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Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals

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Low-carbon investments are necessary for driving the energy system transformation that is called for by both the Paris Agreement and Sustainable Development Goals. Improving understanding of the scale and nature of these investments under diverging technology and policy futures is therefore of great importance to decision makers. Here, using six global modelling frameworks, we show that the pronounced reallocation of the investment portfolio required to transform the energy system will not be initiated by the current suite of countries' Nationally Determined Contributions. Charting a course toward 'well below 2 °C' instead sees low-carbon investments overtaking fossil investments globally by around 2025 or before and growing thereafter. Pursuing the 1.5 °C target demands a marked upscaling in low-carbon capital beyond that of a 2 °C-consistent future. Actions consistent with an energy transformation would increase the costs of achieving the goals of energy access and food security, but reduce the costs of achieving air-quality goals.

Numerous pathways and narratives have been developed to shed light on how society could transform its energy systems in line with the aspirational targets of the Paris Agreement and Sustainable Development Goals (SDGs)[1–4]. These studies make clear that ramping up renewables and boosting efficiency are necessary pre-conditions for limiting the rise in global temperatures to well below 2 °C during the twenty-first century. Rarely, however, have these stories been told using the language of dollars, specifically energy investments, at least at the global level[5–7], which is perhaps surprising, given that investments are often recognized as the 'lifeblood' of the global energy system and that low-carbon investments act as the vehicle for the energy system transformation. Decision makers at all levels, including the G20 (Group of 20 countries), seem to be aware of this and are openly calling for such essential information[8].

Scenario modelling tools are widely used to evaluate the costs, potentials and consequences of different energy, climate and human development futures over the medium-to-long term. Yet, analyses addressing global energy investment needs are fairly uncommon; even more so are multi-model exercises on the topic. The latter is important because each model has its own perspective on how the future could unfold in light of varying assumptions for socioeconomic development, technological change and policy choices. Models also have different structures and solution algorithms.

Here, we present key findings and insights from a multi-model analysis of the energy investments required for achieving increasingly stringent international policy goals over the coming decades. Scenarios are derived from six global energy-economy modelling frameworks, each of which depicts a uniquely evolving energy investment landscape in futures spanning a continuation of today's trends (considering countries' Nationally Determined Contributions (NDCs)) to those that are far more transformative (consistent with achieving the aspirational 2 °C and 1.5 °C targets espoused by the Paris Agreement[9]). We focus our study in particular on the upscaling requirements and portfolio shifts inherent in these diverging futures, with an eye toward the most evident 'investment gaps'. We then compare these requirements with those for achieving other energy-related SDG targets[10]. In short, we find that a transformation of the global energy system need not require a major increase in investments in total. A pronounced reallocation of the investment portfolio is, however, inevitable. The NDCs will not provide the impetus for this structural shift. Instead, to chart a course toward 2 °C and 1.5 °C, annual investments in low-carbon energy (across the entire supply side, not just the power sector) will need to overtake fossil investments globally around 2025 or before. Going

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beyond a 2 °C-consistent pathway and pushing closer to 1.5 °C is found to require a step-change in the amount of low-carbon capital invested per tonne of carbon dioxide (CO_2) avoided. We estimate that to achieve the NDC, 2 °C or 1.5 °C targets globally, there exists a low-carbon energy and energy efficiency investment 'gap' of approximately 130 billion, 320 billion or 480 billion US dollars per year (to 2030; model averages), respectively, representing upwards of one-quarter of total energy investments otherwise foreseen in a baseline scenario; and for some major economies (such as China and India), up to one-half. Moreover, total energy system investments can be up to an order of magnitude larger than the needs for making progress on several other SDG targets, such as energy access, food security, air pollution, education, and clean water and sanitation.

