave of investment in capacity additions will feature near-zero emissions technologies. Successful strategies are likely to require initial measures such as carbon contracts for difference, public procurement and incentives to encourage private sector procurement. As new technologies are deployed and costs decline, there is likely to be a strong case by about 2030 for replacing these initial measures with others such as CO_2 taxes, emissions trading systems and emissions performance standards. Financing support for near-zero emissions capacity additions may also have an important role to play through measures such as low interest and concessional loans and blended finance, as well as through contributions by advanced economies to funds that support projects in emerging market and developing economies. Strategies should also include measures to reduce industrial emissions through material efficiency, for example by revising design regulations, adopting incentives to promote longer product and building lifetimes, and improving systems for collecting and sorting materials for recycling.

There is a strong case for an international agreement on the transition to near-zero emissions for globally traded products by the mid-2020s so as to establish a level playing field. Alternatively, countries may need to resort to measures to shield domestic near-zero emissions production from competition from products that create emissions. Any such policy would need to be designed to respect the regulatory frameworks governing international trade, such as those of the World Trade Organization.

Even with accelerated innovation timelines and strong policies in place, some high-emitting capacity additions will be needed to meet demand in the next decade before near-zero emissions technologies are available. It would make sense for governments to require any new capacity to incorporate retrofit-ready designs so that unabated capacity added in the next few years has the technical capacity and space requirement to integrate near-zero emissions technologies in coming years. Beyond 2030, investment in the NZE is confined to innovative near-zero emissions process routes.

Governments should not overlook the need for measures to spur deployment of already available near-zero emissions technologies in light manufacturing industries. Adopting a carbon price and then sufficiently increasing the price over time – through carbon taxes or emissions trading systems for larger manufacturers – may be the simplest way to achieve that objective. Other regulatory measures such as tradeable low-carbon fuel and emissions standards could yield the same outcome, but may involve greater administrative complexity. Technology mandates are likely to be needed to achieve the energy efficiency savings in the NZE, such as minimum energy performance standards for new motors and boilers. Tailored programmes and incentives for small and medium enterprises could also play a helpful role.

3.6 Transport

3.6.1 Energy and emission trends in the Net-Zero Emissions Scenario

The global transport sector emitted over 7 Gt CO_2 in 2020, and nearly 8.5 Gt in 2019 before the Covid-19 pandemic.[7] In the NZE, transport sector CO_2 emissions are slightly over 5.5 Gt in 2030. By 2050 they are around 0.7 Gt – a 90% drop relative to 2020 levels. CO_2 emissions decline even with rapidly rising passenger travel, which nearly doubles by 2050, and rising freight activity, which increases by two-and-a-half-times from current levels, and an increase in the global passenger car fleet from 1.2 billion vehicles in 2020 to close to 2 billion in 2050.

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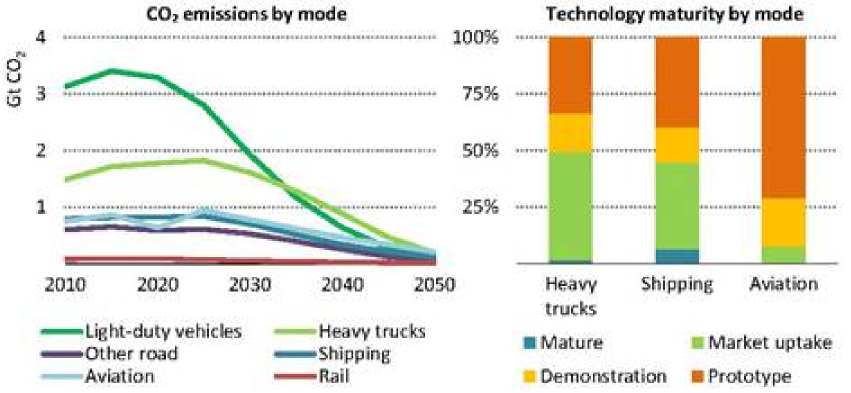
[7] Unless otherwise noted, CO_2 emissions reported here are direct emissions from fossil fuel combusted during the operation of vehicles.

The transport modes do not decarbonise at the same rate because technology maturity varies markedly between them (Figure 3.21). CO_2 emissions from two/three-wheelers almost cease by 2040, followed by cars, vans and rail in the late 2040s. Emissions from heavy trucks, shipping and aviation fall by an annual average of 6% between 2020 and 2050, but still collectively amount to more than 0.5 Gt CO_2 in 2050. This reflects projected activity growth and that many of the technologies needed to reduce CO_2 emissions in long distance transport are currently under development and do not start to make substantial inroads into the market in the coming decade.

Figure 3.21 ▷ Global CO_2 transport emissions by mode and share of emissions reductions to 2050 by technology maturity in the NZE



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Passenger cars can make use of low-emissions technologies on the market, but major advances are needed for heavy trucks, shipping and aviation to reduce their emissions

Notes: Other road = two/three wheelers and buses. Shipping and aviation include both domestic and international operations. See Box 2.4 for details on the maturity categories.

Decarbonisation of the transport sector in the NZE relies on policies to promote modal shifts and more efficient operations across passenger transport modes (see sections 2.5.7 and 4.4.3),[8] as well as improvements in energy efficiency. It also depends on two major technology transitions: shifts towards electric mobility (electric vehicles [EVs] and fuel cell electric vehicles [FCEVs])[9] and shifts towards higher fuel blending ratios and direct use of

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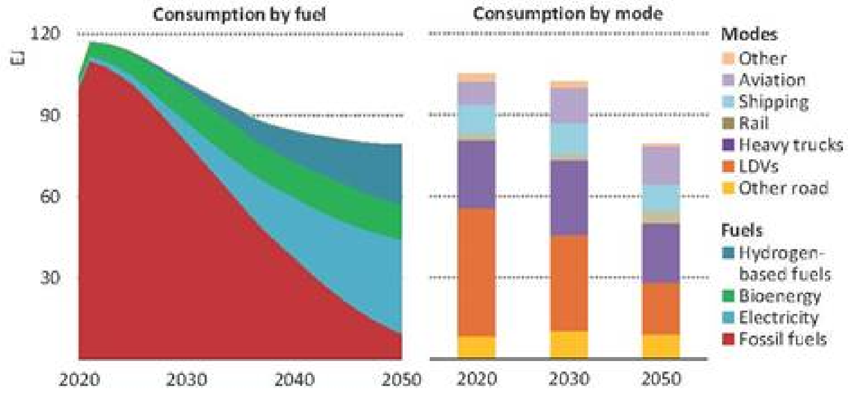
[8] Examples of efficient operations include: seamless integration of various modes (inter-modality) and "Mobility as a Service" in passenger transport; logistics measures in road freight, e.g. backhauling, night-time deliveries, real-time routing; slow steaming in shipping; and air traffic management, e.g. landing and take-off scheduling in aviation.

[9] EVs include battery electric vehicles, plug-in hybrid electric-gasoline vehicles and plug-in hybrid electric-diesel vehicles. FCEVs contain a battery and electric motor and are capable of operating without tailpipe emissions.

low-carbon fuels (biofuels and hydrogen-based fuels). These shifts are likely to require interventions to stimulate investment in supply infrastructure and to incentivise consumer uptake.

Transport has traditionally been heavily reliant on oil products, which accounted for more than 90% of transport sector energy needs in 2020 despite inroads from biofuels and electricity (Figure 3.22). In the NZE, the share of oil drops to less than 75% in 2030 and slightly over 10% by 2050. By the early 2040s, electricity becomes the dominant fuel in the transport sector worldwide in the NZE: it accounts for nearly 45% of total final consumption in 2050, followed by hydrogen-based fuels (28%) and bioenergy (16%). Biofuels almost reach a 15% blending share in oil products by 2030 in road transport, which reduces oil needs by around 4.5 million barrels of oil equivalent per day (mboe/d). Beyond 2030, biofuels are increasingly used for aviation and shipping, where the scope for using electricity and hydrogen is more limited. Hydrogen carriers (such as ammonia) and low-emissions synthetic fuels also supply increasing shares of energy demand in these modes.

Figure 3.22 ▷ Global transport final consumption by fuel type and mode in the NZE



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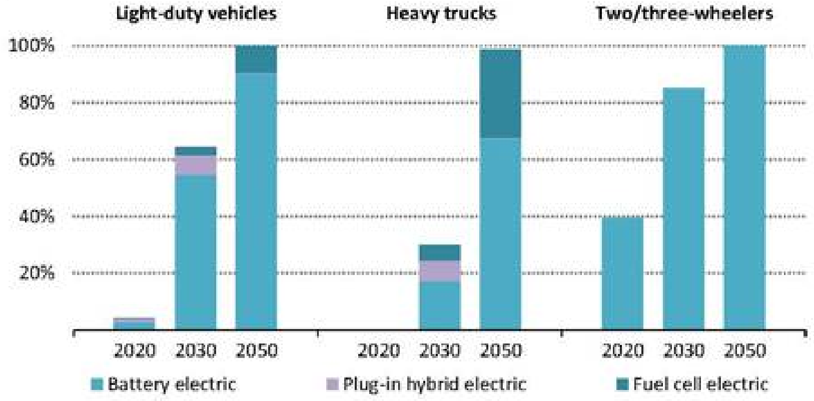
Electricity and hydrogen-based fuels account for more than 70% of transport energy demand by 2050

Note: LDVs = Light-duty vehicles; Other road = two/three wheelers and buses.

Road vehicles

Electrification plays a central role in decarbonising road vehicles in the NZE. Battery cost declines of almost 90% in a decade have boosted sales of electric passenger cars by 40% on average over the past five years. Battery technology is already relatively commercially competitive. FCEVs start to make inroads in the 2020s in the NZE. The electrification of heavy trucks moves more slowly due to the weight of the batteries, high energy and power requirements required for charging, and limits on driving ranges. But fuel cell heavy trucks make significant progress, mainly after 2030 (Figure 3.23). The number of battery electric, plug-in hybrid and fuel cell electric light-duty vehicles (cars and vans) on the world's roads reaches 350 million in 2030 and almost 2 billion in 2050, up from 11 million in 2020. The number of electric two/three-wheelers also rises rapidly, from just under 300 million today to 600 million in 2030 and 1.2 billion in 2050. The electric bus fleet expands from 0.5 million in 2020 to 8 million in 2030 and 50 million in 2050.

Figure 3.23 ▷ Global share of battery electric, plug-in hybrid and fuel cell electric vehicles in total sales by vehicle type in the NZE



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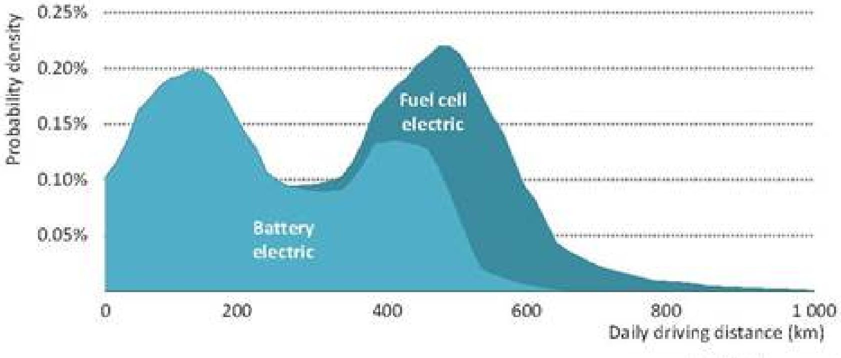
Sales of battery electric, plug-in hybrid and fuel cell electric vehicles soar globally

Note: Light-duty vehicles = passenger cars and vans; Heavy trucks = medium- and heavy-freight trucks.

Light-duty vehicles are electrified faster in advanced economies over the medium term and account for around 75% of sales by 2030. In emerging and developing economies, they account for about 50% of sales. Almost all light-duty vehicle sales in advanced economies are battery electric, plug-in hybrid or fuel cell electric by the early 2030s and in emerging and developing economies by the mid-2030s.

For heavy trucks that operate over long distances, currently biofuels are the main viable commercial alternative to diesel, and they play an important role in lowering emissions from heavy-duty trucks over the 2020s. Beyond 2030, the number of electric and hydrogen-powered heavy trucks increases in the NZE as supporting infrastructure is built and as costs decline (lower battery costs, energy density improvements and lower costs to produce and deliver hydrogen) (IEA, 2020b). This coincides with a reduction in the availability of sustainable bioenergy, as limited supplies increasingly go to hard-to-abate segments such as aviation and shipping, though biofuels still meet about 10% of fuel needs for heavy-duty trucks in 2050 (see Chapter 2). Advanced economies have a higher market share of battery electric and fuel cell electric heavy-duty trucks sales in 2030, more than twice the level in emerging market and developing economies, although this gap closes towards 2050.

Figure 3.24 ▷ Heavy trucks distribution by daily driving distance, 2050



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Driving distance is the key factor affecting powertrain choice for trucks

Realising the objectives of the NZE depends on rapid scaling up of battery manufacturing (current announced production capacity for 2030 would cover only 50% of required demand in that year), and on the rapid introduction on the market of next generation battery technology (solid state batteries) between 2025 and 2030. Electrified road systems using conductive or inductive power transfer to provide electricity to trucks offer an alternative for battery electric and fuel cell electric trucks on long-distance operations, but these systems too would need rapid development and deployment.

Aviation[10]

The NZE assumes that air travel, measured in revenue-passenger kilometres, increases by only around 3% per year to 2050 relative to 2020. This compares with about around 6% over the 2010-19 period. The NZE assumes that aviation growth is constrained by comprehensive government policies that promote a shift towards high-speed rail and rein in expansion of long-haul business travel, e.g. through taxes on commercial passenger flights (see section 2.5.2).

Global CO_2 emissions from aviation rise in the NZE from about 640 Mt in 2020 (down from around 1 Gt in 2019) to a peak of 950 Mt by around 2025. Emissions then fall to 210 Mt in 2050 as the use of low-emissions fuels grows. Emissions are hard to abate because aviation

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[10] Aviation considered here includes both domestic and international flights. While the focus here is on commercial passenger aviation, dedicated freight and general (military and private) aviation, which collectively account for more than 10% of fuel use and emissions, are also included in the energy and emissions accounting.

requires fuel with a high energy density. Emissions in aviation comprise just over 10% of unabated CO_2 emissions from fossil fuels and industrial processes in 2050.

In the NZE, the global use of jet kerosene declines to about 3 EJ in 2050 from 9 EJ in 2020 (and around 14.5 EJ in 2019 before the Covid-19 crisis), and its share of total energy use falls from almost 100% to just over 20%. The use of sustainable aviation fuel (SAF) starts to increase significantly in the late-2020s. In 2030, around 15% of total fuel consumption in aviation is SAF, most of which is biojet kerosene (a type of liquid biofuel). This is estimated to increase the ticket price for a mid-haul flight (1 200 km) by about USD 3 per passenger. By 2050, biojet kerosene meets 45% of total fuel consumption in aviation and synthetic hydrogen-based fuels meet about 30%. This is estimated to increase the ticket price for a mid-haul flight in 2050 by about USD 10 per passenger. The NZE also sees the adoption of commercial battery electric and hydrogen aircraft from 2035, but they account for less than 2% of fuel consumption in 2050.

Operational improvements, together with fuel efficiency technologies for airframes and engines, also help to reduce CO_2 emissions by curbing the pace of fuel demand growth in the NZE. These improvements are incremental, but revolutionary technologies such as open rotors, blended wing-body airframes and hybridisation could bring further gains and enable the industry to meet the International Civil Aviation Organization's (ICAO) ambitious 2050 efficiency targets (IEA, 2020b).

Maritime shipping[11]

Maritime shipping was responsible for around 830 Mt CO_2 emissions worldwide in 2020 (880 Mt CO_2 in 2019), which is around 2.5% of total energy sector emissions. Due to a lack of available low-carbon options on the market and the long lifetime of vessels (typically 25-35 years), shipping is one of the few transport modes that does not achieve zero emissions by 2050 in the NZE. Nevertheless, emissions from shipping decline by 6% annually to 120 Mt CO_2 in 2050.

In the short term, there is considerable potential for curbing fuel consumption in shipping through measures to optimise operational efficiency and improve energy efficiency. Such approaches include slow steaming and the use of wind-assistance technologies (IEA, 2020b). In the medium to long term, significant emissions reductions are achieved in the NZE by switching to low-carbon fuels such as biofuels, hydrogen and ammonia. Ammonia looks likely to be a particularly good candidate for scaling up, and a critical fuel for long-range transoceanic journeys that need fuel with high energy density.

Ammonia and hydrogen are the main low-carbon fuels for shipping adopted over the next three decades in the NZE, their combined share of total energy consumption in shipping reaching around 60% in 2050. The 20 largest ports in the world account for more than half of global cargo (UNCTAD, 2018); they could become industrial hubs to produce hydrogen and

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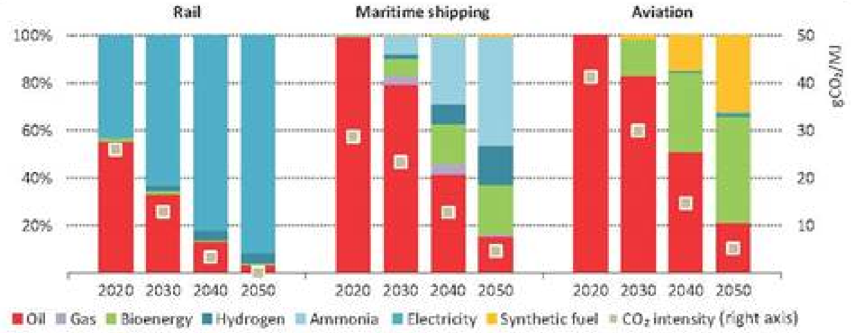
[11] Maritime shipping here includes both domestic and international operations.

ammonia for use in both chemical and refining industries, as well as for refuelling ships. Internal combustion engines for ammonia-fuelled vessels are currently being developed by two of the largest manufacturers of maritime engines and are expected to become available on the market by 2024. Sustainable biofuels provide almost 20% of total shipping energy needs in 2050. Electricity plays a very minor role, as the relatively low energy density of batteries compared with liquid fuels makes it suitable only for shipping routes of up to 200 km. Even with an 85% increase in battery energy density in the NZE as solid state batteries come to market, only short-distance shipping routes can be electrified.

Rail

Rail transport is the most energy-efficient and least carbon-intensive way to move people and second only to shipping for carrying goods. Passenger rail almost doubles its share of total transport activity to 20% by 2050 in the NZE, with particularly rapid growth in urban and high-speed rail (HSR), the latter of which contributes to curbing growth in air travel. Global CO_2 emissions from the rail sector fall from 95 Mt CO_2 in 2020 (100 Mt CO_2 in 2019) to almost zero by 2050 in the NZE, driven primarily by rapid electrification.

Figure 3.25 ▷ **Global energy consumption by fuel and CO_2 intensity in non-road sectors in the NZE**



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Railways rely heavily on electricity to decarbonise, while shipping and aviation curb emissions mainly by switching to low-emissions fuels

Note: Synthetic fuel = low-emissions synthetic hydrogen-based fuels.

In the NZE, all new tracks on high-throughput corridors are electrified from now on, while hydrogen and battery electric trains, which have recently been demonstrated in Europe, are adopted on rail lines where throughput is too low to make electrification economically viable. Oil use, which accounted for 55% of total energy consumption in the rail sector in 2020, falls to almost zero in 2050: it is replaced by electricity, which provides over 90% of rail energy needs and by hydrogen which provides another 5%.

3.6.2 Key milestones and decision points

Table 3.4 ▷ Key milestones in transforming the global transport sector

Category	
Road transport	• 2035: no new passenger internal combustion engine car sales globally
Aviation and shipping	• Implementation of strict carbon emissions intensity reduction targets as soon as possible.