Modelling tools employed

The six global energy-economy models, or integrated assessment model (IAM) frameworks, drawn upon in this study include AIM/CGE[11,12], IMAGE[13], MESSAGEix-GLOBIOM[14,15], POLES[16,17], REMIND-MAgPIE[18,19] and WITCH-GLOBIOM[20,21]; in addition, we use the nationally focused GCAM-USA[22,23] model for an analysis of power sector investments. (See Methods and Supplementary Methods for details on the modelling frameworks used and policy scenarios run.) These models span a range from least-cost optimization to computable general equilibrium models, and from game-theoretic to recursive-dynamic simulation models. Such diversity is beneficial for shedding light on those model findings that are robust to diverging assumptions and on potential outliers deserving of further investigation. Of particular importance for the current study, the six models have broad coverage of different types of energy technologies across the entirety of the global energy system, including resource extraction, power generation, fuel conversion, pipelines and transmission, energy storage and end-use demand devices, and are therefore well-positioned to assess the evolving nature of the energy and climate mitigation investment portfolio over time. To highlight uncertainties in our analysis, throughout this paper we make use of both multi-model means and ranges (minimum–maximum) when reporting our results. Given that our estimates are unable to capture all possible investment outcomes for a particular policy scenario, these means and ranges should be interpreted as being consistent with a 'middle-of-the-road' storyline for population, socioeconomic development and technology optimism, all under varying levels of climate policy stringency (see below). Key socioeconomic and policy assumptions are harmonized in this study.

To put the multi-model results for energy investment needs into the context of investment needs for achieving or making progress on other sustainability objectives by 2030, namely the United Nations' SDGs, we carry out additional calculations using external models and methodologies. We focus in particular on energy access[24] (SDG7, Target 7.1), food security (2.1), air pollution[25] (3.9), quality education[26] (4.1), and clean water and sanitation[27,28] (6.1, 6.2, 6.3, 6.4). The advantage of using investments to compare across sustainability dimensions is that their disparate objectives are otherwise difficult, if not impossible, to relate.

Scenarios depicted

Four scenarios are explored in this paper (see Methods). 'Current policies' (CPol) serves as each model's reference case (or baseline). The scenario takes into account those energy- and climate-related policies that were already 'on the books' of countries as of 2015; in other words, it reflects the early bridges to the low-carbon economy that policymakers have already implemented in various parts of the world. In addition to the reference case, the modelling teams each ran three scenarios in which policies for low-carbon energy, energy efficiency and climate change mitigation are tightened: 'Nationally Determined Contributions' (NDC), 'Well Below 2 Degrees' (2C) and 'Toward 1.5 Degrees' (1.5C). Population and socioeconomic development assumptions across all scenarios are in line with the 'middle-of-the-road' storyline of the Shared Socioeconomic Pathways (SSP2)[14,29].

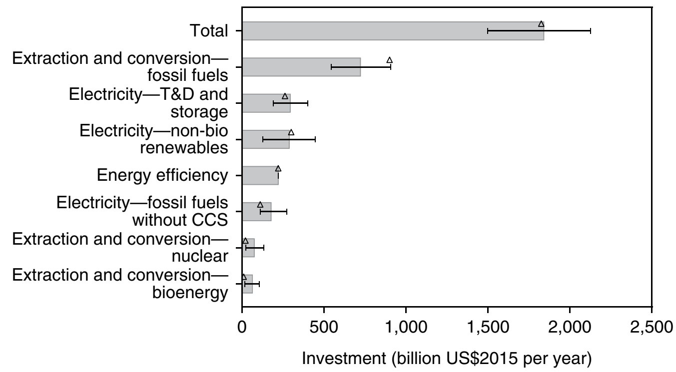

Fig. 1 | Global energy investments by category in 2015. Triangles represent IEA estimates and are taken from ref. [30]. Bar values represent multi-model means; bar whiskers give the minimum–maximum ranges across the models. Base-year 2015 estimates for energy efficiency investments are available only from IEA[30], not from the models, given differing calculation methodologies. IEA values for efficiency investments are thus assumed for all the models in 2015. T&D, transmission and distribution; CCS, carbon capture and storage.

Base-year energy investments and their uncertainties

Total investments in the global energy system were approximately US$1,800 billion per year in 2015 (values in 2015 US$; excluding fuel and operations and maintenance costs), according to the International Energy Agency (IEA)[30,31]. This amounted to over 2% of global gross domestic product (GDP) and 10% of gross capital formation in that year. The vast majority of these investments (approximately US$1,600 billion per year) were made to add or replace equipment on the supply side of the energy system, while a further US$220 billion per year was invested in energy efficiency across the end-use sectors (buildings, transport and industry). A breakdown of 2015 investments among the supply-side sectors is illustrated in Fig. 1. (Supplementary Note 1 provides additional details, including an elaboration of the uncertainties surrounding historical estimates of energy investments.) The IEA values shown here are calculated based on similar methodologies to this study's six models; we therefore use estimates from the models to cross-check the IEA (see uncertainty bars in Fig. 1). The latter appears to be well within the bounds of uncertainty for total investments, yet for several of the sub-categories there are notable differences. For instance, the IEA generally estimates higher investments in fossil fuel extraction and conversion than the models. This is due to a mix of factors, including, among others, uncertainties surrounding exactly when investments responsible for new capacity additions are made (important for oil refinery 'creep' for instance), the varied treatment of expenditures for oil and natural gas exploration across models, and the fact that 2015 is actually a 'constrained projection year' in some frameworks.