Category	2020	2030	2050
Road transport			
Share of PHEV, BEV and FCEV in sales: cars	5%	64%	100%
two/three-wheelers	40%	85%	100%
bus	3%	60%	100%
vans	0%	72%	100%
heavy trucks	0%	30%	99%
Biofuel blending in oil products	5%	13%	41%
Rail			
Share of electricity and hydrogen in total energy consumption	43%	65%	96%
Activity increase due to modal shift (index 2020=100)	100	100	130
Aviation			
Synthetic hydrogen-based fuels share in total aviation energy consumption	0%	2%	33%
Biofuels share in total aviation energy consumption	0%	16%	45%
Avoided demand from behaviour measures (index 2020=100)	0	20	38
Shipping			
Share in total shipping energy consumption: Ammonia	0%	8%	46%
Hydrogen	0%	2%	17%
Bioenergy	0%	7%	21%
Infrastructure			
EV public charging (million units)	1.3	40	200
Hydrogen refuelling units	540	18 000	90 000
Share of electrified rail lines	34%	47%	65%

Note: PHEV = plug-in hybrid electric vehicles; BEV = battery electric vehicles; FCEV = fuel cell electric vehicles.

Electrification is the main option to reduce CO_2 emissions from road and rail modes, the technologies are already on the market and should be accelerated immediately, together with the roll-out of recharging infrastructure for EVs. Deep emission reductions in the hard-to-abate sectors (heavy trucks, shipping and aviation) require a massive scale up of the required technologies over the next decade, which today are largely at the prototype and demonstration stages, together with plans for the development of associated infrastructure, including hydrogen refuelling stations.

The transformation of transport required to be on track to reduce emissions in line with the NZE calls for a range of government decisions over the next decade. In the next few years, all governments need to eliminate fossil fuel subsidies and encourage switching to low-carbon technologies and fuels across the entire transport sector. Before 2025, governments need to define clear R&D priorities for all the technologies that can contribute to decarbonise transport in line with their strategic priorities and needs. Ideally this would be informed by international dialogue and collaboration. R&D is critical in particular for battery technology, which should be an immediate priority.

To achieve the emissions reductions required by the NZE, governments also need to move quickly to signal the end of sales of new internal combustion engine cars. Early commitments would help the private sector to make the necessary investment in new powertrains, relative supply chains and refuelling infrastructure (see section 4.3.4). This is particularly important for the supply of battery metals, which require long-term planning (IEA, 2021a).

By 2025, the large-scale deployment of EV public charging infrastructure in urban areas needs to be sufficiently advanced to allow households without access to private chargers to opt for EVs. Governments should ensure sustainable business models for companies installing chargers, remove barriers to planning and construction, and put in place regulatory, fiscal and technological measures to enable and encourage smart charging, and to ensure that EVs support electricity grid stability and stimulate the adoption of variable renewables (IEA, 2021b).

For heavy trucks, battery electric trucks are just beginning to become available on the market, and fuel cell electric technologies are expected to come to market in the next few years. Working in collaboration with truck manufacturers, governments should take steps in the near term to prioritise the rapid commercial adoption of battery electric and fuel cell electric trucks. By 2030, they should take stock of the competitive prospects for these technologies, so as to focus R&D on the most important challenges and allow adequate time for strategic infrastructure deployment, thus paving the way for large-scale adoption during the 2030s.

Governments need to define their strategies for low-carbon fuels in shipping and aviation by 2025 at the latest, given the slow turnover rate of the fleets, after which they should rapidly implement them. International co-operation and collaboration will be crucial to success. Priority action should target the most heavily used ports and airports so as to maximise the impact of initial investment. Harbours near industrial areas are ideally placed to become low-carbon fuel hubs.

Box 3.3 ▷ What would be the implications of an all-electric approach to emissions reductions in the road transport sector?

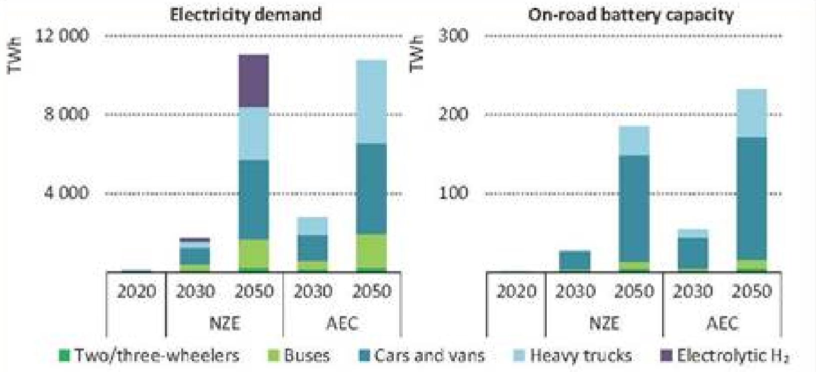
The use of a variety of fuels in road transport is a core component of the NZE. However, governments might want to consider an all-electric route to eliminate CO_2 emissions from transport, especially if other technologies such as FCEVs and advanced biofuels fail to develop as projected. We have therefore developed an *All-Electric Case* which looks at the implications of electrifying all road vehicle modes. In the NZE, decarbonisation of road transport occurs primarily via the adoption of plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs) and advanced biofuels. The All-Electric Case assumes the same rate of road transport decarbonisation as the NZE, but achieved via battery electric vehicles alone.

The All-Electric Case depends on even further advances in battery technologies than the NZE that lead to energy densities of at least 400 Watt hours per kilogramme (Wh/kg) by the 2030s at costs that would make BEV trucks preferable to FCEV trucks in long-haul operations. This would mean 30% more BEVs (an additional 350 million) on the road in 2030 than in the NZE. Over sixty five million public chargers would be needed to support the vehicles, requiring a cumulative investment of around USD 300 billion, 35% higher than the NZE. This would require faster expansion of battery manufacturing. The annual global battery capacity additions for BEVs in 2030 would be almost 9 TWh, requiring 80 giga-factories (assuming 35 GWh per year output) more than in the NZE, or an average of over two per month from now to 2030.

The increased use of electricity for road transport would also create additional challenges for the electricity sector. The total electricity demand for road transport (11 000 TWh or 15% of total electricity consumption in 2050), would be roughly the same in both cases, when account is taken of demand for electrolytic hydrogen. However, the electrolytic hydrogen in the NZE can be produced flexibly, in regions and at times with surplus renewables-based capacity and from dedicated (off-grid) renewable power. Peak power demand in the All-Electric Case, taking into consideration the flexibility that enables smart charging of cars, is about one-third (2 000 GW) higher than in the NZE, mainly due to the additional evening/overnight charging of buses and trucks. If not coupled with energy storage devices, ultra-fast chargers for heavy-duty vehicles could cause additional spikes in demand, putting even more strain on electricity grids.

While full electrification of road transport is possible, it could involve additional challenges and undesirable side effects. For example, it could increase pressure on electricity grids, requiring significant additional investment, and increasing the vulnerability of the transport system to power disruptions. Fuel diversification could bring benefits in terms of resilience and energy security.

Figure 3.26 ▸ Global electricity demand and battery capacity for road transport in the NZE and the All-Electric Case



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Both direct electricity consumption and vehicle battery capacity in 2050 increase by about a quarter in the All-Electric Case relative to the NZE

Note: AEC = All-Electric Case.

3.7 Buildings

3.7.1 Energy and emission trends in the Net-Zero Emissions Scenario

Floor area in the buildings sector worldwide is expected to increase 75% between 2020 and 2050, of which 80% is in emerging market and developing economies. Globally, floor area equivalent to the surface of the city of Paris is added every week through to 2050. Moreover, buildings in many advanced economies have long lifetimes and around half of the existing buildings stock will still be standing in 2050. Demand for appliances and cooling equipment continues to grow, especially in emerging market and developing economies where 650 million air conditioners are added by 2030 and another 2 billion by 2050 in the NZE. Despite this demand growth, total CO_2 emissions from the buildings sector decline by more than 95% from almost 3 Gt in 2020 to around 120 Mt in 2050 in the NZE.[12]

Energy efficiency and electrification are the two main drivers of decarbonisation of the buildings sector in the NZE (Figure 3.27). That transformation relies primarily on technologies

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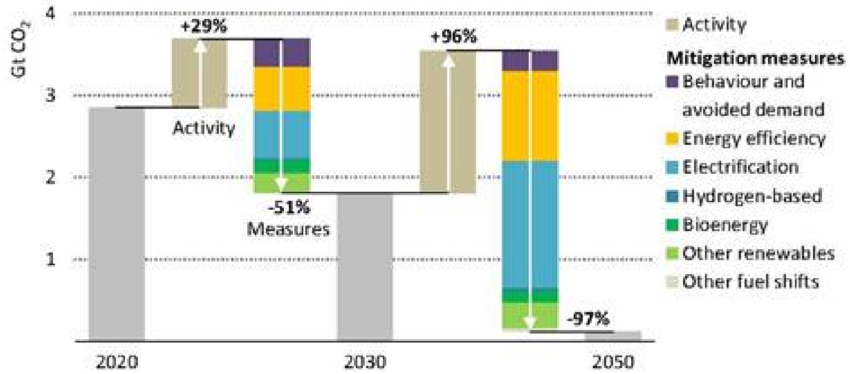
[12] All CO_2 emissions in this section refer to direct CO_2 emissions unless otherwise specified. The NZE also pursues reductions in emissions linked to construction materials used in buildings. These embodied emissions are cut by 40% per square metre of new floor area by 2030, with material efficiency strategies cutting cement and steel use by 50% by 2050 relative to today through measures at the design, construction, use and end-of-life phases.

already available on the market, including improved envelopes for new and existing buildings, heat pumps, energy-efficient appliances, and bioclimatic and material-efficient building design. Digitalisation and smart controls enable efficiency gains that reduce emissions from the buildings sector by 350 Mt CO_2 by 2050. Behaviour changes are also important in the NZE, with a reduction of almost 250 Mt CO_2 in 2030 reflecting changes in temperature settings for space heating or reducing excessive hot water temperatures. Additional behaviour changes such as greater use of cold temperature clothes washing and line drying, facilitate the decarbonisation of electricity supply. There is scope for these reductions to be achieved rapidly and at no cost.

Figure 3.27 ▷ Global direct CO_2 emissions reductions by mitigation measure in buildings in the NZE

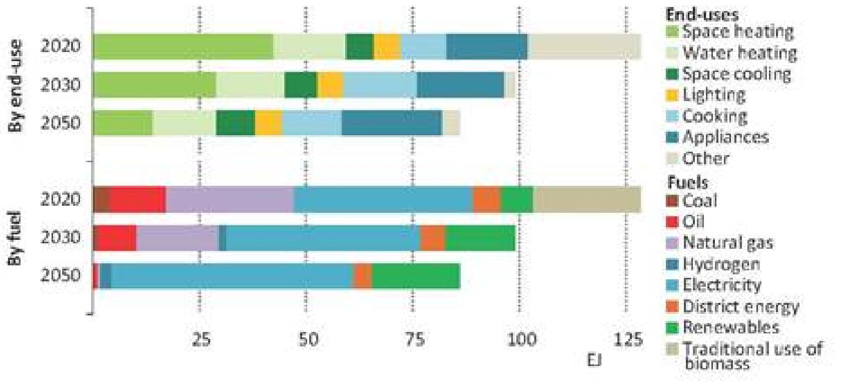


Electrification and energy efficiency account for nearly 70% of buildings-related emissions reductions through to 2050, followed by solar thermal, bioenergy and behaviour

Notes: Activity = change in energy service demand related to rising population, increased floor area and income per capita. Behaviour = change in energy service demand from user decisions, e.g. changing heating temperatures. Avoided demand = change in energy service demand from technology developments, e.g. digitalisation.

Rapid shifts to zero-carbon-ready technologies see the share of fossil fuels in energy demand in the buildings sector drop to 30% by 2030, and to 2% by 2050 in the NZE. The share of electricity in the energy mix reaches almost 50% by 2030 and 66% by 2050, up from 33% in 2020 (Figure 3.28). All end-uses today dominated by fossil fuels are increasingly electrified in the NZE, with the share of electricity in space heating, water heating and cooking increasing from less than 20% today to more than 40% in 2050. District energy networks and low-carbon gases, including hydrogen-based fuels, remain significant in 2050 in regions with high heating needs, dense urban populations and existing gas or district heat networks. Bioenergy meets nearly one-quarter of overall heat demand in the NZE by 2050, over 50% of bioenergy use is for cooking, nearly all in emerging market and developing economies, where 2.7 billion people gain access to clean cooking by 2030 in the NZE. Space heating demand drops by two-thirds between 2020 and 2050, driven by improvement in energy efficiency and behavioural changes such as the adjustment of temperature set points.

Figure 3.28 ▷ Global final energy consumption by fuel and end-use application in buildings in the NZE



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Fossil fuel use in the buildings sector declines by 96% and space heating energy needs by two-thirds to 2050, thanks mainly to energy efficiency gains

Note: Other includes desalination and traditional use of solid biomass which is not allocated to a specific end-use.

Zero-carbon-ready buildings

The NZE pathway for the buildings sector requires a step change improvement in the energy efficiency and flexibility of the stock and a complete shift away from fossil fuels. To achieve this, more than 85% of buildings need to comply with zero-carbon-ready building energy codes by 2050 (Box 3.4). This means that mandatory zero-carbon-ready building energy codes for all new buildings need to be introduced in all regions by 2030, and that retrofits need to be carried out in most existing buildings by 2050 to enable them to meet zero-carbon-ready building energy codes.

Retrofit rates increase from less than 1% per year today to about 2.5% per year by 2030 in advanced economies: this means that around 10 million dwellings are retrofitted every year. In emerging market and developing economies, building lifetimes are typically lower than in advanced economies, meaning that retrofit rates by 2030 in the NZE are lower, at around 2% per year. This requires the retrofitting of 20 million dwellings per year on average to 2030. To achieve savings at the lowest cost and to minimise disruption, retrofits need to be comprehensive and one-off.

Box 3.4 ▷ Towards zero-carbon-ready buildings

Achieving decarbonisation of energy use in the sector requires almost all existing buildings to undergo a single in-depth retrofit by 2050, and new construction to meet stringent efficiency standards. Building energy codes covering new and existing buildings are the fundamental policy instrument to drive such changes. Building energy codes currently exist or are under development in only 75 countries, and codes in around 40 of these countries are mandatory for both the residential and services sub-sectors. In the NZE, comprehensive zero-carbon-ready building codes are implemented in all countries by 2030 at the latest.

What is a zero-carbon-ready building?

A zero-carbon-ready building is highly energy efficient and either uses renewable energy directly, or uses an energy supply that will be fully decarbonised by 2050, such as electricity or district heat. This means that a zero-carbon-ready building will become a zero-carbon building by 2050, without any further changes to the building or its equipment.

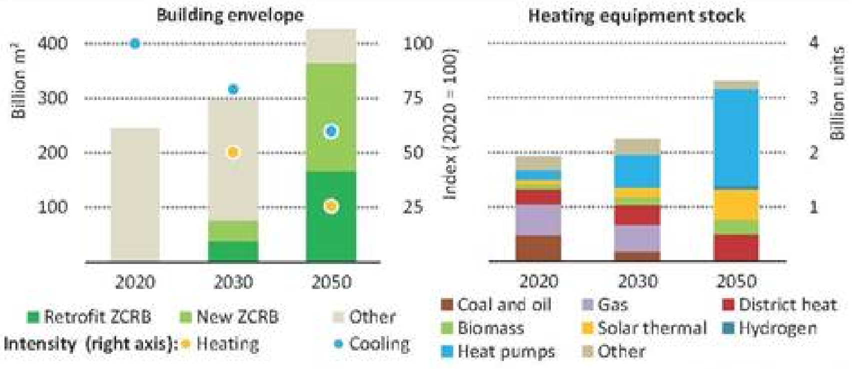
Zero-carbon-ready buildings should adjust to user needs and maximise the efficient and smart use of energy, materials and space to facilitate the decarbonisation of other sectors. Key considerations include:

- **Scope.** Zero-carbon-ready building energy codes should cover building operations (scope 1 and 2) as well as emissions from the manufacturing of building construction materials and components (scope 3 or embodied carbon emissions).
- **Energy use.** Zero-carbon-ready energy codes should recognise the important part that passive design features, building envelope improvements and high energy performance equipment play in lowering energy demand, reducing both the operating cost of buildings and the costs of decarbonising the energy supply.
- **Energy supply.** Whenever possible, new and existing zero-carbon-ready buildings should integrate locally available renewable resources, e.g. solar thermal, solar PV, PV thermal and geothermal, to reduce the need for utility-scale energy supply. Thermal or battery energy storage may be needed to support local energy generation.
- **Integration with power systems.** Zero-carbon-ready building energy codes need buildings to become a flexible resource for the energy system, using connectivity and automation to manage building electricity demand and the operation of energy storage devices, including EVs.
- **Buildings and construction value chain.** Zero-carbon-ready building energy codes should also target net-zero emissions from material use in buildings. Material efficiency strategies can cut cement and steel demand in the buildings sector by more than a third relative to baseline trends, and embodied emissions can be further reduced by more robust uptake of bio-sourced and innovative construction materials.

Heating and cooling

Building envelope improvements in zero-carbon-ready retrofit and new buildings account for the majority of heating and cooling energy intensity reductions in the NZE, but heating and cooling technology also makes a significant contribution. Space heating is transformed in the NZE, with homes heated by natural gas falling from nearly 30% of the total today to less than 0.5% in 2050, while homes using electricity for heating rise from nearly 20% of the total today to 35% in 2030 and about 55% in 2050 (Figure 3.29). High efficiency electric heat pumps become the primary technology choice for space heating in the NZE, with worldwide heat pump installations per month rising from 1.5 million today to around 5 million by 2030 and 10 million by 2050. Hybrid heat pumps are also used in some of the coldest climates, but meet no more than 5% of heating demand in 2050.

Figure 3.29 ▷ Global building and heating equipment stock by type and useful space heating and cooling demand intensity changes in the NZE



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By 2050, over 85% of buildings are zero-carbon-ready, reducing average useful heating intensity by 75%, with heat pumps meeting over half of heating needs

Notes: ZCRB refers to buildings meeting zero-carbon-ready building energy codes. Other for building envelope refers to envelopes that do not meet zero-carbon-ready building energy codes. Other for heating equipment stock includes resistive heaters, and hybrid and gas heat pumps.

Not all buildings are best decarbonised with heat pumps, however, and bioenergy boilers, solar thermal, district heat, low-carbon gases in gas networks and hydrogen fuel cells all play a role in making the global building stock zero-carbon-ready by 2050. Bioenergy meets 10% of space heating needs by 2030 and more than 20% by 2050. Solar thermal is the preferred renewable technology for water heating, especially where heat demand is low; in the NZE it meets 35% of demand by 2050, up from 7% today. District heat networks remain an attractive option for many compact urban centres where heat pump installation is impractical, in the NZE they provide more than 20% of final energy demand for space heating in 2050, up from a little over 10% today.

There are no new coal and oil boilers sold globally from 2025 in the NZE. Sales of gas boilers fall by more than 40% from current levels by 2030 and by 90% by 2050. By 2025 in the NZE, any gas boilers that are sold are capable of burning 100% hydrogen and therefore are zero-carbon-ready. The share of low-carbon gases (hydrogen, biomethane, synthetic methane) in gas distributed to buildings rises from almost zero to 10% by 2030 to above 75% by 2050.

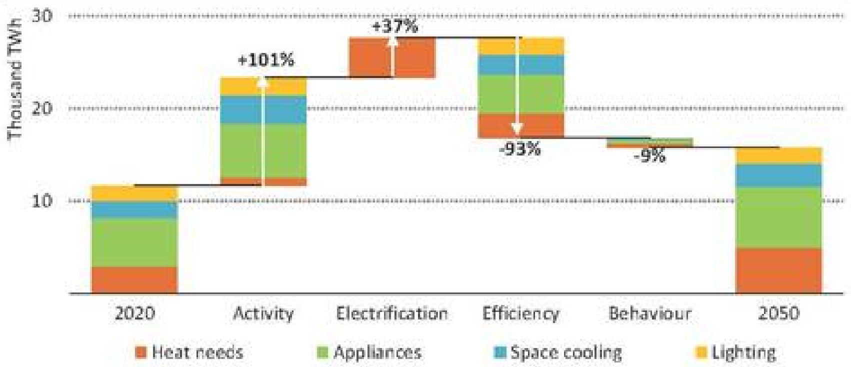
Buildings that meet the standards of zero-carbon-ready building energy codes drive down the need not only for space heating but also for space cooling – the fastest growing end-use in buildings since 2000. Space cooling represented only 5% of total buildings energy consumption worldwide in 2020, but demand for cooling is likely to grow strongly in the coming decades with rising incomes and a hotter climate. In the NZE, 60% of households have an air conditioner in 2050, up from 35% in 2020. High-performance building envelopes, including bioclimatic designs and insulation, can reduce the demand for space cooling by 30-50%, while providing greater resilience during extreme heat events. In the NZE, electricity demand for space cooling grows annually by 1% to reach 2 500 TWh in 2050. Without 2 000 TWh of savings from residential building envelope improvements and higher efficiency equipment, space cooling demand would be almost twice as high.

Appliances and lighting

Electric appliances and lighting become much more efficient over the next three decades in the NZE thanks to policy measures and technical advances. By 2025 in the NZE, over 80% of all appliances and air conditioners sold in advanced economies are the best available technologies today in these markets, and this share increases to 100% by the mid-2030s. In emerging market and developing economies, which account for over half of appliances and air conditioners by 2050, the NZE assumes a wave of policy action over the next decade which leads to 80% of equipment sold in these markets in 2030 being as efficient as the best available technologies in advanced economies today, increasing to close to 100% by 2050 (Figure 3.30). The share of light-emitting diode (LED) lamps in total lightbulb sales reaches 100% by 2025 in all regions. Minimum energy performance standards are complemented by requirements for smart control of appliances to facilitate demand-side response in all regions.

Energy use in buildings will be increasingly focused on electric, electronic and connected equipment and appliances. The share of electricity in energy consumption in buildings rises from 33% in 2020 to around two-thirds in 2050 in the NZE, with many buildings incorporating decentralised electricity generation using local solar PV panels, battery storage and EV chargers. The number of residential buildings with solar PV panels increases from 25 million to 240 million over the same period. In the NZE, smart control systems shift flexible uses of electricity in time to correspond with generation from local renewables, or to provide flexibility services to the power system, while optimised home battery and EV charging allow households to interact with the grid. These developments help improve electricity supply security and lower the cost of the energy transition by making it easier and cheaper to integrate renewables into the system.

Figure 3.30 ▷ Global change in electricity demand by end-use in the buildings sector



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Energy efficiency is critical to mitigate electricity demand growth for appliances and air conditioning, with savings more than offsetting the impact of electrifying heat

3.7.2 Key milestones and decision points

Table 3.5 ▷ Key milestones in transforming global buildings sector

Category	
New buildings	• From 2030: all new buildings are zero-carbon-ready.
Existing buildings	• From 2030: 2.5% of buildings are retrofitted to be zero-carbon-ready each year.

Category	2020	2030	2050
Buildings			
Share of existing buildings retrofitted to the zero-carbon-ready level	<1%	20%	>85%
Share of zero-carbon-ready new buildings construction	5%	100%	100%
Heating and cooling			
Stock of heat pumps (million units)	180	600	1 800
Million dwellings using solar thermal	250	400	1 200
Avoided residential energy demand from behaviour	n.a.	12%	14%
Appliances and lighting			
Appliances: unit energy consumption (index 2020=100)	100	75	60
Lighting: share of LED in sales	50%	100%	100%
Energy access			
Population with access to electricity (billion people)	7.0	8.5	9.7
Population with access to clean cooking (billion people)	5.1	8.5	9.7
Energy infrastructure in buildings			
Distributed solar PV generation (TWh)	320	2 200	7 500
EV private chargers (million units)	270	1 400	3 500

Near-term government decisions are required for energy codes and standards for buildings, fossil fuel phase out, use of low-carbon gases, acceleration of retrofits and financial incentives to encourage investment in building sector energy transitions. Decisions will be most effective if they focus on decarbonising the entire value chain, taking into account not only buildings but also the energy and infrastructure networks that supply them, as well as wider considerations including the role of the construction sector and urban planning. Such decisions are likely to bring wider benefits, notably in reducing fuel poverty.

Near-term government action is needed to ensure that zero-carbon-ready buildings become the new norm across the world before 2030 for both new construction and retrofits. This requires governments to act before 2025 to ensure that zero-carbon-ready compliant building energy codes are implemented by 2030 at the latest. While this goal applies to all regions, ways to achieve zero-carbon-ready buildings vary significantly across regions and climate zones, and the same is true for heating and cooling technology strategies. Governments should consider paving the way by making public buildings zero-carbon-ready in the coming decade.

Governments will need to find ways to make new zero-carbon-ready buildings and retrofits affordable and attractive to owners and occupants by overcoming financial barriers, addressing split incentive barriers and minimising disruption to building use. Building energy performance certificates, green lease agreements, green bond financing and pay-as-you save models could all play a part.

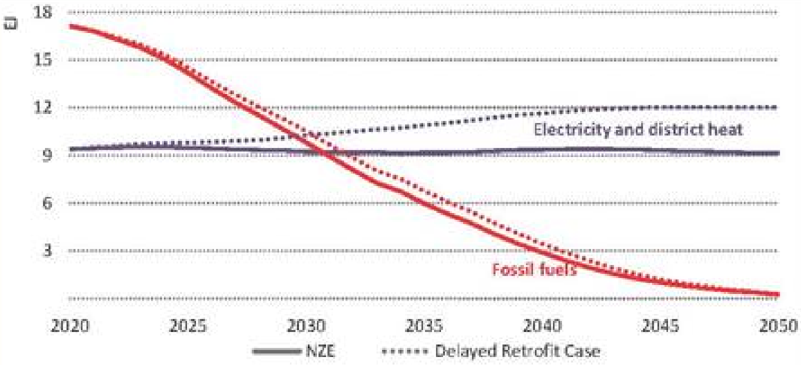
Making zero-carbon-ready building retrofits a central pillar of economic recovery strategies in the early 2020s is a no-regrets action to jumpstart progress towards a zero-emissions building sector. Foregoing the opportunity to make energy use in buildings more efficient would drive up electricity demand linked to electrification of energy use in the buildings sector and make decarbonising the energy system significantly more difficult and more costly (Box 3.5).

Box 3.5 ⊳ What would be the impact of global retrofit rates not rising to 2.5%?

Decarbonising heating in existing buildings in the NZE rests upon a deep retrofit of the majority of the existing building stock. Having almost all buildings meet zero-carbon-ready building energy codes by 2050 would require retrofit rates of 2.5% each year by 2030, up from less than 1% today. Retrofits can be disruptive for occupants, require high upfront investment and may face permitting difficulties. These issues make achieving the required pace and depth of retrofits in the coming years the biggest challenge facing the buildings sector.

Any delay in reaching 2.5% of annual retrofits by 2030 would require such a steep subsequent ramp up as to make retrofitting the vast majority of buildings by 2050 virtually impossible. Modelling indicates that a delay of ten years in the acceleration of retrofitting, would increase residential space heating energy demand by 25% and space cooling demand by more than 20%, translating to a 20% increase in electricity demand in 2050 relative to the NZE (Figure 3.31). This would put more strain on the power sector, which would need to install more low-carbon generation capacity. Policies and fuel switching would still drive down fossil fuel demand in the *Delayed Retrofit Case*, but an additional 15 EJ of fossil fuels would be burned by 2050, emitting 1 Gt of CO_2.

Figure 3.31 ▷ Global residential space heating and cooling energy demand in the NZE and Delayed Retrofit Case



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Delays in the ramp up of retrofit rates and depth would be almost impossible to catch up, placing further strain on the power sector and pushing up fossil fuel demand

Governments need to establish policies for coal and oil boilers and furnaces for space and water heating, which in the NZE are no longer available for sale from 2025. They also need to take action to ensure that new gas boilers are able to operate with low-carbon gases (hydrogen ready) in decarbonised gas networks. This puts a premium on the availability of compelling alternatives to the types of boilers being phased out, including the use of heat pumps, efficient wood stoves (using sustainable supplies of wood), district energy, solar PV, solar thermal and other renewable energy technologies. Which alternatives are best will depend to some extent on local conditions, but electrification will be the most energy-efficient and cost-effective low-carbon option in most cases, and decarbonising and expanding district energy networks is likely to make sense where densities allow. The use of biomethane or hydrogen in existing or upgraded gas networks may be the best option in areas where more efficient alternatives are not possible.

Governments also face decisions on minimum energy performance standards (MEPS). The NZE sees all countries introduce MEPS for all main appliance categories set at the most stringent levels prevailing in advanced economies by 2025 at the latest. Among others, this would mean ending the sale of incandescent, halogen and compact fluorescent lamps by that time. Setting MEPS at the right level will require careful planning; international collaboration to align standards and objectives could play a helpful role in keeping costs down.

The systemic nature of the NZE means that strategies and policies for buildings will work best if they are aligned with those being adopted for power systems, urban planning and mobility. This would help to ensure the successful scaling up of building-integrated PV technologies, battery storage and smart controls to make buildings active service providers to grids. It would also help to foster the deployment of smart EV charging infrastructure. Policies incentivising dense and mixed-use urban planning coupled with easy access to local services and public transport could reduce reliance on personal vehicles (see Chapter 2). There are also links between buildings strategies and measures to reduce the embodied carbon emissions of new construction, which falls by 95% by 2050 in the NZE.

Wider implications of achieving net-zero emissions

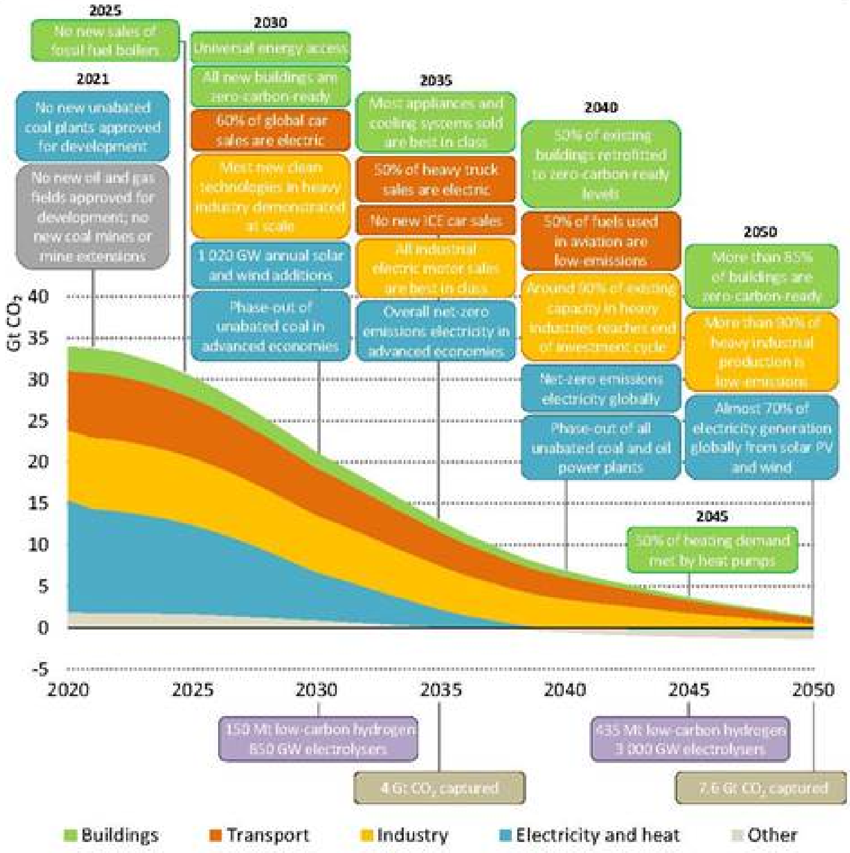
SUMMARY

- **Economy:** In our Net-Zero Emissions by 2050 Scenario (NZE), global CO_2 emissions reach net zero by 2050 and investment rises across electricity, low-emissions fuels, infrastructure and end-use sectors. Clean energy employment increases by 14 million to 2030, but employment in oil, gas and coal declines by around 5 million. There are varying results for different regions, with job gains not always occurring in the same place, or matching the same skill set, as job losses. The increase in jobs and investment stimulates economic output, resulting in a net increase in global GDP to 2030. But oil and gas revenues in producer economies are 80% lower in 2050 than in recent years and tax revenues from retail oil and gas sales in importing countries are 90% lower.
- **Energy industry:** There is a major contraction in fossil fuel production, but companies that produce these fuels have skills and resources that could play a key role in developing new low-emissions fuels and technologies. The electricity industry scales up to meet demand rising over two-and-a-half-fold to 2050 and becomes more capital intensive, focusing on renewables, sources of flexibility and grids. Large energy-consuming companies, vehicle manufacturers and their suppliers adjust designs and retool factories while improving efficiency and switching to alternative fuel supplies.
- For **citizens** who lack access to electricity and clean cooking, the NZE delivers universal access by 2030. This costs around USD 40 billion a year over the next decade and adds less than 0.2% to CO_2 emissions. For citizens the world over, the NZE brings profound changes, and their active support is essential if it is to succeed. Around three-quarters of behavioural changes in the NZE can be directly influenced or mandated by government policies. The cost of energy is also an important issue for citizens, and the proportion of disposable household income spent on energy over the period to 2050 remains stable in emerging market and developing economies, despite a large increase in demand for modern energy services.
- **Government** action is central to achieve net-zero emissions globally by 2050; it underpins the decisions made by all other actors. Four particular points are worth stressing. First, the NZE depends on actions that go far beyond the remit of energy ministers, and requires a co-ordinated cross-government approach. Second, the fall in oil and gas demand in the NZE may reduce some traditional energy security risks, but they do not disappear, while potential new vulnerabilities emerge from increasing reliance on electricity systems and critical minerals. Third, accelerated innovation is needed. The emissions cuts to 2030 in the NZE can be mostly achieved with technologies on the market today, but almost half of the reductions in 2050 depend on technologies that are currently under development. Fourth, an unprecedented level of international co-operation is needed. This helps to accelerate innovation, develop international standards and facilitate new infrastructure to link national markets. Without the co-operation assumed in the NZE, the transition to net-zero emissions would be delayed by decades.

4.1 Introduction

Achieving net-zero emissions by 2050 is a monumental task, especially against a backdrop of increasing economic and population growth. It calls for an unwavering focus from all governments, working together with industries and citizens, to ensure that the transition to global net-zero emissions proceeds in a co-ordinated way without delay. In this chapter, we look at what the changes that deliver net-zero emissions globally by 2050 in the NZE would mean for the economy, the energy industry, citizens and governments.

Figure 4.1 ▷ Selected global milestones for policies, infrastructure and technology deployment in the NZE



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There are multiple milestones on the way to global net-zero emissions by 2050. If any sector lags, it may prove impossible to make up the difference elsewhere.

Wide-ranging measures and regulations in the NZE help to influence or change the purchases that individuals make, the way they heat and cool their homes, and their means of transport. Many industries, especially those that are currently involved in the production of energy or are large-scale users of energy, also face change. Some of the shifts for individuals and industries may be unpopular, underscoring the fact that it is essential to ensure that the energy transition is transparent, just and cost-effective, and to persuade citizens of the need for reform. These changes deliver significant benefits. There are around 790 million people who do not have access to electricity today and 2.6 billion people who do not have access to clean cooking options. The NZE shows how emissions reductions can go hand-in-hand with efforts to provide universal access to electricity and clean cooking, and to improve air quality. It provides significant opportunities too, with clean energy technologies providing many new business opportunities and jobs, and with innovations that stimulate new industrial capacities.

Underpinning all of these changes are decisions taken by governments. This will require wholehearted buy-in from all levels of government and from all countries. The magnitude of the changes required to reach global net-zero emissions by 2050 are not within the power of government energy or environment departments alone to deliver, nor within the power of individual countries. It will involve an unprecedented level of global collaboration, with recognition of and sensitivity to differences in the stages of development of individual countries, and an appreciation of the difficulties faced by particular communities and members of society, especially those who may be negatively affected by the transition to net-zero emissions. In the NZE, governments start by setting unequivocal long-term targets, ensuring that these are fully supported from the outset by explicit, near-term targets and policy measures that clearly set out the pathway, and that recognise each country's unique starting conditions, to support the deployment of new infrastructure and technologies (Figure 4.1).

4.2 Economy

4.2.1 Investment and financing

The transition to net-zero emissions by 2050 requires a substantial ramp up in the investment of electricity, infrastructure and the end-use sectors. The largest increase over the next decade is in electricity generation: annual investment increases from about USD 0.5 trillion over the past five years to USD 1.6 trillion in 2030 (Figure 4.2). By 2030, annual investment in renewables in the electricity sector is around USD 1.3 trillion, slightly more than the highest level ever spent on fossil fuel supply (USD 1.2 trillion in 2014). Annual investment in clean energy infrastructure increases from around USD 290 billion over the past five years to about USD 880 billion in 2030. This is for electricity networks, public electric vehicle (EV) charging stations, hydrogen refuelling stations and import and export terminals, direct air capture and CO_2 pipelines and storage facilities. Annual investment in low-carbon technologies in end-use sectors rises from USD 530 billion in recent years to USD 1.7 trillion in 2030.[1] This includes spending on deep retrofitting of buildings, transformation of industrial processes, and the purchase of new low-emissions vehicles and more efficient appliances.

After 2030, annual electricity generation investment falls by one-third to 2050. A lot of infrastructure for a low-emissions electricity sector is established within the first decade of the NZE, and the cost of renewables continues to decline after 2030. In end-use sectors, there are continued increases in investment in EVs, carbon capture, utilisation and storage (CCUS) and hydrogen use in industry and transport, and more efficient buildings and appliances.

Global investment in fossil fuel supply falls steadily from about USD 575 billion on average over the past five years to USD 110 billion in 2050 in the NZE, with upstream fossil fuel investment restricted to maintaining production at existing oil and natural gas fields. This investment reflects the fact that fossil fuels are still used in 2050 in the NZE in processes where they are paired with CCUS, in non-emitting processes (such as petrochemical manufacturing), and in sectors where emissions reductions are most challenging (with emissions offset by carbon dioxide removal). Investment in low-emissions fuels increases more than thirty-fold between 2020 and 2050, reaching about USD 135 billion in 2050. This is split roughly equally between the production of hydrogen and hydrogen-based fuels, and the production of biofuels.

Over the 2021-50 period in the NZE, annual average total energy sector investment as a share of gross domestic product (GDP) is around 1% higher than over the past five years. The private sector is central to finance higher investment needs. It requires enhanced collaboration between developers, investors, public financial institutions and governments. Collaboration will be especially important over the next five to ten years for the development of large infrastructure projects and for technologies in the demonstration or prototype phase today such as some hydrogen and CCUS applications. Companies and investors have declared strong interest to invest in clean energy technologies, but turning interest into actual investment at the levels required in the NZE also depends on public policies.

Some obstacles to investment need to be tackled. Many emerging market and developing economies are reliant on public sources to finance energy projects and new industrial facilities. In some cases, improvements in regulatory and policy frameworks would facilitate the international flow of long-term capital to support the development of both new and existing clean energy technologies. The rapid growth in investment in transport and buildings in the NZE presents a different kind of challenge for policy makers. In many cases, an increase in capital spending for an efficient appliance or low-emissions vehicle would be more than offset by lower expenditure on fuels and electricity over the product lifetime, but some low-income households and small and medium enterprises may not be able to afford the upfront capital required.