Future energy investment needs across the scenarios

A growing population with increasing demand for energy implies larger overall levels of global energy investment going forward. And in fact this is what is exhibited by nearly all of the models' scenarios: total average annual investments over the 2016–2050 period (undiscounted) are higher than in 2015 (Fig. 2). Investment estimates by IEA and the International Renewable Energy Agency (IRENA) for scenarios analogous to this study's NDC and 2C cases exhibit the same dynamics[6]. Model differences can be explained by endogenously determined technology choices and varying representations

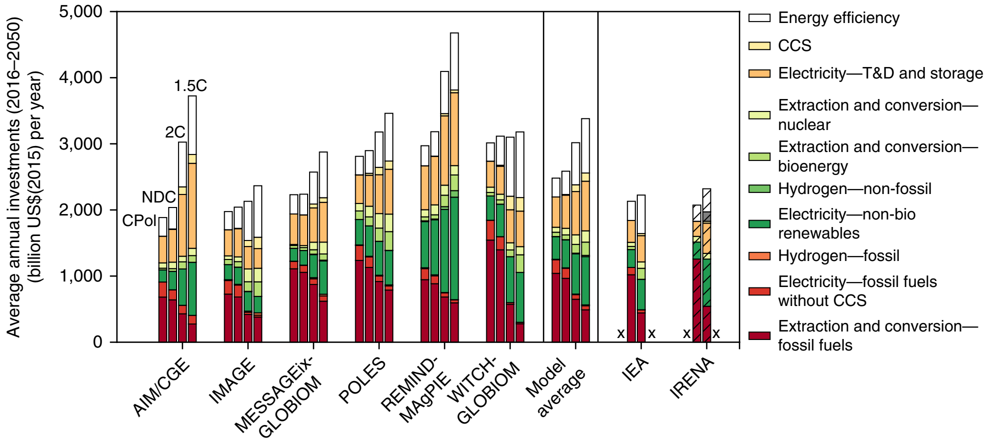

Fig. 2 | Projected global-average annual energy investments by category from 2016 to 2050 according to different models. Values are calculated by cumulating the models' undiscounted investment estimates and averaging them over the full 2016–2050 period. The source of IEA and IRENA supply-side investment numbers is ref. [6]. The lack of complete data in the IRENA case does not allow for a full breakdown of results into the investment categories used here (hence the cross-hatching). For each model framework, the results are shown in the order (left to right) CPol, NDC, 2C, 1.5C. Analogous versions of the CPol and 1.5C scenarios are not available from IEA and IRENA (hence the x markers). Energy efficiency investments for IEA and IRENA are calculated by the authors using the same methodology as for the models, except that the IEA and IRENA baselines are taken as their respective NDC analogous scenarios; this leads to a slight underestimate of the IEA and IRENA efficiency investments.

for how unit-level capital costs evolve over time. (For underlying yearly, regional and sectoral investment data underlying the figures and tables in this paper, please see Supplementary Data 1.) Note that here we focus on the investment period to 2050, even though each of the IAMs runs to 2100 in its scenarios. Moreover, given the nature of these models, we expressly address the question of "Where are the investment needs?", not "Who pays for them?"

The impact of future energy and climate policies on total energy investments depends on the nature and extent of those policies. Meeting countries' most recent pledges (NDC scenario) would probably necessitate only a marginal increase in total future investments, relative to a continuation of current trends (CPol). In contrast, more aggressive policies promoting an energy system transformation (2C and 1.5C pathways) would, according to most models, require a marked increase (Fig. 2). IEA's and IRENA's estimates for the total investment needs in a 2C-consistent scenario are found to be toward the lower end of the range of the models. One of the principal reasons that supply-side investments do not increase more than one might expect in these pathways, or that some models project them to decline, is the rapid acceleration in demand-side energy efficiency and conservation investments foreseen, relative to the CPol and NDC cases. (There is no generally accepted methodology for calculating such investments; see Methods for a description of ours.) As a share of global GDP, the total energy investments projected by the models do not rise significantly from today in any of the scenarios, hovering just over 2% (model range: 1.5–2.6%) in CPol and NDC and growing to 2.5% (1.6–3.4%) and 2.8% (1.8–3.9%) in the 2C and 1.5C pathways, respectively. Regional results can, however, be quite different.

Moreover, we note that the models exhibiting the largest increase in supply-side investments in the 2C and 1.5C pathways (AIM/CGE and REMIND-MAgPIE) are also the ones with the most rapid upscaling of renewable electricity capacity, principally solar photovoltaic and wind. This, by extension, has implications for increased electricity transmission and distribution (T&D) and storage investments. In Supplementary Notes 2, 6 and 7 and Supplementary Figs. 1 and 2, we show and explain some of these trends, including relating the models' assumed capital costs for different electricity generation technologies to the deployment levels and investment magnitudes that are seen.

A shifting energy investment landscape

Of perhaps greater importance to investors than total capital flows is how the energy investment portfolio might be expected to evolve over time under varying assumptions for future energy and climate policies. That portfolio continues to look very similar to today in the CPol baseline, and to a large extent also in the NDC case (Fig. 2 and Table 1). In contrast, the transformational 2C and 1.5C pathways exhibit a much more pronounced shift from fossil (especially coal) (Fig. 3; see Supplementary Note 3 for further discussion). Additionally, several models provide evidence of greatly increased investment requirements for electricity T&D and storage, driven by greater demands for delivering electricity to the end-use sectors (buildings, industry and transport) and by the intermittency of variable renewable electricity sources.

Declines in unabated (that is, not equipped with carbon capture and storage, CCS) coal, gas and oil investments imply increases in renewables, nuclear and demand-side energy efficiency (and to a lesser extent fossils equipped with CCS; see Fig. 3), especially in the more transformative 2C and 1.5C pathways. The models provide evidence of an inverse relationship between average annual low-carbon energy investments over the near and medium terms (to 2030 and 2050, respectively) and cumulative carbon emissions over the long term (to 2100; see Fig. 4): in other words, as investments in low-carbon energy and energy efficiency are progressively scaled up, cumulative CO_2 emissions can be expected to consistently decline. Though absolute investment numbers may vary to some extent, the inverse investment–emissions relationship is common across nearly all models for the two different time periods, even if the slopes vary. The IMAGE model exhibits unique behaviour over the near term (Fig. 4a), with the NDC scenario showing greater low-carbon energy investment requirements than the 2C pathway. This results from explicitly modelled renewable energy capacity targets that derive from the NDC pledges but are not modelled in the other scenarios, and lower demands for electricity generation (and thus capacity additions) over the 2020–2030 period in the more stringent 2C (and 1.5C), owing to the substantial carbon price. Though the underlying dynamics of other models may be similar, the inter-temporal effects in IMAGE are far stronger.

Table 1 | Projected global and regional average annual energy investments by category from 2016 to 2050