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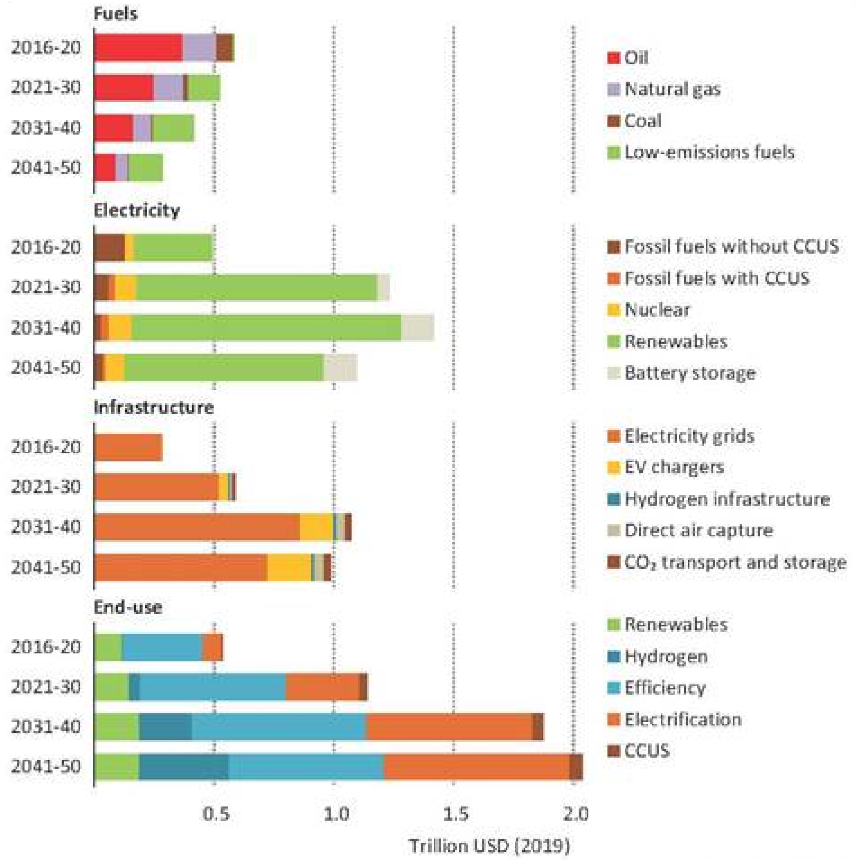
[1] Investment levels presented in this report include a broader accounting of efficiency improvements in buildings and differ from that reported in the IEA World Energy Investment report (IEA, 2020a). End-use efficiency investments are the incremental cost of improving the energy performance of equipment relative to a conventional design.

Figure 4.2 ▷ Global average annual energy investment needs by sector and technology in the NZE



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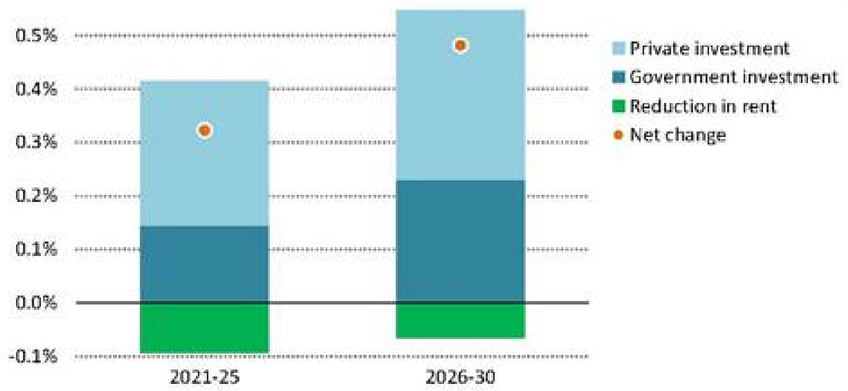
Investment increases rapidly in electricity generation, infrastructure and end-use sectors. Fossil fuel investment drops sharply, partly offset by a rise in low-emissions fuels.

Notes: CCUS = carbon capture, utilisation and storage; EV = electric vehicle. 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.

4.2.2 Economic activity

The energy transition required for net-zero emissions by 2050 will affect all economic activities directly or indirectly. In co-ordination with the International Monetary Fund, we have modelled the medium-term global macroeconomic impact of the changes in the energy sector that occur in the NZE. This analysis shows that the surge in private and government spending on clean energy technologies in the NZE creates a large number of jobs and stimulates economic output in the engineering, manufacturing and construction industries. This results in annual GDP growth that is nearly 0.5% higher than the levels in the Stated Policies Scenario (STEPS)[2] during latter half of the 2020s (Figure 4.3).[3]

Figure 4.3 ▷ Change in annual growth rate of global GDP in the NZE relative to the STEPS



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The surge in government and private investment in the NZE has a positive impact on global GDP, but there are large differences between regions

Notes: GDP = gross domestic product. Reduction in rents stem mainly from lower fossil fuel income.
Source: IEA analysis based on IMF.

There are large differences in macroeconomic impacts between regions. The decline in fossil fuel use and prices results in a fall in GDP in the producer economies,[4] where revenues from oil and gas sales often cover a large share of public spending on education, health care and other public services. The drop in oil and gas demand, and the consequent fall in international prices for oil and gas, cause net income in producer economies to drop to historic lows (Figure 4.4). Some countries with the lowest cost oil resources (including members of the

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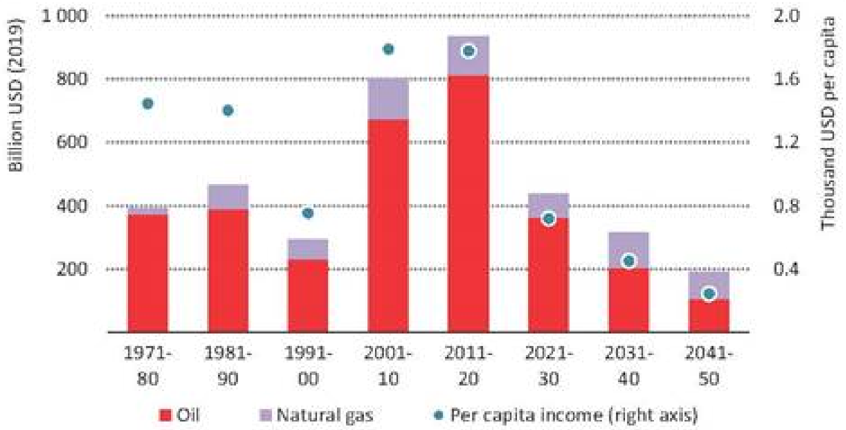
[2] The IEA Stated Policies Scenario is the projection for the global energy system based on the policies and measures that governments around the world have already put in place and on announced policies as expressed in official targets and plans, such as Nationally Determined Contributions put forward under the Paris Agreement (see Chapter 1).

[3] The estimated general equilibrium macroeconomic impact of the increase in public and private investment and the reduction in oil-related revenue contained in the NZE has been provided by the International Monetary Fund using its Global Integrated Monetary and Fiscal Model (GIMF).

[4] Producer economies are large oil and gas exporters that rely on hydrocarbon revenues to finance a significant proportion of their national budgets, including countries in the Middle East, Russia and the Caspian region.

Organization of the Petroleum Exporting Countries [OPEC]) gain market share in these circumstances, but even they would see large falls in revenues. Structural reforms would be needed to address the societal challenges, including those to accelerate the process of reforming inefficient fossil fuel subsidies and to speed up moves to use hydrocarbon resources to produce low-emissions fuels, e.g. hydrogen and hydrogen-based fuels (see section 4.3.1).

Figure 4.4 ▷ **Income from oil and gas sales in producer economies in the NZE**



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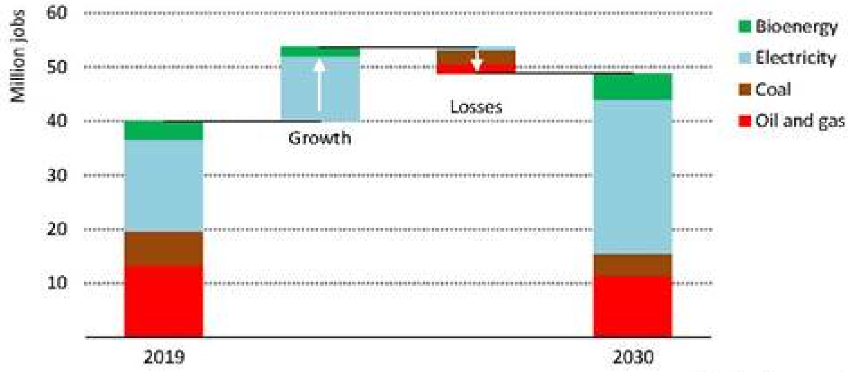
Structural reforms and new sources of revenue are needed in producer economies, but these are unlikely to compensate fully for a large drop in oil and gas income

The macroeconomic effects of the NZE are very uncertain. They depend on a host of factors including: how government expenditure is financed; benefits from improvements to health; changes in consumer bills; broad impact of changes in consumer behaviour; and potential for productivity spill-overs from accelerated energy innovation. Nonetheless, impacts are likely to be lower than assessments of the cost of climate change damages (OECD, 2015). It is also likely that a co-ordinated, orderly transition can be executed without major global systemic financial impacts, but this will require close attention from governments, financial regulators and the corporate sector.

4.2.3 Employment

Employment in the energy sector shifts markedly in the NZE in response to changes in investment and spending on energy. We estimate that today roughly 40 million people around the world work directly in the oil, gas, coal, renewables, bioenergy and energy network industries (IEA, 2020b). In the NZE, clean energy employment increases by 14 million to 2030, while employment in oil, gas and coal fuel supply and power plants declines by around 5 million, leading to a net increase of nearly 9 million jobs (Figure 4.5).

Figure 4.5 ▷ Global energy sector employment in the NZE, 2019-2030



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Overall employment in the energy sector increases by almost 9 million to 2030 as jobs created in clean energy sectors outpace losses in fossil fuels

Jobs created would not necessarily be in the same area where jobs are lost, plus the skill sets required for the clean energy jobs may not be directly transferable. Job losses would be most pronounced in communities that are heavily dependent on fossil energy production or transformation activities. Even where the number of direct energy jobs lost is small, the impact on the local economy may be significant. Government support would almost certainly be needed to manage these transitions in a just, people-centred way. In preparation, a better understanding of current energy industry employment is needed. A useful action would be for governments to adopt more detailed surveying approaches for energy industry employment, such as those used in the *US Energy & Employment Report* (NASEO and Energy Futures Initiative, 2021).

In addition to the 14 million new clean energy jobs created in the NZE, other new jobs are created by changes in spending on more efficient appliances, electric and fuel cell vehicles, and building retrofits and energy-efficient construction. These changes would require a further 16 million workers, meaning that there would be 30 million more people working in clean energy, efficiency and low-emissions technologies by 2030 in the NZE (Figure 4.6).[5] Investment in electricity generation, electricity networks, EV manufacturing and energy efficiency are among the areas that will open up new employment opportunities. For example, jobs in solar and wind more than quadruple in the NZE over current levels. Nearly two-thirds of workers in these sectors by 2030 in the NZE would be highly skilled and the

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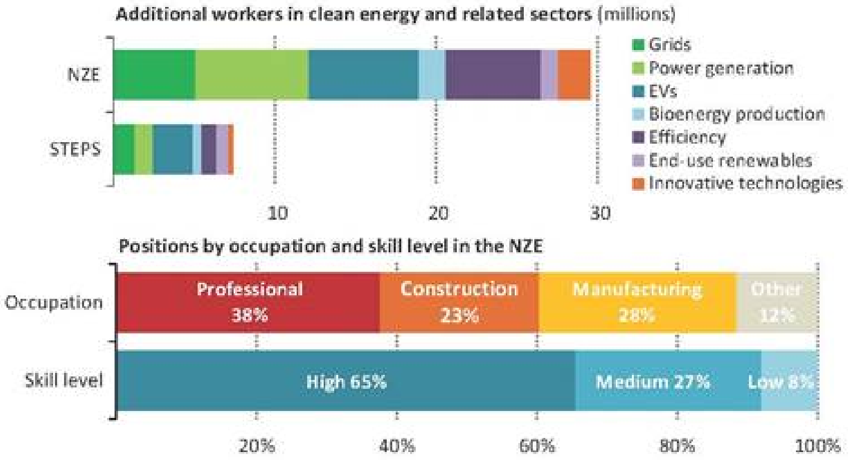
[5] This includes new jobs and jobs filled by moving current employment from one type of production to another.

majority require substantial training. In addition, with the more than doubling of total energy investment, new employment opportunities will arise in associated areas such as wholesale trading, financial and legal services.

In many cases it may be possible to shift workers to new product lines within the same company, for example in vehicle manufacturing as production reconfigures to EVs. However, there would be larger risks for specialised supply chain companies that provide products and services, e.g. internal combustion engines that are replaced by new components such as batteries.

Figure 4.6 ▷ New workers in clean energy and related sectors and shares by skill level and occupation in the NZE and the STEPS in 2030



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About 30 million new workers are needed by 2030 to meet increased demand for clean energy, efficiency, and low-emissions technologies; over half are highly skilled positions

Note: EVs = electric vehicles.

The new jobs created in the NZE tend to have more geographic flexibility and a wider distribution than is the case today. Around 40% are jobs located close to where the work is being done, e.g. building efficiency improvements or wind turbine installation, and the remaining are jobs tied to manufacturing sites. Today the manufacturing capacity for a number of clean energy technologies, such as batteries and solar photovoltaic panels, is concentrated in particular areas, notably China. The rapid increase in demand for clean energy technologies in the NZE requires new production capacity to come online that could be located in any region. Those countries and companies that move first may enjoy strategic advantages in capturing burgeoning demand.

4.3 Energy industry

4.3.1 Oil and gas

The energy transition envisioned in the NZE involves a major contraction of oil and gas production with far-reaching implications for all the companies that produce these fuels. Oil demand falls from around 90 million barrels per day (mb/d) in 2020 to 24 mb/d in 2050, while natural gas demand falls from 3 900 billion cubic metres (bcm) to around 1 700 bcm. No fossil fuel exploration is required in the NZE as no new oil and natural gas fields are required beyond those that have already been approved for development. This represents a clear threat to company earnings, but there are also opportunities. The resources and skills of the oil and gas industry are a good match with some of the new technologies needed to tackle emissions in sectors where reductions are likely to be most challenging, and to produce some of the low-emissions liquids and gases for which there is a rapid increase in demand in the NZE (see Chapter 2). By partnering with governments and other stakeholders, the oil and gas industry could play a leading role in developing these fuels and technologies at scale, and in establishing new business models.

The oil and gas industry is highly diverse, and various companies could pursue very different strategies in the transition to net-zero emissions. Minimising emissions from core oil and gas operations however should be a first-order priority for all oil and gas companies. This includes tackling methane emissions that occur during operations (they fall by 75% between 2020 and 2030 in the NZE) and eliminating flaring. Companies should also electrify operations using renewable electricity wherever possible, either by purchasing electricity from the grid or by integrating off-grid renewable energy sources into upstream facilities or transport infrastructure. Producers that can demonstrate strong and effective action to reduce emissions can credibly argue that their oil and gas resources should be preferred over higher emissions options.

Some oil and gas companies may choose to become "energy companies" focused on low-emissions technologies and fuels, including renewable electricity, electricity distribution, EV charging and batteries. Several technologies that are critical to the achievement of net-zero emissions, such as CCUS, hydrogen, bioenergy and offshore wind, look especially well-suited to some of the existing skills, competencies and resources of oil and gas companies.

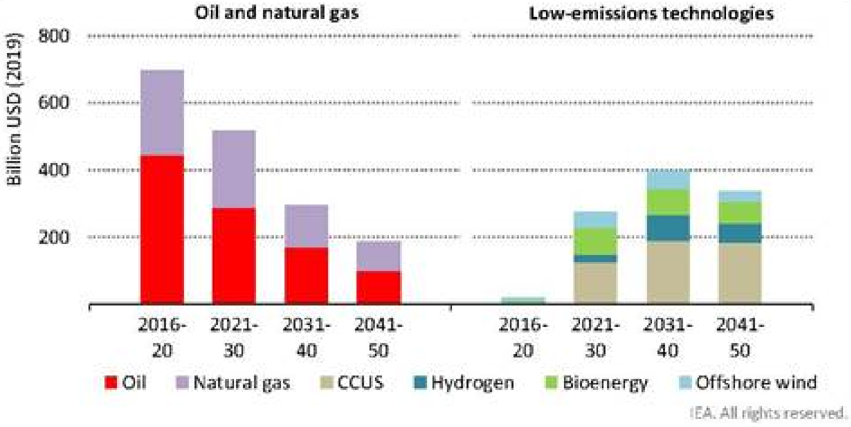
- **Carbon capture, utilisation and storage**. The oil and gas industry is already the global leader in developing and deploying CCUS. Of the 40 million tonnes (Mt) of CO_2 captured today at large-scale facilities, around three-quarters is captured from oil and gas operations, which often produce concentrated streams of CO_2 that are relatively easy and cost effective to capture (IEA, 2020c). The oil and gas industry also has the large-scale engineering, pipeline, sub-surface and project management skills and capabilities to handle large volumes of CO_2 and to help scale up the deployment of CCUS.

- **Low-emissions hydrogen and hydrogen-based fuels.** Oil and gas companies could contribute to developing and deploying low-emissions hydrogen in several ways (IEA, 2019a). Nearly 40% of hydrogen production in 2050 in the NZE is from natural gas in facilities equipped with CCUS, providing an important opportunity for companies and countries to utilise their natural gas resources in a way that is consistent with net-zero emissions. Of the total output of 530 Mt of hydrogen in 2050, about 30% is processed into ammonia and synthetic fuels (equivalent to around 7.5 mboe/d). The transformation processes involved have many potential synergies with the skills and equipment used in oil and gas processing and refining. Oil and gas companies also have long experience of transporting liquids and gases by pipeline and ships.
- **Advanced biofuels and biomethane.** The production of advanced biofuels grows substantially in the NZE, but this depends critically on continued technological innovation. Many oil and gas companies have active R&D programmes in these areas and could become leading producers. Biomethane – a low-emissions alternative to natural gas – can be produced in large centralised facilities, which could be a good fit with the knowledge and technical expertise of existing gas producers (IEA, 2020d).
- **Offshore wind.** About 40% of the lifetime costs of a standard offshore wind project involve significant synergies with the offshore oil and gas sector (IEA, 2019b). The oil and gas industry has considerable experience of working in offshore locations, which could be of value in the construction of foundations and subsea structures for offshore wind farms, especially when using vessels during installation and operation. The experience of maintaining safety standards in oil and gas companies could also be helpful during maintenance and inspection of offshore wind farms once they are in operation.

Oil and gas companies are well-placed to accelerate the pace of development and deployment of these technologies, and to gain a commercial edge over other companies. In the NZE, investment in low-emissions technologies suited to the skills and expertise of oil and gas companies exceeds that in traditional oil and gas operations by 2030. Total capital spending on these technologies and on traditional oil and gas operations averages USD 650 billion per year over 2021-50, just less than annual investment in oil and gas projects between 2016 and 2020 (Figure 4.7).

Not all oil and gas companies will choose to follow a strategy of diversifying into other types of energy. For example, it is far from certain that national oil companies will be charged by their state owners to diversify and develop low-emissions energy sources outside their core area of activity; other companies may decide simply to concentrate on supplying oil and natural gas as cleanly and efficiently as possible, and to return income to shareholders. What is clear, however, is that no oil and gas company would be unaffected by the NZE and that all parts of the industry need to decide how to respond (IEA, 2020e).

Figure 4.7 ⊳ Annual average investment in oil and gas and low-emissions technologies with synergies for the oil and gas industry in the NZE



Investment in low-emissions technologies suited to the skills and expertise of oil and gas companies exceeds investment in traditional operations by 2030

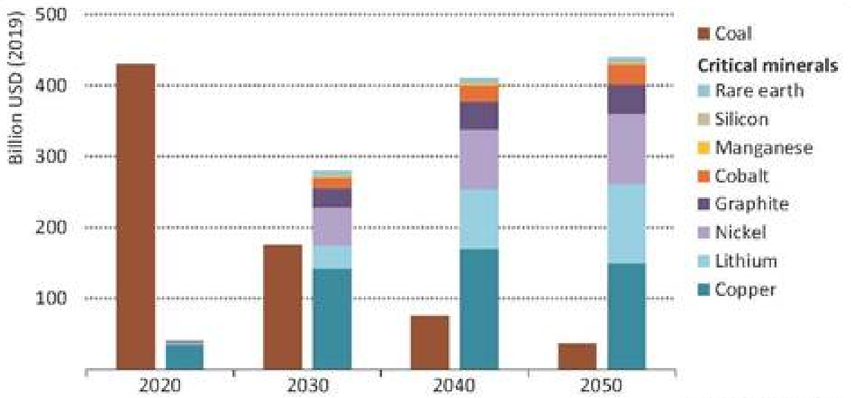
Note: CCUS = carbon capture, utilisation and storage.