		Five regions (billion US$ per year)					Major economies (billion US$ per year)			
	World	ASIA	LAM	MAF	OECD90	REF	China	India	Europe	USA
CPol										
Extraction and conversion—fossil fuels	1,041 (682 to 1,544)	230 (101 to 410)	121 (51 to 215)	320 (119 to 459)	239 (68 to 388)	113 (20 to 190)	138 (70 to 223)	37 (17 to 86)	66 (26 to 138)	120 (45 to 165)
Electricity—fossil fuels without CCS	206 (113 to 300)	94 (46 to 132)	9 (1 to 17)	28 (14 to 51)	60 (34 to 126)	15 (5 to 37)	50 (16 to 80)	26 (8 to 34)	12 (7 to 19)	29 (16 to 52)
Hydrogen—fossil	6 (0 to 13)	2 (0 to 6)	0 (0 to 2)	0 (0 to 1)	4 (0 to 11)	0 (0 to 0)	1 (0 to 3)	0 (0 to 2)	2 (0 to 5)	2 (0 to 4)
Electricity—non-biomass renewables	343 (183 to 698)	145 (74 to 329)	32 (12 to 69)	27 (12 to 71)	126 (53 to 219)	8 (4 to 12)	86 (37 to 173)	33 (8 to 83)	60 (26 to 98)	40 (20 to 71)
Hydrogen—non-fossil	2 (0 to 11)	1 (0 to 5)	0 (0 to 1)	0 (0 to 2)	1 (0 to 3)	0 (0 to 0)	0 (0 to 2)	0 (0 to 1)	0 (0 to 1)	0 (0 to 1)
Extraction and conversion—bioenergy	64 (26 to 129)	19 (4 to 41)	8 (3 to 17)	12 (1 to 28)	26 (9 to 56)	1 (0 to 3)	4 (1 to 13)	4 (1 to 10)	14 (2 to 25)	10 (1 to 18)
Extraction and conversion—nuclear	75 (16 to 113)	34 (5 to 82)	2 (0 to 5)	4 (0 to 11)	24 (1 to 45)	6 (0 to 22)	21 (4 to 54)	6 (0 to 11)	8 (0 to 14)	9 (0 to 21)
Electricity—T&D and storage	458 (393 to 664)	188 (135 to 329)	32 (20 to 51)	54 (28 to 92)	157 (115 to 180)	27 (13 to 40)	101 (70 to 169)	46 (15 to 83)	59 (42 to 73)	63 (46 to 85)
CCS	0 (0 to 3)	0 (0 to 0)	0 (0 to 0)	0 (0 to 0)	0 (0 to 3)	0 (0 to 0)	0 (0 to 0)	0 (0 to 0)	0 (0 to 2)	0 (0 to 0)
Demand-side energy efficiency	285 (274 to 303)	0 (0 to 0)	0 (0 to 0)	0 (0 to 0)	0 (0 to 0)	0 (0 to 0)	0 (0 to 0)	0 (0 to 0)	0 (0 to 0)	0 (0 to 0)
Total (supply + demand)	2,481 (1,885 to 3,014)	713 (383 to 1276)	204 (105 to 284)	445 (323 to 588)	636 (447 to 823)	171 (55 to 292)	402 (251 to 670)	153 (51 to 299)	221 (131 to 301)	273 (217 to 318)
NDC										
Extraction and conversion—fossil fuels	965 (640 to 1,397)	214 (132 to 379)	109 (42 to 193)	305 (131 to 429)	212 (31 to 339)	110 (23 to 190)	127 (98 to 212)	38 (20 to 93)	60 (24 to 123)	105 (21 to 143)
Electricity—fossil fuels without CCS	153 (107 to 199)	67 (38 to 100)	6 (0 to 13)	26 (14 to 46)	40 (24 to 69)	14 (5 to 38)	31 (17 to 50)	24 (7 to 35)	9 (5 to 15)	17 (6 to 27)
Hydrogen—fossil	6 (0 to 15)	2 (0 to 7)	1 (0 to 2)	0 (0 to 1)	3 (0 to 9)	0 (0 to 0)	1 (0 to 3)	0 (0 to 2)	2 (0 to 4)	2 (0 to 4)
Electricity—non-biomass renewables	424 (221 to 833)	181 (86 to 397)	35 (14 to 77)	30 (12 to 81)	162 (66 to 264)	10 (4 to 15)	111 (43 to 199)	38 (9 to 99)	69 (27 to 107)	59 (32 to 100)
Hydrogen—non-fossil	2 (0 to 11)	1 (0 to 5)	0 (0 to 1)	0 (0 to 2)	1 (0 to 3)	0 (0 to 0)	0 (0 to 2)	0 (0 to 1)	0 (0 to 1)	0 (0 to 1)
Extraction and conversion—bioenergy	72 (42 to 136)	21 (5 to 45)	10 (4 to 18)	13 (2 to 29)	29 (10 to 59)	2 (0 to 3)	5 (1 to 17)	5 (1 to 10)	14 (3 to 25)	11 (2 to 19)
Extraction and conversion—nuclear	99 (30 to 161)	48 (8 to 106)	3 (0 to 8)	4 (0 to 12)	32 (5 to 60)	6 (0 to 20)	28 (4 to 68)	6 (0 to 11)	10 (0 to 20)	14 (1 to 29)
Electricity—T&D and storage	501 (423 to 734)	202 (142 to 359)	34 (21 to 57)	56 (30 to 98)	181 (124 to 252)	28 (13 to 44)	109 (82 to 181)	48 (17 to 89)	63 (46 to 79)	76 (53 to 104)
CCS	11 (3 to 30)	4 (0 to 12)	1 (0 to 2)	0 (0 to 1)	5 (1 to 17)	0 (0 to 1)	3 (0 to 10)	0 (0 to 0)	2 (0 to 8)	2 (0 to 6)
Demand-side energy efficiency	352 (313 to 440)	26 (−4 to 71)	8 (1 to 21)	3 (−3 to 6)	31 (13 to 66)	0 (−5 to 4)	18 (−2 to 69)	0 (−1 to 4)	6 (3 to 11)	16 (7 to 36)
Total (supply + demand)	2,586 (2,037 to 3,183)	766 (426 to 1378)	207 (103 to 281)	438 (339 to 568)	695 (466 to 894)	169 (60 to 287)	434 (266 to 705)	160 (58 to 328)	236 (138 to 327)	301 (238 to 346)
2C										
Extraction and conversion—fossil fuels	649 (419 to 917)	137 (40 to 272)	70 (22 to 133)	191 (22 to 305)	150 (29 to 243)	71 (8 to 158)	82 (25 to 149)	22 (9 to 57)	43 (18 to 79)	81 (21 to 130)
Electricity—fossil fuels without CCS	70 (26 to 128)	26 (6 to 44)	2 (0 to 4)	9 (3 to 13)	29 (6 to 77)	4 (2 to 13)	14 (2 to 26)	5 (1 to 11)	6 (2 to 13)	12 (1 to 25)