4.3.2 *Coal*

The precipitous decline in coal use projected in the NZE would have major implications for the future of mining companies and countries with large existing production capacities. Around 470 million tonnes of coal equivalent (Mtce) of coal used in the NZE in 2050 is in facilities equipped with CCUS (80% of global coal demand in 2050), which prevents an even sharper decline in demand. But no new coal mines or mine extensions are needed in the NZE. Retraining and regional revitalisation programmes would be essential to reduce the social impact of job losses at the local level and to enable workers and communities to find alternative livelihoods. There could also be opportunities to locate new clean energy facilities, including the new processing facilities that are needed for critical minerals, in the areas most affected by mine closures.

For mining companies, however, the contraction in coal demand in the NZE could be offset by the need to increase mining of other raw minerals, including those vital to many clean energy technologies, such as copper, lithium and nickel (IEA, 2021a). Global demand for these critical minerals rises rapidly in the NZE (Figure 4.8). For example, demand for lithium for use in batteries expands by a factor of 30 by 2030, while demand for rare earths, primarily used for making EV motors and wind turbines, increases by a factor of ten by 2030. Critical mineral resources are not always located in the same locations or countries as existing coal mines, but the skills and experience of mining companies will be essential to ensure that the supply of these minerals is able to match demand at reasonable prices. By the 2040s, the size of the global market for these minerals approaches that for coal today.

Figure 4.8 ▷ Global value of coal and selected critical minerals in the NZE



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The market for critical minerals approaches that of coal today in the 2040s

Notes: Includes total revenue for coal and for selected critical minerals used in clean energy technologies. The prices of critical minerals are based on conservative assumptions about cost increases (around a 10%-20% increase from current levels to 2050).

4.3.3 Electricity

Getting to net-zero emissions calls for a massive expansion of the electricity sector to power the needs of a growing global economy, the electrification of end-uses that previously used fossil fuels, and the production of hydrogen from electrolysis. While electricity demand increases more than two-and-a-half times, the rapid transformation of the industry means that total electricity supply costs triple from 2020 to 2050 in the NZE, raising average costs per unit of electricity generation modestly (Figure 4.9).

The electricity supply industry also becomes much more capital intensive, accelerating a recent trend. The share of capital in total costs rises from less than 60% in 2020 (already ten percentage points higher than in 2010) to about 80% in 2050. This is largely due to a massive increase in renewable energy and the corresponding need for more network capacity and sources of flexibility, including battery storage. In the late 2020s and 2030s, the upgrading and replacement of existing solar and wind capacity as they come to the end of their operating lives also boosts capital needs.[6] New nuclear power capacity additions add further capital spending in the NZE. The rising capital intensity of the electricity industry increases the importance of limiting risk for new investment and ensuring sufficient revenues in all years for grid operators to fund rising investment needs – a point underlined by the financial difficulties experienced by some network companies in 2020 due to depressed electricity demand resulting from the Covid-19 crisis (IEA, 2020f).

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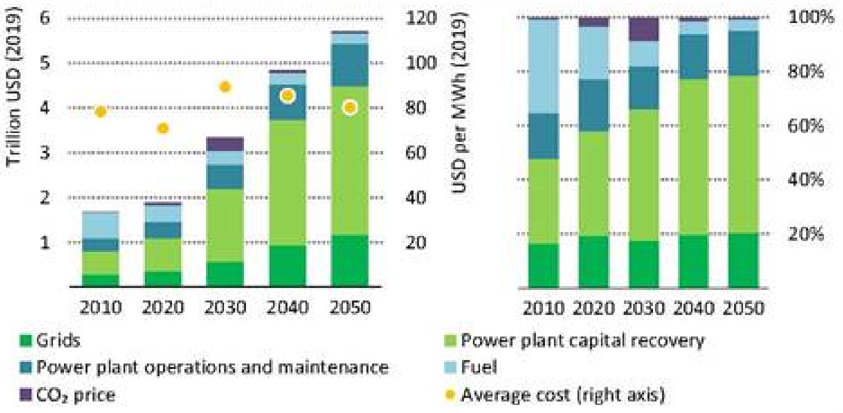
[6] They typically need replacing after 25-30 years of operation, whereas many conventional hydropower, nuclear and coal plants operate far longer albeit with periodic additional investment.

Figure 4.9 ▷ Global electricity supply costs by component in the NZE



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Electricity system costs triple to 2050, raising average supply costs modestly; the massive growth of renewables makes the industry more capital intensive

Notes: Electricity supply costs include all the direct costs to produce and transmit electricity to consumers. Battery storage systems are included in power plant capital recovery.

The rising share of renewables in the electricity generation mix has important implications for the design of electricity markets. When the shares of solar, wind, other variable renewables and nuclear power reach high levels, available electricity supply at no marginal cost is often above electricity demand, resulting in a wholesale price of electricity that is zero or even negative. By 2050, without changes in electricity market design, about 7% of wind and solar output in the NZE would be above and beyond what can be integrated (and so curtailed), and the share of zero-price hours in the year would increase to around 30% in major markets from close to zero today, despite the active use of demand response. If the share of renewables in the electricity generation mix is to rise as envisioned in the NZE, it would therefore be highly desirable to effect significant changes in the design of electricity markets so as to provide signals for investment, including investment in sources of flexibility such as battery storage and dispatchable power plants.

The increase in electricity use inevitably raises associated costs. Operating and maintaining power plants worldwide costs close to USD 1 trillion in 2050 in the NZE, two-and-a-half times the level in 2020. In 2020, upkeep at fossil fuel power plants accounted for USD 150 billion, and renewables required nearly as much, mostly for hydropower. By 2050, the cost of operating and maintaining renewables reaches USD 780 billion, most it needed for wind and solar photovoltaics (PV) as a result of their massive scaling up: offshore wind alone accounts for USD 90 billion.

The sharp reduction of fossil fuel use in the electricity industry and lower fuel prices mean that costs related to fuel and CO_2 prices are significantly reduced. This continues a recent trend driven by near record-low natural gas prices in many markets. Even with rising CO_2 prices over time, the rapid decarbonisation of electricity means that fuel and CO_2 make up a declining share of total costs, falling from about one-quarter in 2020 to 5% in 2050. The balance of fuel costs shifts towards low-emissions sources, mainly nuclear power and bioenergy (including with CCUS), though some still remains related to natural gas and coal used in power plants equipped with CCUS.

One challenge in this context is what to do about the coal-fired power plants in operation. In 2020, over 2 100 gigawatts (GW) of power plants worldwide used coal to produce electricity and heat, and they emitted nearly 30% of all energy-related CO_2 emissions. Options include retrofitting coal-fired power plants with CCUS technologies, co-firing with biomass or ammonia; repurposing coal plants to focus on providing flexibility; and, where feasible, phasing them out. In the NZE, all unabated coal-fired power plants are phased out in advanced economies by 2030 and in emerging market and developing economies by 2040. As a result, emissions from coal-fired power plants fall from 9.8 gigatonnes (Gt) in 2020 to 3.0 Gt in 2030 and to just 0.1 Gt by 2040 (residual emissions from coal with CCUS plants).[7]

Another challenge is related to the scale of capacity retirements envisaged and associated site rehabilitation, starting with coal. The pace of retirement of coal-fired power plants over 2020-50 is nearly triple that of the past decade. Decommissioning at each site can often last a decade and entail significant cost, and may involve closing a mine as well. In some cases, it may be financially attractive to build a renewable energy project on the same site, taking advantage of the grid connection and limiting the cost of rehabilitation. Thousands of natural gas-fired and oil-fired power plants are also retired by 2050, though these sites are often strategically located on the grid and many are likely to be replaced directly with battery storage systems.

The large fleet of ageing nuclear reactors in advanced economies means their decommissioning increases, despite many reactor lifetime extensions. In the NZE, annual average nuclear retirements globally are 60% higher over the next 30 years than in the last decade. Each nuclear decommissioning project can span decades, with costs ranging from several hundred million dollars to well over USD 1 billion for large reactors (NEA, 2016).

4.3.4 *Energy-consuming industries*

The changes in the NZE would have an enormous impact on industries that manufacture vehicles and their material and component suppliers. Around 95% of all the cars and nearly all of the trucks sold worldwide in 2020 were conventional vehicles with an internal combustion engine. In the NZE, about 60% of global car sales in 2030 are EVs, and 85% of

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[7] A CO_2 capture rate of 90% is assumed, though higher rates are technically possible with reduced efficiencies and additional costs (IEA, 2020g).

heavy-duty trucks sold in 2040 are EVs or fuel cell vehicles. In the NZE, vehicle component suppliers and vehicle manufacturers alike retool factories, change designs to incorporate batteries and fuel cells, and adjust supply chains to minimise the lifecycle emissions intensities of vehicles. This provides opportunities to redesign existing parts and manufacturing processes to improve efficiency and lower costs.

The rapid increase in EV sales in the NZE requires an immediate scale up of new supply chains for batteries as well as recharging and low-emissions refuelling infrastructure. In the NZE, battery production capacity increases to more than 6.5 terawatt-hours (TWh) by 2030, compared with less than 0.2 TWh in 2020. Any delay in expanding battery manufacturing capacity would have a detrimental impact on the roll-out of EVs and slow cost reductions for other clean energy technologies that benefit in the NZE from having similar manufacturing processes and know-how (such as fuel cell vehicles and electrolysers).

In aviation and shipping, liquid low-emissions fuels are central to cut emissions. Switching to some of these would have little impact on vessel design: the use of hydrogen-based fuels or biofuels in shipping would only require changes to the motor and fuel system, and bio-kerosene or synthetic kerosene can operate with existing aircraft. New bunkering and refuelling infrastructure are needed in the NZE, however, and the use of these low-emissions fuels also requires new safety and standardisation standards, protocols for permitting, construction and design, as well as international regulation, monitoring, reporting and verification of their production and use.

In heavy industrial sectors – steel, cement and chemicals – most deep emissions reduction technologies are not available on the market today. In the NZE, material producers soon demonstrate near-zero emission processes, aided by government risk-sharing mechanisms, and start to adapt their existing production assets. For multinational companies, this includes developing technology transfer strategies to roll-out processes across plants. International co-operation would help to ensure a level playing field for all. Within countries, efforts focus on industrial hubs in order to accelerate emissions reductions across multiple industrial sectors by promoting economies of scale for new infrastructure (such as CO_2 transport and storage) and supplies of low-emissions energy.

Materials producers work with governments in the NZE to create an international certification system for near-zero emission materials to differentiate them from conventional ones. This would enable buyers of materials such as vehicle manufacturers and construction companies to enter into commercial agreements to purchase near-zero emissions materials at a price premium. In most cases, the premium would result in only a modest impact on the final price of the product price given that materials generally account for a small portion of manufacturing costs (Material Economics, 2019).

4.4 Citizens

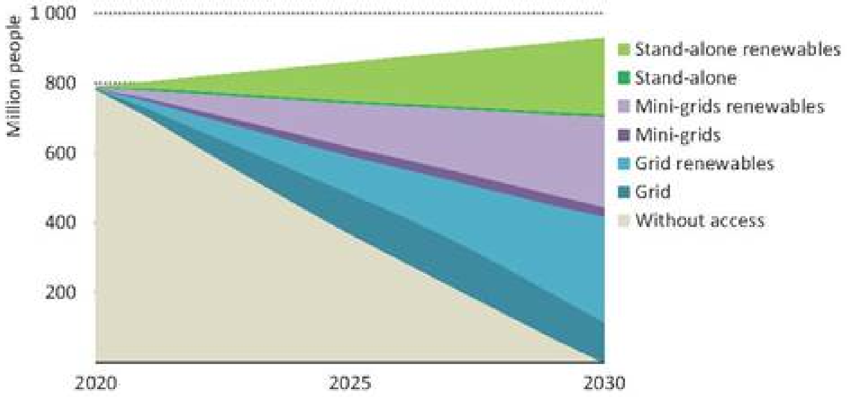
4.4.1 *Energy-related Sustainable Development Goals*

An inclusive and people-centred transition is key to the world moving rapidly, collectively and consistently toward net-zero emissions by mid-century. The NZE achieves the United Nations energy-related Sustainable Development Goals (SDGs) of universal access to clean modern energy by 2030 (SDG 7.1) and reducing premature deaths caused by air pollution (SDG 3.9). The technologies, options and measures used to achieve full access to low-emissions electricity and clean cooking solutions by 2030 in the NZE also help to reduce greenhouse gas (GHG) emissions from household energy use.

Energy access

About 790 million people worldwide did not have access to electricity in 2020, most of them living in sub-Saharan Africa and developing Asia. Around 2.6 billion people did not have access to clean cooking options: 35% of them were in sub-Saharan Africa, 25% in India and 15% in China. A lack of access to energy not only impedes economic development, but also causes serious harm to health and is a barrier to progress on gender equality and education.[8]

Figure 4.10 ▷ People gaining access to electricity by type of connection in emerging market and developing economies in the NZE



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More than 80% of people gaining access to electricity by 2030 are supplied renewable power and just over half via off-grid systems

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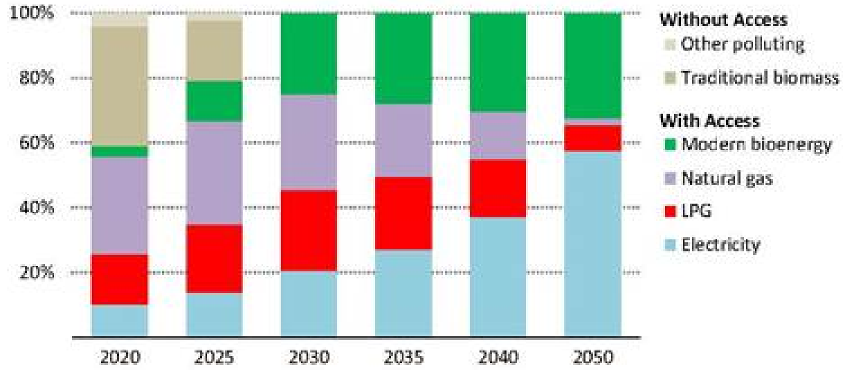
[8] Households relying on the traditional use of biomass for cooking dedicate around 1.4 hours each day collecting firewood and several hours cooking with inefficient stoves, a burden largely borne by women (IEA, 2017).

Around 45% of those who lack access to electricity by 2030 gain it via a connection to a main grid, while the rest are served by mini-grids (30%) and stand-alone solutions (25%) (Figure 4.10). Almost all off-grid or mini-grid solutions are 100% renewable. Decentralised systems that rely on diesel generators, which are also deployed in some grid-connected systems to compensate for low reliability, are phased out later and replaced with solar storage systems. Achieving full access does not lead to a significant increase in global emissions: in 2030 it adds less than 0.2% to CO_2 emissions. Achieving full access to electricity also brings efficiency gains and accelerates the electrification of appliances, which become critical to emissions reductions in buildings after 2030 in emerging market and developing economies.

For clean cooking, 55% of those gaining access by 2030 in the NZE do so through improved biomass cookstoves (ICS) fuelled by modern biomass, biogas or ethanol, 25% through the use of liquefied petroleum gas (LPG) and 20% via electric cooking solutions (Figure 4.11). LPG is the main fuel adopted in urban areas and ICS is the main option in rural areas. The use of LPG results in a slight increase in CO_2 emissions in 2030 but a net reduction in overall GHG emissions due to reduced methane, nitrous oxides and black carbon emissions from the traditional use of biomass. In addition, LPG is increasingly decarbonised after 2030 using bio-sourced butane and propane (bioLPG) produced sustainably from municipal solid waste (MSW) and other renewable feedstocks. The technical potential of bioLPG production from MSW in 2050 in Africa could be enough to satisfy the cooking needs of more than 750 million people (GLPGP, 2020; Liquid Gas Europe, 2021).

Figure 4.11 ▷ **Primary cooking fuel by share of population in emerging market and developing economies in the NZE**



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Traditional biomass is entirely replaced with modern energy by 2030, mainly in the form of bioenergy and LPG; by 2050, electricity, bioenergy and bioLPG meet most cooking needs

Notes: Modern bioenergy includes improved cook stoves, biogas and ethanol. Liquefied petroleum gas (LPG) includes fossil and renewable fuel.

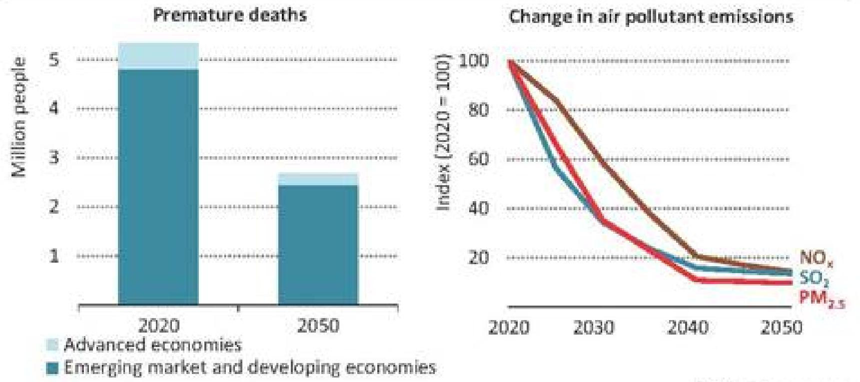
The achievement of universal access to clean energy by 2030 requires governments and donors to put expanding access at the heart of recovery plans and programmes. There would be multiple benefits: investing heavily in energy access would provide an immediate economic boost, create local jobs and bring durable improvements to social well-being by modernising health services and food chains. In the NZE, around USD 35 billion is spent each year improving access to electricity and almost USD 7 billion each year on clean cooking solutions for people in low-income countries from now to 2030.

Air pollution and health

More than 90% of people around the world are exposed to polluted air today. Such pollution led to around 5.4 million premature deaths in 2020, undermining economic productivity and placing extra stress on healthcare systems. Most of these deaths were in emerging market and developing economies. Just over half were caused by exposure to outdoor air pollution; the remainder resulted from breathing polluted air indoors, caused mainly by the traditional use of biomass for cooking and heating.

Energy-related emissions of the three major air pollutants – sulphur dioxide (SO_2), nitrogen oxides (NO_X) and fine particulate matter ($PM_{2.5}$) – fall rapidly in the NZE. SO_2 emissions fall by 85% between 2020 and 2050, mainly as a result of the large-scale phase-out of coal-fired power plants and industrial facilities. NO_X emissions also drop by around 85% as a result of the increased use of electricity, hydrogen and ammonia in the transport sector. The increased uptake of clean cooking fuels in developing countries, together with air pollution control measures in industry and transport, results in a 90% drop in $PM_{2.5}$ emissions (Figure 4.12). The reduction in air pollution in the NZE leads to roughly a halving in premature deaths in 2050 compared with 2020, saving the lives of about 2 million people per year, around 85% of them in emerging market and developing economies.

Figure 4.12 ▷ Global premature deaths and air pollutant emissions in the NZE



Reductions in major air pollutants mean 2 million fewer premature deaths per year

Sources: IEA analysis based on IIASA.

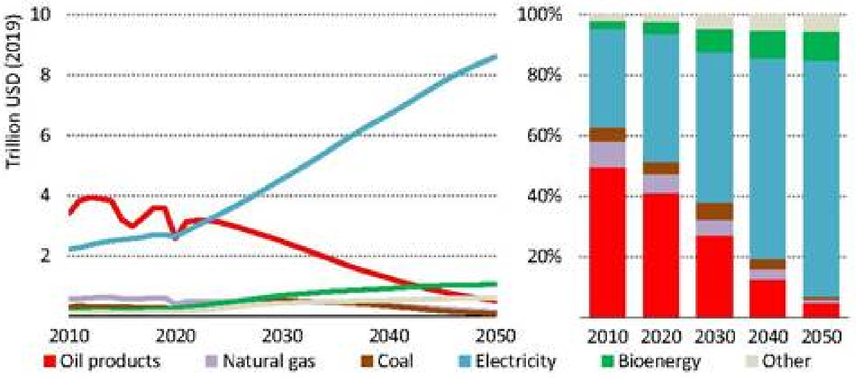
4.4.2 Affordability

Total spending on energy

Energy affordability is a key concern for governments, businesses and households. Global direct spending on energy, i.e. the total fuel bills paid by all end users, which totalled USD 6.3 trillion in 2020, increases by 45% to 2030 and 75% to 2050, in large part reflecting population and GDP growth over this period. As a share of global GDP, the figures look rather different: total direct spending on energy holds steady at around 8% out to 2030 (similar to the average over the last five years), but then declines to 6% in 2050. This decline offsets a significant share of the higher cost of buying new, more efficient energy-consuming equipment.

A portion of the increase in energy spending in the NZE is related to rising CO_2 prices and the removal of consumption subsidies for fossil fuels and electricity. CO_2 pricing (taxes and trading schemes) paid by end users at its peak generates global revenues in the NZE of close to USD 700 billion each year between 2030 and 2035, before declining steadily due to declining overall emissions: these revenues could be recycled into economies or otherwise used to improve consumer welfare, particularly for low-income households. The NZE also sees the progressive removal of consumption subsidies for fossil fuels, many of which disproportionally benefit wealthier segments of the population that use more of the subsidised fuel. Phasing out the subsidies would provide more efficient price signals for consumers, and spur more energy conservation and measures to improve energy efficiency. The impact of phasing out subsidies on lower income households could be offset through direct payment schemes or other means at lower overall costs to the economy.

Figure 4.13 ▷ Global energy spending by fuel in the NZE



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Total energy spending increases by 75% to 2050, mainly on electricity

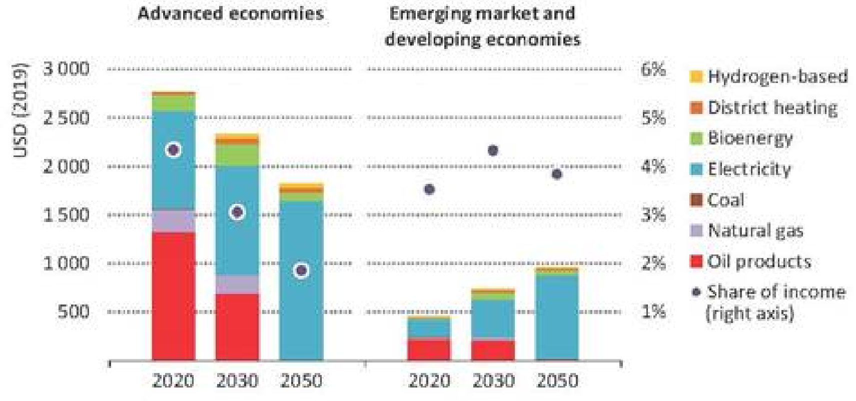
Note: Other = hydrogen-based and synthetic fuels, and district heating.

The transformation of the global energy system in the NZE drives a major shift in the composition of energy spending. Spending on electricity at USD 2.7 trillion in 2020 (45% of total energy spending) exceeded spending on oil products for the first time and it rises to over USD 8.5 trillion in 2050 (80% of total energy spending) (Figure 4.13). Retail electricity prices increase by 50% on average, contributing to the total increase. Spending on oil, which has dominated overall energy spending for decades, goes into long-term decline in the 2020s, its share of spending falling from 40% in 2020 to just 5% in 2050. Spending on natural gas and coal also declines in the long term, offset by higher spending on low-emissions fuels. Spending on bioenergy reaches about USD 900 billion per year by 2040, while other low-emissions fuels, including hydrogen-based products, gain a foothold and establish a market worth of around USD 600 billion per year by 2050.

Household spending on energy

Direct spending by households on energy, including for heating, cooling, electricity and fuel for passenger cars, falls as a share of disposable income in the NZE, though there are large differences between countries (Figure 4.14).

Figure 4.14 ▷ Average annual household energy bill in the NZE



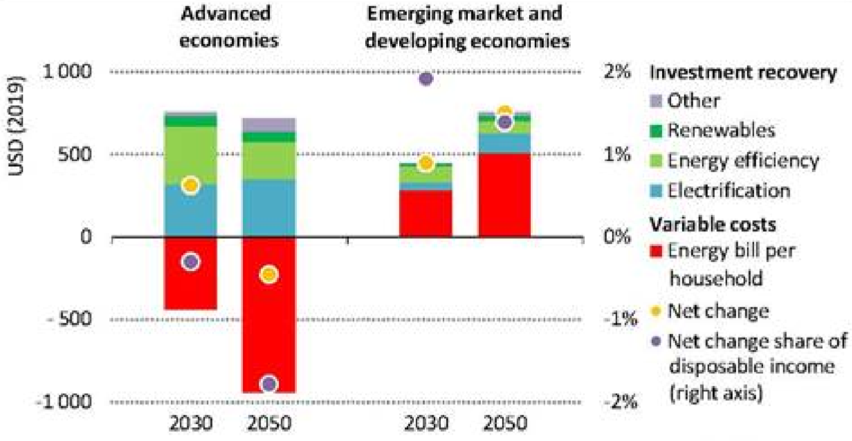
The proportion of disposable household income spent on energy is stable in emerging market and developing economies, and drops substantially in advanced economies

Note: Hydrogen-based includes hydrogen, ammonia and synthetic fuels.

In advanced economies, the average annual bill declines from about USD 2 800 in 2020 to USD 2 300 in 2030, thanks to a strong push on energy efficiency and cost-effective electrification. Oil products make up close to half of household energy bills in 2020, but this falls to 30% in 2030 and almost zero in 2050, due to a rapid shift to EVs and to downward pressure on oil prices. Natural gas bills, which make up almost 10% of the total today, also fall to almost zero in 2050 with the electrification of heating and cooking. Electricity rises from about 35% of household fuel bills in 2020 to 90% in 2050, increasing the sensitivity of households to electricity prices and consumption. Increasing incomes mean that household spending on energy as a share of disposable income drops from 4% in 2020 to 2% in 2050.

In emerging market and developing economies, there is a huge increase in demand for modern energy services linked to expanding populations, economic growth, rising incomes and universal access to electricity and clean cooking options. As in advanced economies, electricity accounts for the vast majority of energy bills in 2050. The use of more efficient appliances and equipment curbs some of the increase in demand, but household bills still increase in the NZE by over 60% to 2030 and more than double by 2050. As a percentage of disposable income, however, bills in emerging market and developing economies remain around 4%, and there are large social and economic benefits from increased energy use.

Figure 4.15 ▷ **Change in household spending on energy plus energy-related investment in the NZE relative to 2020**



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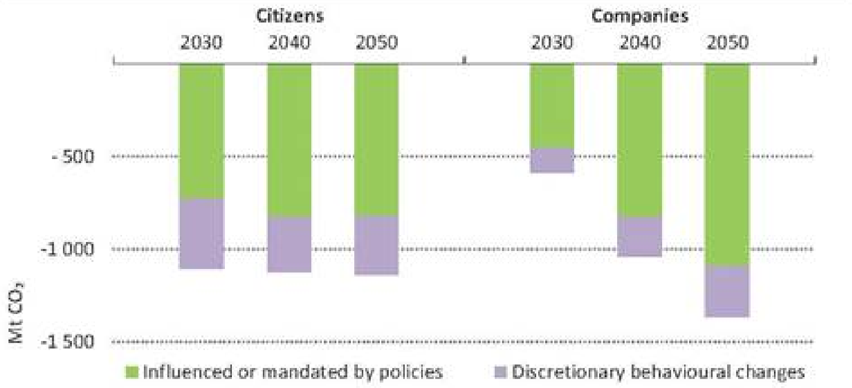
Total household spending on energy increases modestly in emerging market and developing economies, leaving over 90% of additional income available for other uses

Taking into account additional investment in electricity-consuming equipment such as efficient appliances and electric vehicles, spending on energy plus related investment is USD 1.30 higher per day per household globally in 2050 than in 2020 in the NZE. This modest increase means that expenditure on energy makes up a smaller share of disposable income in 2050 than it does today, though the impacts vary by country. In advanced economies, additional investment in electrification, energy efficiency and renewable energy costs about USD 750 per household by 2030 and USD 720 in 2050, which is fully offset by reductions in the level of energy bills (Figure 4.15). In emerging market and developing economies, a growing basket of energy services means increased use of energy, and total energy-related household spending increases. Additional investment moderates the change in energy bills, with the result that total energy-related spending takes 2 percentage points more of household disposable income in 2030 and 1 percentage point more in 2050 than today.

4.4.3 Behavioural changes

Behavioural changes play an important part in reducing energy demand and emissions in the NZE, especially in sectors where technical options for cutting emissions are limited in 2050. While it is citizens and companies that modify their behaviour, the changes are mostly enabled by the policies and investments made by governments, and in some instances, they are required by laws or regulations. The Covid-19 pandemic has increased general awareness of the potential effectiveness of behavioural changes, such as mask-wearing, and working and schooling at home. The crisis demonstrated that people can make behavioural changes at significant speed and scale if they understand the changes to be justified, and that it is necessary for governments to explain convincingly and to provide clear guidance about what changes are needed and why they are needed.

Figure 4.16 ▷ **Emissions reductions from policy-driven and discretionary behavioural changes by citizens and companies in the NZE**



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Three-quarters of the emissions saved by behavioural changes could be directly influenced or mandated by government policies

Around three-quarters of the emissions saved by behavioural changes between 2020 and 2050 in the NZE could be directly influenced or mandated by government policy (Figure 4.16). They include mitigation measures such as phasing out polluting cars from large cities and reducing speed limits on motorways. The other one-quarter involves more discretionary behavioural changes, such as reducing wasteful energy use in homes and offices, though even these types of changes could be promoted through awareness campaigns and other means. Around 10% of emissions savings directly influenced or mandated by government policy would require new or redirected investment in infrastructure. For example, the shift in the NZE from regional flights to high-speed rail would necessitate building around 170 000 kilometres of new track globally by 2050 (a tripling of 2020 levels).

Behavioural changes made by citizens and companies play a roughly equal role in reducing emissions in the NZE. Most changes in road transport and energy-saving in homes would depend on individuals, whereas the private sector has the primary role in reducing energy demand in commercial buildings and pursuing materials efficiency in manufacturing. Companies can also influence behavioural changes indirectly, for example, by promoting the use of public transport by employees that commute or encouraging working from home. However, a simple distinction between the role for individuals and companies masks a complex underlying dynamic: it is ultimately citizens as consumers of energy-related goods and services who shape corporate strategies, but at the same time companies do much to influence and generate consumer demand through marketing and advertising. In the NZE, consumers and companies move together in adopting behavioural changes, with governments setting the direction of those changes and facilitating them via effective and sustained policy support.

The behavioural changes in the NZE happen to different extents in different regions, and reflect a range of geographical and infrastructure constraints, as well as existing behavioural norms and cultural preferences. In countries with low rates of car ownership or energy service demand in buildings, many of the behavioural changes in advanced economies in NZE would not be relevant or appropriate. As a result, around half of the emissions savings from behavioural changes are in emerging market and developing economies, despite around 95% of activity growth in buildings and road transport between 2020 and 2050 occurring there. Nevertheless, there are significant opportunities in emerging market and developing economies for materials efficiency and urban design to decouple growth in economic prosperity and energy services from increases in emissions. For example, around 85% of CO_2 emissions reductions from cement and steel making in 2050 are due to gains in materials efficiency in emerging market and developing economies.

Cities are important to the behavioural changes in the NZE. Urban design can reduce the average city dweller's carbon footprint by up to 60% by shaping lifestyle choices and influencing day-to-day behaviour. For example, compact cities with clustered amenities can shorten average trip lengths; digitalisation can help shared private mobility to become the de facto option to accommodate much of the growth in service demand; and urban green infrastructure can reduce cooling demand (Feyisa, Dons & Meilby, 2014).

4.5 Governments

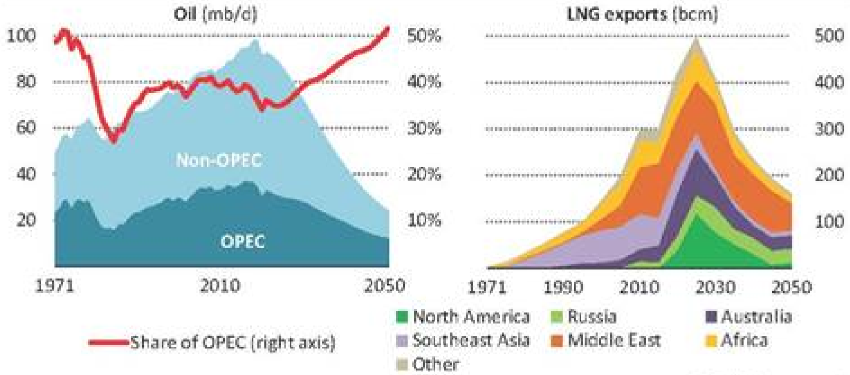
4.5.1 Energy security

Energy security is an important consideration for governments and those they serve, and the pathway to net-zero emissions must take account of it. Concerns about energy security have traditionally been associated with oil and natural gas supplies. The drop in oil and gas demand and the increased diversity of the energy sources used in the NZE may reduce some risks, but they do not disappear. There are also new potential vulnerabilities associated with the need to maintain reliable, flexible and secure electricity systems, and with the increase in demand for raw minerals for clean energy technologies. Improving energy efficiency remains the central measure for increasing energy security – even with rapid growth in low-emissions electricity generation, the safest energy supplies are those that are not needed.

Oil and gas security

No new oil and natural gas fields are required in the NZE beyond those already approved for development, and supplies become increasingly concentrated in a small number of low-cost producers. For oil, OPEC's share of global oil supply grows from around 37% in recent years to 52% in 2050, a level higher than at any point in the history of oil markets (Figure 4.17). For natural gas, inter-regional liquefied natural gas (LNG) trade increases from 420 bcm in 2020 over the next five years but it then falls to around 160 bcm in 2050. Nearly all exports in 2050 come from the lowest cost and lowest emissions producers. This means that the importance of ensuring adequate supplies of oil and natural gas to the smooth functioning of the global energy system would be quantitatively lower in 2050 than today, but it does not suggest that the risk of a shortfall in supply or sudden price rise is necessarily going to diminish, and a shortfall or sudden price rise would still have large repercussions for a number of sectors.

Figure 4.17 ▷ Global oil supply and LNG exports by region in the NZE



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Increased reliance on OPEC and other producer economies suffering from falling oil and gas revenues could pose a risk to supply security in consuming countries

Even if the timing and ambition of emission reduction policies are clear, the changes in the NZE clearly have implications for producers and consumers alike. Many producer economies would see oil and gas revenues drop to some of the lowest ever levels (see section 4.2.2). Even if these producers increase their market share, and diversify their economies and sources of tax revenue, they are likely to struggle to finance essential spending at current levels. This could have knock-on effects for social stability, and that in turn could potentially threaten the smooth delivery of oil and gas to consuming countries. Moves on the part of producer economies to gain market share or a failure to maintain upstream operations while managing the extreme strains that would be placed on their fiscal balances could lead to turbulent and volatile markets, greatly complicating the task facing policy makers.

Electricity security

The rapid electrification of all sectors in the NZE, and the associated increase in electricity's share of total final consumption from 20% in 2020 to nearly 50% in 2050, puts electricity even more at the heart of energy security across the world than it already is (IEA, 2020h). Greater reliance on electricity has both positive and negative implications for overall energy security. One advantage for energy-importing countries is that they become more self-sufficient, since a much higher share of electricity supply is based on domestic sources in the NZE than is the case for other fuels. However the increased importance of electricity means that any electricity system disruption would have larger impacts. Electricity infrastructure is often more vulnerable to physical shocks such as extreme weather events than pipelines and underground storage facilities, and climate change is likely to put increasing pressure on electricity systems, for example through more frequent droughts that might decrease the availability of water for hydropower and for cooling at thermal power plants. The resilience of electricity systems needs to be enhanced to mitigate these risks and maintain electricity security, including through more robust contingency planning, with solutions based on digital technologies and physical system hardening (IEA, 2021b).

Cybersecurity could pose an even greater risk to electricity security as systems incorporate more digitalised monitoring and controls in a growing number of power plants, electricity network assets and storage facilities. Policy makers have a central part to play in ensuring that the cyber resilience of electricity is enhanced, and there are a number of ways in which they can pursue this (IEA, 2021c).

Maintaining electricity security also requires a range of measures to ensure flexibility, adequacy and reliability at all times. Enhanced electricity system flexibility is of particular importance as the share of variable renewables in the generation mix rises. As a consequence, electricity system flexibility quadruples globally in the NZE in parallel with a more than two-and-a half-fold increase in electricity supply.[9] A portfolio of flexibility sources – including power plants, energy storage and demand response supported by electricity

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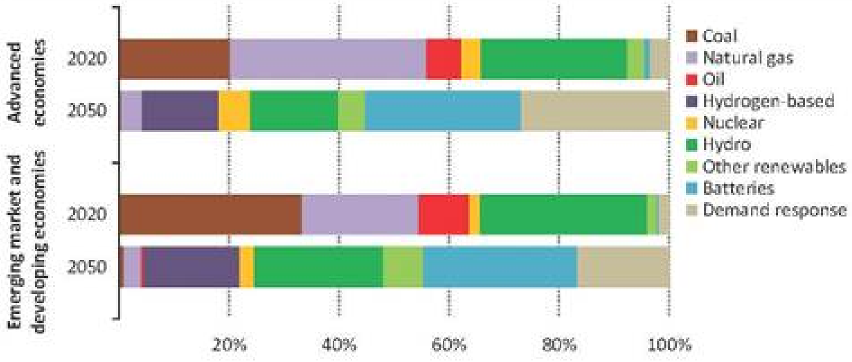
[9] Electricity system flexibility is quantified here based on hour-to-hour ramping needs, which is only one aspect of flexibility that also includes actions on much shorter time scales to maintain frequency and other ancillary services.

networks – is used to match supply and demand at all times of the year, under varying weather conditions and levels of demand. There is a significant shift in the NZE from using coal- and gas-fired power plants for the provision of flexibility to the use of renewables, hydrogen, battery storage, and demand-side response (Figure 4.18).

Figure 4.18 ▷ Electricity system flexibility by source in the NZE



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To meet four-times the amount of hour-to-hour flexibility needs, batteries and demand response step up to become the primary sources of flexibility

Electricity demand also becomes much more flexible as a result of the use of demand response measures, e.g. to shift consumption to times when renewable energy is plentiful. Conventional sources of demand response such as moderating industry activities remain important, but new areas of demand response such as smart charging of EVs unlock valuable new ways of supplementing them.[10] As the EV fleet expands in the NZE, EVs provide a significant portion of total electricity system flexibility. Although the technology already exists, the roll-out of smart charging has been slow to date due to institutional and regulatory barriers; these hurdles are overcome in the NZE. Measures are also implemented to ensure that the digitalisation of charging and other sources of flexibility does not compromise cybersecurity, and that potential social acceptance issues are addressed.

Energy storage also plays an important role in the provision of flexibility in the NZE. The deployment of battery storage systems is already starting to accelerate and to contribute to the management of short-duration flexibility needs, but the massive scale up to 3 100 GW of storage in 2050 (with four hour duration on average) envisaged in the NZE hinges on overcoming current regulatory and market design barriers. Pumped hydropower offers an attractive means of providing flexibility over a matter of hours and days, while hydrogen has

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[10] Smart chargers share real-time data with a centralised platform to allow system operators to optimise charging profiles based on how much energy the vehicle needs over a specified span of time, how much is available, the price of wholesale electricity, grid congestion and other parameters.

the potential to play an important part in longer term seasonal storage since it can be stored in converted gas storage facilities that have several orders of magnitude more capacity than battery storage projects.