Continued

Table 1 | Projected global and regional average annual energy investments by category from 2016 to 2050 (continued)

		Five regions (billion US$ per year)					Major economies (billion US$ per year)			
	World	ASIA	LAM	MAF	OECD90	REF	China	India	Europe	USA
Hydrogen—fossil	8 (0 to 17)	3 (0 to 8)	0 (0 to 1)	1 (0 to 2)	4 (0 to 8)	1 (0 to 2)	1 (0 to 4)	1 (0 to 3)	1 (0 to 3)	2 (0 to 4)
Electricity—non-biomass renewables	609 (295 to 1,255)	278 (97 to 626)	46 (30 to 88)	59 (27 to 156)	200 (87 to 354)	21 (5 to 41)	166 (45 to 306)	67 (22 to 174)	75 (38 to 129)	79 (41 to 142)
Hydrogen—non-fossil	9 (0 to 42)	4 (0 to 17)	1 (0 to 6)	1 (0 to 7)	2 (0 to 11)	0 (0 to 0)	3 (0 to 11)	1 (0 to 3)	1 (0 to 4)	1 (0 to 6)
Extraction and conversion—bioenergy	132 (67 to 200)	50 (17 to 103)	22 (6 to 44)	44 (8 to 158)	48 (27 to 78)	4 (1 to 7)	9 (3 to 20)	13 (3 to 27)	18 (6 to 30)	23 (7 to 40)
Extraction and conversion—nuclear	145 (84 to 220)	81 (21 to 141)	4 (0 to 11)	8 (0 to 20)	34 (18 to 61)	9 (2 to 30)	46 (5 to 95)	19 (4 to 50)	9 (5 to 12)	15 (2 to 29)
Electricity—T&D and storage	654 (338 to 1,048)	272 (125 to 523)	44 (31 to 76)	75 (36 to 152)	228 (136 to 355)	34 (10 to 80)	156 (45 to 259)	63 (40 to 138)	71 (46 to 98)	100 (68 to 156)
CCS	102 (34 to 204)	35 (8 to 76)	5 (3 to 10)	16 (12 to 21)	38 (10 to 88)	10 (1 to 21)	18 (3 to 57)	9 (3 to 21)	11 (1 to 23)	16 (4 to 40)
Demand-side energy efficiency	636 (483 to 893)	157 (79 to 263)	29 (20 to 44)	75 (48 to 91)	94 (50 to 219)	35 (13 to 74)	90 (44 to 170)	35 (16 to 71)	27 (9 to 67)	40 (16 to 96)
Total (supply + demand)	3,017 (2,130 to 4,094)	1,043 (680 to 1,829)	223 (161 to 307)	479 (291 to 571)	827 (562 to 1004)	188 (78 to 250)	583 (347 to 922)	235 (120 to 453)	263 (164 to 359)	369 (286 to 415)
1.5C										
Extraction and conversion—fossil fuels	490 (275 to 788)	110 (26 to 236)	51 (10 to 123)	129 (19 to 211)	119 (19 to 228)	53 (7 to 108)	63 (18 to 127)	19 (5 to 49)	33 (19 to 71)	66 (13 to 124)
Electricity—fossil fuels without CCS	62 (22 to 130)	21 (4 to 35)	2 (0 to 3)	8 (2 to 12)	28 (6 to 87)	3 (1 to 10)	12 (2 to 23)	4 (1 to 7)	6 (2 to 14)	11 (2 to 25)
Hydrogen—fossil	13 (0 to 35)	4 (0 to 10)	1 (0 to 2)	1 (0 to 3)	6 (0 to 20)	1 (0 to 4)	2 (0 to 5)	1 (0 to 3)	2 (0 to 5)	4 (0 to 13)
Electricity—non-biomass renewables	730 (248 to 1,550)	327 (72 to 768)	51 (24 to 99)	79 (20 to 214)	238 (128 to 433)	30 (5 to 60)	194 (35 to 370)	79 (17 to 216)	86 (46 to 152)	96 (61 to 180)
Hydrogen—non-fossil	19 (0 to 99)	8 (0 to 39)	2 (0 to 13)	3 (0 to 15)	6 (0 to 31)	0 (0 to 1)	4 (0 to 21)	2 (0 to 6)	3 (0 to 11)	2 (0 to 13)
Extraction and conversion—bioenergy	200 (94 to 284)	101 (24 to 323)	25 (17 to 49)	99 (11 to 453)	68 (34 to 107)	10 (2 to 32)	16 (7 to 23)	21 (3 to 49)	24 (12 to 37)	28 (14 to 69)
Extraction and conversion—nuclear	171 (110 to 265)	91 (29 to 164)	5 (1 to 17)	10 (0 to 25)	44 (23 to 67)	10 (3 to 30)	52 (5 to 122)	20 (5 to 49)	10 (8 to 13)	20 (3 to 30)
Electricity—T&D and storage	750 (298 to 1,285)	312 (102 to 548)	48 (25 to 77)	88 (30 to 164)	262 (131 to 477)	39 (9 to 100)	182 (36 to 325)	72 (34 to 141)	76 (45 to 103)	112 (66 to 198)
CCS	124 (41 to 205)	41 (9 to 68)	9 (3 to 12)	16 (4 to 23)	49 (15 to 96)	9 (1 to 19)	19 (4 to 45)	11 (3 to 23)	14 (2 to 24)	22 (9 to 47)
Demand-side energy efficiency	822 (691 to 992)	241 (174 to 318)	36 (17 to 53)	96 (73 to 138)	163 (100 to 308)	50 (19 to 82)	133 (105 to 196)	60 (33 to 109)	48 (20 to 102)	70 (43 to 125)
Total (supply + demand)	3,381 (2,366 to 4,677)	1,256 (837 to 2,084)	230 (162 to 350)	529 (278 to 750)	985 (697 to 1,196)	206 (89 to 289)	677 (364 to 1,034)	288 (190 to 526)	302 (196 to 407)	431 (338 to 507)

Multi-model means are provided along with minimum–maximum ranges across models in parentheses. Values are calculated by cumulating the models' undiscounted investment estimates and averaging them over the full 2016–2050 period. Energy efficiency investments listed for the regions (other than 'World') are known to be underestimates, as they include only the 'supply-side offset' component of the calculation, whereas the 'World' energy efficiency investments include both this and the 'base-year efficiency' component. The latter is available as an estimate by IEA only at the global level (see Methods for details), hence the varying treatment. See Supplementary Methods for regional definitions.

An inflection point for the investment–emissions relationship appears to be somewhere around 1,000 billion tonnes (Gt) of CO_2, which is the level targeted by the models in the 2C scenario. After that cumulative emissions threshold has been reached, nearly all of the models show a kink in the curves, such that an additional reduction of a relatively small amount of CO_2 requires a disproportionate increase in investments. Put differently, the incremental low-carbon energy and efficiency investments needed to go beyond the achievement of the 2 °C target and push closer to 1.5 °C could require a step-change in terms of capital invested per tonne of CO_2 avoided, relative to the energy system transformation efforts that have occurred up to that point (from CPol to NDC and then on to 2C). Driving this step-change is greater reliance on, and a far accelerated deployment of, more capital-intensive renewable energy, nuclear power and electricity T&D and storage technologies. At the same time, less capital-intensive fossil energy extraction and conversion technologies see an even faster phase-out in the 1.5C case than in 2C.