Dispatchable power is essential to the secure transition of electricity systems, and in the NZE this comes increasingly from low-emissions sources. Hydropower provides a significant part of flexibility in many electricity systems today, and this continues in the future, with particular emphasis on expanding pumped hydro facilities. Nuclear power and geothermal plants, though designed for baseload generation, also provide a degree of flexibility in the NZE, but there are constraints on how much these sources can be expanded. This leaves an important role for thermal power plants that are equipped with carbon capture or use low-emissions fuels. For example, the use of sustainable biomass or low-emissions ammonia in existing coal plants offers a way of allowing these facilities to continue to contribute to flexibility and capacity adequacy, while at the same time reducing CO_2 emissions. Additional measures will also be necessary to maintain power system stability (Box 4.1).

Box 4.1 ⊳ Power system stability with high shares of variable renewables

Stability is a key feature of electricity security, allowing systems to remain in balance and withstand disturbances such as sudden generator or grid outages. Historically, conventional generators such as nuclear, hydro and fossil fuels have been central to electricity system stability, providing inertia with rotating machines that allow stored kinetic energy to be instantly converted into power in case of a system disturbance, and generating a voltage signal that helps all generators remain synchronous.

In contrast, newer technologies such as solar PV, wind and batteries are connected to the system through converters. They generally do not contribute to system inertia and are configured as "grid-following" units, synchronising to conventional generators. Maintaining system stability will call for new approaches as the share of converter based resources, and in particular variable renewables, rises much higher in electricity systems.

There is a growing body of knowledge and studies on stability in systems with high shares of variable renewables. For example, a recent joint study by the IEA and RTE, the transmission system operator in France, analyses the conditions under which it would be technically feasible to integrate high shares of variable renewables in France (IEA, 2021d). Based on the findings of this study:

- One option to ensure stability for a net zero power system is to maintain a minimum amount of conventional generation from low-carbon technologies during hours of high shares VRE output. This approach to maintain stability comes at the cost of solar and wind curtailment at high shares.
- Updated grid codes can be used to call for variable renewables and batteries to provide fast frequency response services, which can help reduce the amount of conventional generation needed for stability.

- Synchronous condensers are able to provide inertia without generating electricity. The technology is already proven at GW-scale in Denmark and also in South Australia, but experience needs to be expanded at larger scale.
- Grid-forming converters can allow variable renewables and batteries to generate a voltage signal, though experience with this approach needs to move beyond micro-grids and small islands to large interconnected systems.

Demonstration projects, stakeholder consultations and international collaboration will be critical to fully understand the merits of each of these four approaches and the scope for a portfolio of options that would most cost-effectively achieve net zero emissions while maintaining electricity security.

Electricity networks support and enable the use of all sources of flexibility, balancing demand and supply over large areas. Timely investment in grids to minimise congestion and expand the size of the areas where supply and demand are balanced will be critical to making the best use of solar PV and wind projects, and ensuring affordable and reliable supplies of electricity. Expanding long-distance transmission also makes a key contribution in the NZE, since a lack of available land near demand centres and other factors mean new sources of generation are often located in remote areas. It is important that new transmission systems are built with variable, bidirectional operation in mind in order to maximise the use of available flexibility sources, and that regulatory and market arrangements support flexible connections between systems. The key value of interconnections comes from complementary electricity demand and wind patterns: solar PV output is more highly correlated than wind over large areas.

The NZE sees a major increase in demand for critical minerals such as copper, lithium, nickel, cobalt and rare earth elements that are essential for many clean energy technologies. There are several potential vulnerabilities that could hinder the adequate supply of these minerals and lead to price volatility (IEA, 2021a). Today's production and processing operations for many minerals are highly concentrated in a small number of countries, making supplies vulnerable to political instability, geopolitical risks and possible export restrictions. In many cases, there are also concerns about land-use changes, competition for scarce water resources, corruption and misuse of government resources, fatalities and injuries to workers, and human rights abuses, including the use of child labour. New critical mineral projects can have long lead times, so the rapid increase in demand in the NZE could lead to a mismatch in timing between supply and demand. The international trade and investment regime is key to maintaining reliable mineral supplies, but policy support and international co-ordination will be needed to ensure the application of rigorous environmental and social regulations.

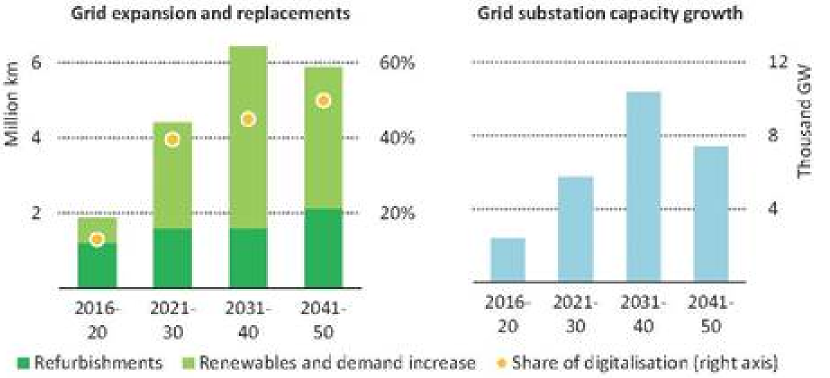
4.5.2 Infrastructure

Getting to net-zero emissions will require huge amounts of new infrastructure and lots of modifications to existing assets. Energy infrastructure is transformed in the NZE as all countries and regions move from systems supporting the use of fossil fuels and the distribution of conventionally generated electricity to systems based largely on renewable electricity and low-emissions fuels. In many emerging market and developing economies, the provision of large amounts of infrastructure would be necessary in the coming decades in any case, creating a window of opportunity to support the transition to a net-zero emissions economy. In all countries, governments will play a central role in planning, financing and regulating the development of infrastructure. Some of the main infrastructure components – electricity networks and EV charging, pipelines systems for low-emissions fuels and CO_2, and transport infrastructure – are discussed below.

The rapid increase in electricity demand in the NZE and the transition to renewable energy call for an expansion and modernisation of electricity networks (Figure 4.19). This would require a sharp reversal in the recent trend of declining investment: failure to achieve this would almost certainly make the energy transition for net-zero emissions impossible. Tariff design and permitting procedures also need to be revised to reflect fundamental changes in the provision and uses of electricity. Some of the main considerations include:

- **Long-distance transmission.** Most of the growth in renewables in the NZE comes from centralised sources. Yet the best solar and wind resources are often in remote regions, requiring new transmission connections. Ultra high-voltage direct current systems are likely to play an important role in supporting transmission over long distances.
- **Local distribution.** Energy efficiency gains in households and wider use of rooftop solar PV mean surplus electricity will be available more often, while electric heat pumps and residential EV charging points will require electricity to be more widely available. Together these developments point to the need for substantial increases in distribution network capacity.
- **Grid substations.** The massive expansion of solar PV and wind requires new grid substations: their capacity expands by more than 57 000 GW in the NZE by 2030, doubling current capacity globally.
- **EV charging.** Major new public charging networks are built in the NZE, including in work places, highway service stations and residential complexes, to support EV expansion and long-distance driving on highways.
- **Digitalisation of networks.** With a large increase in the use of connected devices, the digitalisation of grid assets supports more flexible grid operations, better management of variable renewables and more efficient demand response.

Figure 4.19 ▷ Annual average electricity grid expansion, replacement and substation capacity growth in the NZE



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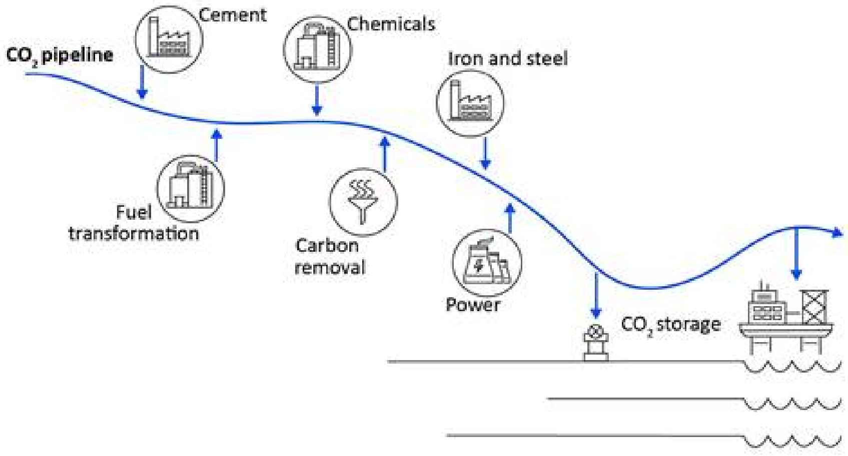
Grid and substation expansion is driven largely by the massive deployment of renewables and electrification of end-uses, with a rising digital share of infrastructure

Note: Substation capacity here assumes active electricity is equal to apparent electricity.

Pipelines continue to play a key role in the transmission and distribution of energy in the NZE:

- Given the rapid decline of fossil fuels, significant investment in new oil and gas pipelines are not needed in the NZE. However investment is needed to link the production of low-emissions liquids and gases with consumption centres, and to convert existing pipelines and associated distribution infrastructure for the use of these low-emissions fuels. Some low-emissions fuels, such as biomethane and synthetic hydrogen-based fuels, can make use of existing infrastructure without any modifications, but pure hydrogen requires a retrofit of existing pipelines. New dedicated hydrogen infrastructure is also needed in the NZE, for example to move hydrogen produced in remote areas with excellent renewable resources to demand centres.
- The expansion of CCUS in the NZE requires investment in CO_2 transport and storage capacity. By 2050, 7.6 Gt of CO_2 is captured worldwide, requiring a large amount of pipeline and shipping infrastructure linking the facilities where CO_2 is captured with storage sites. Industrial clusters, including ports, may offer the best near-term opportunities to build CO_2 pipeline and hydrogen infrastructure, as the various industries in those clusters using the new infrastructure would be able to share the upfront investment needs (Figure 4.20).

Figure 4.20 ▷ Illustrative example of a shared CO_2 pipeline in an industrial cluster



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Deployment of technologies like CCUS and hydrogen and their enabling infrastructure would benefit strongly from a cross-sectoral approach in industrial clusters

Transforming transport infrastructure represents both a challenge and an opportunity. The challenge arises from the potential increase in the energy and carbon intensity of economic growth during the infrastructure development phase.[11] Steel and cement are the two main components of virtually all infrastructure projects, but they are also among the most challenging sectors to decarbonise. The opportunity comes from the scope that exists in some countries to develop infrastructure from scratch in a way that is compatible with the net zero goal. Countries undergoing rapid urbanisation today can design and steer new infrastructure development towards higher urban density and high-capacity mass transit in tandem with EV charging and low-emissions fuelling systems.

Rail has an important part to play as transport infrastructure is developed. The NZE sees large-scale investment in all regions in high-speed trains to replace both long-distance car driving and short-haul aviation. It also sees large-scale investment in all regions in track, control systems, rolling stock modernisation and combined freight facilities to improve speed and flexibility for just-in-time logistical operations and thus support a shift of freight from road to rail, especially for container traffic.

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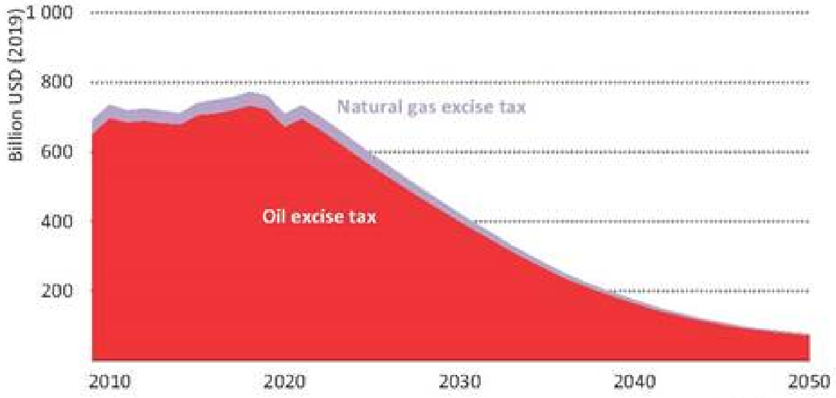
[11] The modelling for the NZE incorporates the increase in steel and cement that is required to build additional transport infrastructure (roads, cars and trucks) and energy infrastructure, e.g. power plants and wind turbines.

4.5.3 Tax revenues from retail energy sales

The slump in the consumption of fossil fuels required to get to net-zero emissions would result in the loss of a large amount of tax revenue in many countries, given that fuels such as oil-based transport fuels and natural gas are often subject to high excise or other special taxes. In recent years, energy-related taxes accounted for around 4% of total government tax revenues in advanced economies on average and 3.5% in emerging market and developing economies, but they provided as much as 10% in some countries (OECD, 2020).

Figure 4.21 ▷ Global revenues from taxes on retail sales of oil and gas in the NZE



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Tax revenues slump from retail sales of oil and gas

Tax revenue from oil and natural gas retail sales falls by close to 90% between 2020 and 2050 in the NZE (Figure 4.21). Governments are likely to need to rely on some combination of other tax revenues and public spending reforms to compensate. Some taxation measures focused on the energy sector could be useful. However, any such taxes would need to be carefully designed to minimise their impact on low-income households, as poorer households spend a higher percentage of their disposable income on electricity and heating. Options for energy-related taxes include:

- **CO_2 prices.** These are introduced in all regions in the NZE, albeit at different levels for countries and sectors, which provide additional revenue streams. The reduction in oil and natural gas excise taxes is more than compensated over the next 15 years by higher revenues from CO_2 prices related to these fuels paid by end users and other sectors, but these too fall as the global energy system moves towards net-zero emissions.
- **Road fees and congestion charges.** These would have the added benefit of discouraging driving and encouraging switching to other less carbon-intensive modes of transport.

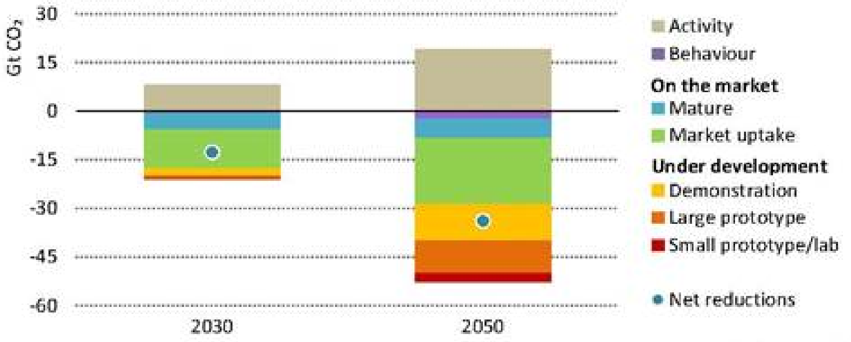
- **Increasing taxation on electricity.** Higher taxes on all electricity sales could generate substantial revenues, especially since large increases in price often have little effect on consumption. This might be counterproductive, however, as it would reduce the cost-effectiveness of both EVs and heat 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



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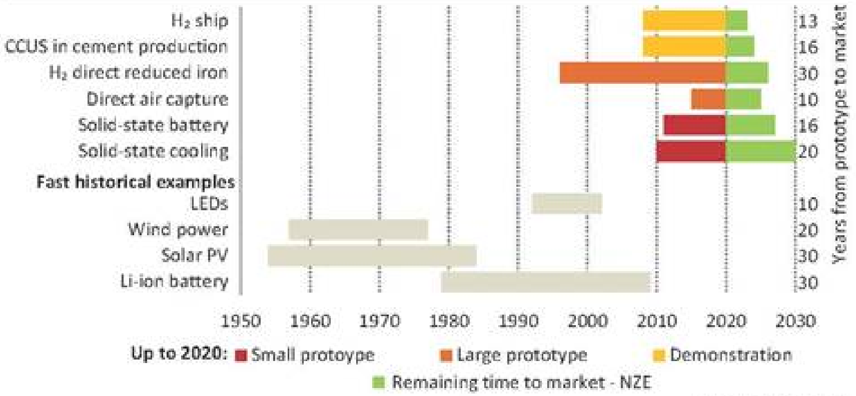
While the emissions reductions in 2030 mostly rely on technologies on the market, those under development today account for almost half of the emissions reductions in 2050

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



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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.

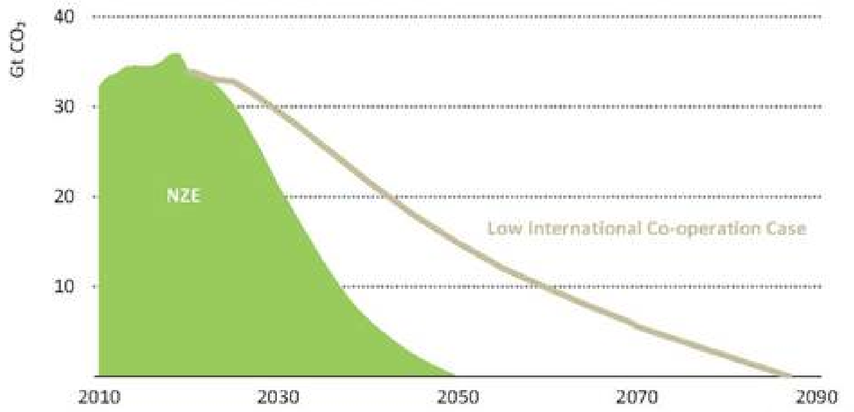
- **Innovation, demonstration and diffusion.** Clean energy R&D and patenting is currently concentrated in a handful of places: United States, Europe, Japan, Korea and China accounted for more than 90% of clean energy patents in 2014-18. Progress towards net-zero emissions would be increased by moving 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 ▷ CO₂ emissions in the Low International Co-operation Case and the NZE



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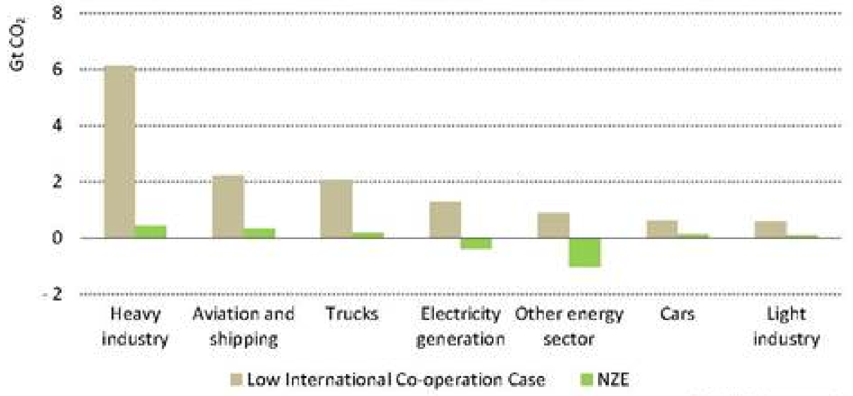
Without international co-operation, the transition to net zero would be delayed by decades

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**



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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

Annex A

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.

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[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	11 506	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.*

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

Annex B

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.

Annex C

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.

Electricity generation: Defined as the total amount of electricity generated by power only or combined heat and power plants including generation required for own use. This is also referred to as gross generation.

Energy sector CO_2 emissions: Carbon dioxide emissions from fuel combustion (excluding non-renewable waste). Note that this does not include fugitive emissions from fuels, CO_2 from transport, storage emissions or industrial process emissions.

Energy sector GHG emissions: CO_2 emissions from fuel combustion plus fugitive and vented methane, and nitrous dioxide (N_2O) emissions from the energy and industry sectors.

Energy services: See useful energy.

Ethanol: Refers to bio-ethanol only. Ethanol is produced from fermenting any biomass high in carbohydrates. Today, ethanol is made from starches and sugars, but second-generation technologies will allow it to be made from cellulose and hemicellulose, the fibrous material that makes up the bulk of most plant matter.

Fischer-Tropsch synthesis: Catalytic production process for the production of synthetic fuels. Natural gas, coal and biomass feedstocks can be used.

Gases: Includes natural gas, biogases, synthetic methane and hydrogen.

Geothermal: Geothermal energy is heat derived from the sub-surface of the earth. Water and/or steam carry the geothermal energy to the surface. Depending on its characteristics, geothermal energy can be used for heating and cooling purposes or be harnessed to generate clean electricity if the temperature is adequate.

Heat (end-use): Can be obtained from the combustion of fossil or renewable fuels, direct geothermal or solar heat systems, exothermic chemical processes and electricity (through resistance heating or heat pumps which can extract it from ambient air and liquids). This category refers to the wide range of end-uses, including space and water heating, and cooking in buildings, desalination and process applications in industry. It does not include cooling applications.

Heat (supply): Obtained from the combustion of fuels, nuclear reactors, geothermal resources and the capture of sunlight. It may be used for heating or cooling, or converted into mechanical energy for transport or electricity generation. Commercial heat sold is reported under total final consumption with the fuel inputs allocated under electricity and heat sectors.

Hydrogen: Hydrogen is used in the energy system to refine hydrocarbon fuels and as an energy carrier in its own right. It is also produced from other energy products for use in chemicals production. As an energy carrier it can be produced from hydrocarbon fuels or from the electrolysis of water with electricity, and can be burned or used in fuel cells for electricity and heat in a wide variety of applications. To be low-carbon hydrogen, either the emissions associated with fossil-based hydrogen production must be prevented (for example by carbon capture, utilisation and storage) or the electricity input to hydrogen produced from water must be low-carbon electricity. In this report, final consumption of hydrogen includes demand for pure hydrogen and excludes hydrogen produced and consumed onsite by the same entity. Demand for hydrogen-based fuels such as ammonia or synthetic hydrocarbons are considered separately.

Hydrogen-based fuels: Include ammonia and synthetic hydrocarbons (gases and liquids). Hydrogen-based is used in figures to refer to hydrogen and hydrogen-based fuels.

Hydropower: The energy content of the electricity produced in hydropower plants, assuming 100% efficiency. It excludes output from pumped storage and marine (tide and wave) plants.

Industry: The sector includes fuel used within the manufacturing and construction industries. Key industry branches include iron and steel, chemicals and petrochemicals, cement, and pulp and paper. Use by industries for the transformation of energy into another form or for the production of fuels is excluded and reported separately under other energy sector. Consumption of fuels for the transport of goods is reported as part of the transport sector, while consumption by off-road vehicles is reported under industry.

International aviation bunkers: Includes the deliveries of aviation fuels to aircraft for international aviation. Fuels used by airlines for their road vehicles are excluded. The domestic/international split is determined on the basis of departure and landing locations and not by the nationality of the airline. For many countries this incorrectly excludes fuels used by domestically owned carriers for their international departures.

International marine bunkers: Covers fuels delivered to ships of all flags that are engaged in international navigation. The international navigation may take place at sea, on inland lakes and waterways, and in coastal waters. Consumption by ships engaged in domestic navigation is excluded. The domestic/international split is determined on the basis of port of departure and port of arrival, and not by the flag or nationality of the ship. Consumption by fishing vessels and by military forces is excluded and included in residential, services and agriculture.

Investment: All investment data and projections reflect spending across the lifecycle of a project, i.e. the capital spent is assigned to the year when it is incurred. Investments for oil, gas and coal include production, transformation and transportation; those for the power sector include refurbishments, uprates, new builds and replacements for all fuels and technologies for on-grid, mini-grid and off-grid generation, as well as investment in transmission and distribution, and battery storage. Investment data are presented in real terms in year-2019 US dollars unless otherwise stated.

Light-duty vehicles (LDV): include passenger cars and light commercial vehicles (gross vehicle weight <3.5 tonnes).

Liquid biofuels: Liquid fuels derived from biomass or waste feedstocks and include ethanol and biodiesel. They can be classified as conventional and advanced liquid biofuels according to the bioenergy feedstocks and technologies used to produce them and their respective maturity. Unless otherwise stated, liquid biofuels are expressed in energy-equivalent volumes of gasoline and diesel.

Liquids: Includes oil, liquid biofuels (expressed in energy-equivalent volumes of gasoline and diesel), synthetic oil and ammonia.

Low-carbon electricity: Includes renewable energy technologies, hydrogen-based generation, nuclear power and fossil fuel power plants equipped with carbon capture, utilisation and storage.

Low-emissions fuels: Include liquid biofuels, biogas and biomethane, hydrogen, and hydrogen-based fuels that do not emit any CO_2 from fossil fuels directly when used and also emit very little when being produced.

Marine: Represents the mechanical energy derived from tidal movement, wave motion or ocean current and exploited for electricity generation.

Merchant hydrogen: Hydrogen produced by one company to sell to others; equivalent to hydrogen reported in total final consumption.

Mini-grids: Small grid systems linking a number of households or other consumers.

Modern bioenergy: Includes modern solid biomass, liquid biofuels and biogases harvested from sustainable sources. It excludes the traditional use of biomass.

Modern energy access: Includes household access to a minimum level of electricity; household access to safer and more sustainable cooking and heating fuels, and stoves; access that enables productive economic activity; and access for public services.

Modern renewables: Includes all uses of renewable energy with the exception of traditional use of solid biomass.

Modern solid biomass: Refers to the use of solid biomass in improved cookstoves and modern technologies using processed biomass such as pellets.

Natural gas: Comprises gases occurring in deposits, whether liquefied or gaseous, consisting mainly of methane. It includes both "non-associated" gas originating from fields producing hydrocarbons only in gaseous form, and "associated" gas produced in association with crude oil as well as methane recovered from coal mines (colliery gas). Natural gas liquids (NGLs), manufactured gas (produced from municipal or industrial waste, or sewage) and quantities vented or flared are not included. Gas data in cubic metres are expressed on a gross calorific value basis and are measured at 15 °C and at 760 mm Hg ("Standard Conditions"). Gas data expressed in tonnes of oil equivalent, mainly for comparison reasons with other fuels, are on a net calorific basis. The difference between the net and the gross calorific value is the latent heat of vaporisation of the water vapour produced during combustion of the fuel (for gas the net calorific value is 10% lower than the gross calorific value).

Natural gas liquids (NGLs): Liquid or liquefied hydrocarbons produced in the manufacture, purification and stabilisation of natural gas. These are those portions of natural gas which are recovered as liquids in separators, field facilities or gas processing plants. NGLs include but are not limited to ethane (when it is removed from the natural gas stream), propane, butane, pentane, natural gasoline and condensates.

Network gases: Includes natural gas, biomethane, synthetic methane and hydrogen blended in a gas network.

Non-energy use: Fuels used for chemical feedstocks and non-energy products. Examples of non-energy products include lubricants, paraffin waxes, asphalt, bitumen, coal tars and oils as timber preservatives.

Nuclear: Refers to the primary energy equivalent of the electricity produced by a nuclear plant, assuming an average conversion efficiency of 33%.

Off-grid systems: Stand-alone systems for individual households or groups of consumers.

Offshore wind: Refers to electricity produced by wind turbines that are installed in open water, usually in the ocean.

Oil: Oil production includes both conventional and unconventional oil. Petroleum products include refinery gas, ethane, liquid petroleum gas, aviation gasoline, motor gasoline, jet fuels, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirit, lubricants, bitumen, paraffin, waxes and petroleum coke.

Other energy sector: Covers the use of energy by transformation industries and the energy losses in converting primary energy into a form that can be used in the final consuming sectors. It includes losses by gas works, petroleum refineries, blast furnaces, coke ovens, coal and gas transformation and liquefaction, biofuels production and the production of hydrogen and hydrogen-based fuels. It also includes energy own use in coal mines, in oil and gas extraction, in direct air capture, in biofuels production and in electricity and heat production. Transfers and statistical differences are also included in this category.

Power generation: Refers to fuel use in electricity plants, heat plants and combined heat and power (CHP) plants. Both main activity producer plants and small plants that produce fuel for their own use (auto-producers) are included.

Productive uses: Energy used towards an economic purpose: agriculture, industry, services and non-energy use. Some energy demand from the transport sector, e.g. freight, could also be considered as productive, but is treated separately.

Renewables: Includes bioenergy, geothermal, hydropower, solar photovoltaics (PV), concentrating solar power (CSP), wind and marine (tide and wave) energy for electricity and heat generation.

Residential: Energy used by households including space heating and cooling, water heating, lighting, appliances, electronic devices and cooking equipment.

Services: Energy used in commercial facilities, e.g. hotels, offices, catering, shops, and institutional buildings, e.g. schools, hospitals, offices. Energy use in services includes space heating and cooling, water heating, lighting, equipment, appliances and cooking equipment.

Shale gas: Natural gas contained within a commonly occurring rock classified as shale. Shale formations are characterised by low permeability, with more limited ability of gas to flow through the rock than is the case with a conventional reservoir. Shale gas is generally produced using hydraulic fracturing.

Shipping/navigation: This transport sub-sector includes both domestic and international navigation and their use of marine fuels. Domestic navigation covers the transport of goods or persons on inland waterways and for national sea voyages (starts and ends in the same country without any intermediate foreign port). International navigation includes quantities of fuels delivered to merchant ships (including passenger ships) of any nationality for consumption during international voyages transporting goods or passengers.

Solar photovoltaic (PV): Electricity produced from solar photovoltaic cells.

Solid biomass: Includes charcoal, fuelwood, dung, agricultural residues, wood waste and other solid wastes.

Steam coal: Type of coal that is mainly used for heat production or steam-raising in power plants and, to a lesser extent, in industry. Typically, steam coal is not of sufficient quality for steel making. Coal of this quality is also commonly known as thermal coal.

Synthetic methane: Low-carbon synthetic methane is produced through the methanation of low-carbon hydrogen and carbon dioxide from a biogenic or atmospheric source.

Synthetic oil: Low-carbon synthetic oil produced through Fischer Tropsch conversion or methanol synthesis from syngas, a mixture of hydrogen (H_2) and carbon monoxide (CO).

Total energy supply (TES): Represents domestic demand only and is broken down into electricity and heat generation, other energy sector and total final consumption.

Total final consumption (TFC): Is the sum of consumption by the various end-use sectors. TFC is broken down into energy demand in the following sectors: industry (including manufacturing and mining), transport, buildings (including residential and services) and other (including agriculture and non-energy use). It excludes international marine and aviation bunkers, except at world level where it is included in the transport sector.

Total final energy consumption (TFEC): Is a variable defined primarily for tracking progress towards target 7.2 of the UN Sustainable Development Goals. It incorporates total final consumption (TFC) by end-use sectors but excludes non-energy use. It excludes international marine and aviation bunkers, except at world level. Typically this is used in the context of calculating the renewable energy share in total final energy consumption (Indicator 7.2.1 of the Sustainable Development Goals), where TFEC is the denominator.

Total primary energy demand (TPED): See total energy supply

Traditional use of solid biomass: Refers to the use of solid biomass with basic technologies, such as a three-stone fire, often with no or poorly operating chimneys.

Transport: Fuels and electricity used in the transport of goods or people within the national territory irrespective of the economic sector within which the activity occurs. This includes fuel and electricity delivered to vehicles using public roads or for use in rail vehicles; fuel delivered to vessels for domestic navigation; fuel delivered to aircraft for domestic aviation; and energy consumed in the delivery of fuels through pipelines. Fuel delivered to international marine and aviation bunkers is presented only at the world level and is excluded from the transport sector at a domestic level.

Trucks: Includes medium trucks (gross vehicle weight 3.5-15 tonnes) and heavy trucks (>15 tonnes).

Useful energy: Refers to the energy that is available to end-users to satisfy their needs. This is also referred to as energy services demand. As result of transformation losses at the point of use, the amount of useful energy is lower than the corresponding final energy demand for most technologies. Equipment using electricity often has higher conversion efficiency than equipment using other fuels, meaning that for a unit of energy consumed electricity can provide more energy services.

Wind: electricity produced by wind turbines from the kinetic energy of wind.

Woody energy crops: Short-rotation plantings of woody biomass for bioenergy production, such as coppiced willow and miscanthus.

Variable renewable energy (VRE): Refers to technologies whose maximum output at any time depends on the availability of fluctuating renewable energy resources. VRE includes a broad array of technologies such as wind power, solar PV, run-of-river hydro, concentrating solar power (where no thermal storage is included) and marine (tidal and wave).

Zero-carbon-ready buildings: A zero-carbon-ready building is highly energy efficient and either uses renewable energy directly, or an energy supply that can be fully decarbonised, such as electricity or district heat.

Zero-emissions vehicles (ZEVs): Vehicles which are capable of operating without tailpipe CO_2 emissions (battery electric vehicles and fuel cell vehicles).

Regional and country groupings

Advanced economies: OECD regional grouping and Bulgaria, Croatia, Cyprus[1,2], Malta and Romania.

Africa: North Africa and sub-Saharan Africa regional groupings.

Asia Pacific: Southeast Asia regional grouping and Australia, Bangladesh, China, India, Japan, Korea, Democratic People's Republic of Korea, Mongolia, Nepal, New Zealand, Pakistan, Sri Lanka, Chinese Taipei, and other Asia Pacific countries and territories.[3]

Caspian: Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan.

Central and South America: Argentina, Plurinational State of Bolivia (Bolivia), Brazil, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay, Bolivarian Republic of Venezuela (Venezuela), and other Central and South American countries and territories.[4]

China: Includes the (People's Republic of) China and Hong Kong, China.

Figure C.1 ▷ Main country groupings

Note: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Developing Asia: Asia Pacific regional grouping excluding Australia, Japan, Korea and New Zealand.

Emerging market and developing economies: All other countries not included in the advanced economies regional grouping.

Eurasia: Caspian regional grouping and the Russian Federation (Russia).

Europe: European Union regional grouping and Albania, Belarus, Bosnia and Herzegovina, North Macedonia, Gibraltar, Iceland, Israel[5], Kosovo, Montenegro, Norway, Serbia, Switzerland, Republic of Moldova, Turkey, Ukraine and United Kingdom.

European Union: Austria, Belgium, Bulgaria, Croatia, Cyprus[1,2], Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain and Sweden.

IEA (International Energy Agency): OECD regional grouping excluding Chile, Colombia, Iceland, Israel, Latvia, Lithuania and Slovenia.

Latin America: Central and South America regional grouping and Mexico.

Middle East: Bahrain, Islamic Republic of Iran (Iran), Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic (Syria), United Arab Emirates and Yemen.

Non-OECD: All other countries not included in the OECD regional grouping.

Non-OPEC: All other countries not included in the OPEC regional grouping.

North Africa: Algeria, Egypt, Libya, Morocco and Tunisia.

North America: Canada, Mexico and United States.

OECD (Organisation for Economic Co-operation and Development): Australia, Austria, Belgium, Canada, Chile, Colombia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States.

OPEC (Organisation of the Petroleum Exporting Countries): Algeria, Angola, Republic of the Congo (Congo), Equatorial Guinea, Gabon, the Islamic Republic of Iran (Iran), Iraq, Kuwait, Libya, Nigeria, Saudi Arabia, United Arab Emirates and Bolivarian Republic of Venezuela (Venezuela).

Southeast Asia: Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic (Lao PDR), Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam. These countries are all members of the Association of Southeast Asian Nations (ASEAN).

Sub-Saharan Africa: Angola, Benin, Botswana, Cameroon, Republic of the Congo (Congo), Côte d'Ivoire, Democratic Republic of the Congo, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Mauritius, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania (Tanzania), Togo, Zambia, Zimbabwe and other African countries and territories.[6]

Country notes

[1] Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the island. There is no single authority representing both Turkish and Greek Cypriot people on the island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".

[2] Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

[3] Individual data are not available and are estimated in aggregate for: Afghanistan, Bhutan, Cook Islands, Fiji, French Polynesia, Kiribati, Macau (China), Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste and Tonga and Vanuatu.

[4] Individual data are not available and are estimated in aggregate for: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Bonaire, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), French Guiana, Grenada, Guadeloupe, Guyana, Martinique, Montserrat, Saba, Saint Eustatius, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and Grenadines, Saint Maarten, Turks and Caicos Islands.

[5] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

[6] Individual data are not available and are estimated in aggregate for: Burkina Faso, Burundi, Cabo Verde, Central African Republic, Chad, Comoros, Djibouti, Kingdom of Eswatini, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Réunion, Rwanda, Sao Tome and Principe, Seychelles, Sierra Leone, Somalia and Uganda.

Abbreviations and Acronyms

AFOLU	agriculture forestry and other land use
APC	Announced Pledges Case
ASEAN	Association of Southeast Asian Nations
BECCS	bioenergy equipped with CCUS
BEV	battery electric vehicles
CCUS	carbon capture, utilisation and storage
CDR	carbon dioxide removal
CFL	compact fluorescent lamp
CH_4	methane
CHP	combined heat and power; the term co-generation is sometimes used
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CO_2-eq	carbon-dioxide equivalent
COP	Conference of Parties (UNFCCC)
CSP	concentrating solar power
DAC	direct air capture
DACCS	direct air capture with carbon capture and storage
DER	distributed energy resources
DSI	demand-side integration
DSO	distribution system operator
DSR	demand-side response
EAF	electric arc furnaces
EHOB	extra-heavy oil and bitumen
ETP	Energy Technology Perspectives
EU	European Union
EV	electric vehicle
FCEV	fuel cell electric vehicle
GDP	gross domestic product
GHG	greenhouse gases
GTL	gas-to-liquids
HEFA	hydrogenated esters and fatty acids
ICE	internal combustion engine
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
IOC	international oil company
IPCC	Intergovernmental Panel on Climate Change
LCC	Low CCUS Case
LDVs	light-duty vehicles
LCV	light-commercial vehicle
LED	light-emitting diode

LNG	liquefied natural gas
LPG	liquefied petroleum gas
MEPS	minimum energy performance standards
NDCs	Nationally Determined Contributions
NEA	Nuclear Energy Agency (an agency within the OECD)
NGLs	natural gas liquids
NGV	natural gas vehicle
NOC	national oil company
NO_X	nitrogen oxides
N_2O	nitrous dioxide
NZE	Net-Zero Emissions Scenario
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PHEV	plug-in hybrid electric vehicles
PLDV	passenger light-duty vehicle
PM	particulate matter
$PM_{2.5}$	fine particulate matter
PPP	purchasing power parity
PV	photovoltaics
R&D	research and development
RD&D	research, development and demonstration
SAF	sustainable aviation fuel
SDG	Sustainable Development Goals (United Nations)
SO_2	sulphur dioxide
SR1.5	IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels
STEPS	Stated Policies Scenario
T&D	transmission and distribution
TES	total energy supply
TFC	total final consumption
TFEC	total final energy consumption
TPED	total primary energy demand
UEC	unit energy consumption
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UK	United Kingdom
US	United States
VRE	variable renewable energy
WEO	*World Energy Outlook*
WHO	World Health Organization
ZEV	Zero-emissions vehicle

Annex D

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Important Information

Engine No. 1 LLC, Engine No. 1 LP, Engine No. 1 NY LLC, Christopher James, Charles Penner (collectively, “Engine No. 1”), Gregory J. Goff, Kaisa Hietala, Alexander Karsner, and Anders Runevad (collectively and together with Engine No. 1, the “Participants”) have filed with the Securities and Exchange Commission (the “SEC”) a definitive proxy statement and accompanying form of WHITE proxy to be used in connection with the solicitation of proxies from the shareholders of Exxon Mobil Corporation (the “Company”). All shareholders of the Company are advised to read the definitive proxy statement and other documents related to the solicitation of proxies by the Participants, as they contain important information, including additional information related to the Participants. The definitive proxy statement and an accompanying WHITE proxy card will be furnished to some or all of the Company’s shareholders and is, along with other relevant documents, available at no charge on Engine No.1’s campaign website at https://reenergizexom.com/materials/ and the SEC website at http://www.sec.gov/.

Information about the Participants and a description of their direct or indirect interests by security holdings is contained in the definitive proxy statement filed by the Participants with the SEC on March 15, 2021. This document is available free of charge from the sources described above.