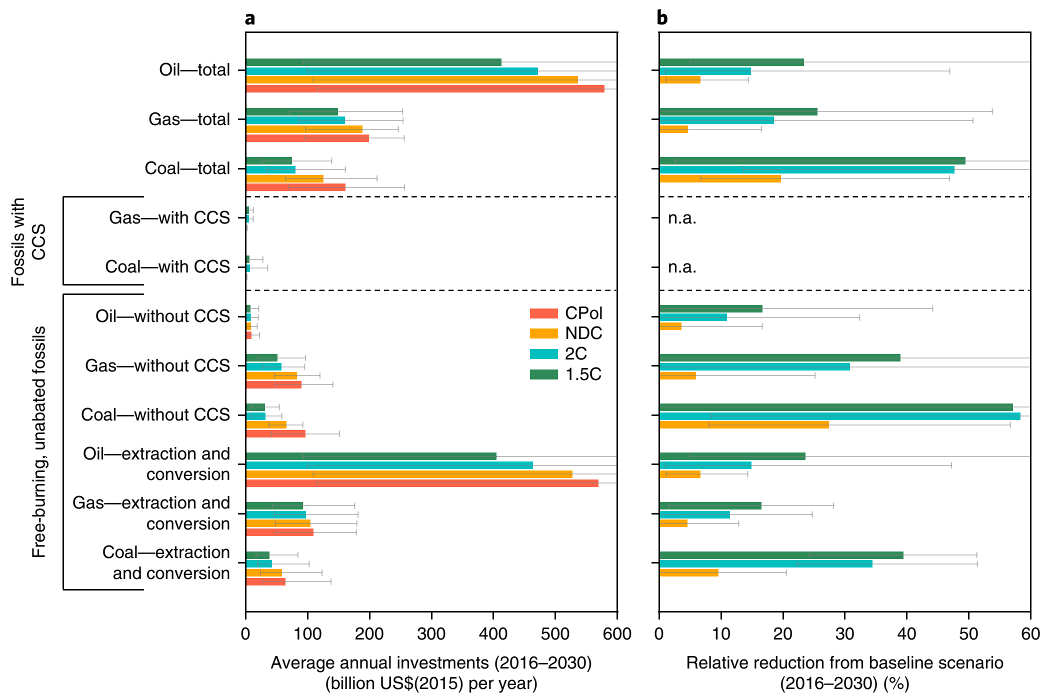

Fig. 3 | Projected global-average annual investments in fossil fuel supply and changes by category from 2016 to 2030. a, Average annual investments. **b**, Relative reduction in investments from the CPol baseline scenario. Values are calculated by cumulating the models' undiscounted investment estimates and averaging them over the full 2016–2030 period. Bar values represent multi-model means; bar whiskers give the minimum–maximum ranges across the models. Relative changes cannot be calculated for natural gas and coal electricity generation with CCS because the values in the CPol baseline are zero (thus n.a. = not applicable).

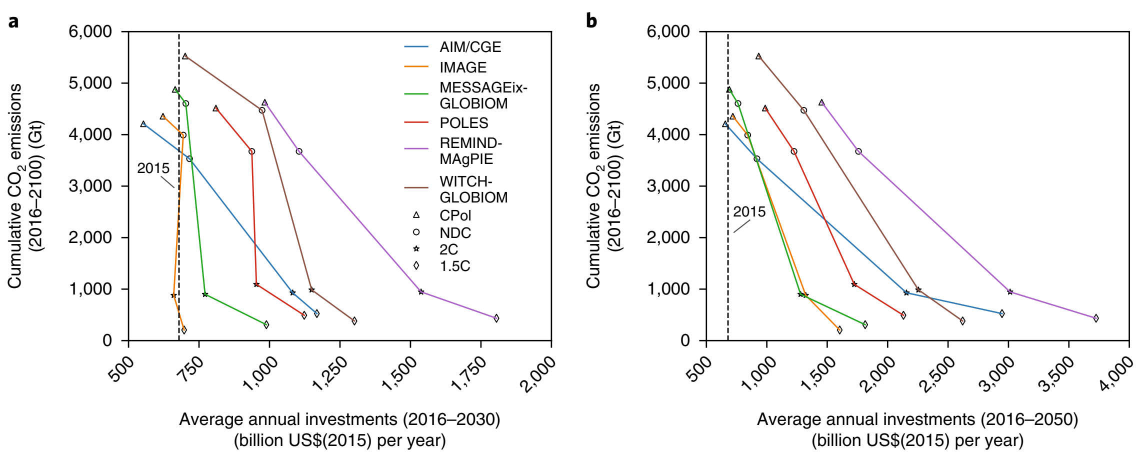

Fig. 4 | Projected global average annual low-carbon energy investments and cumulative carbon emissions. a, Values for 2016–2030. **b**, Values for 2016–2050. Values are calculated by cumulating the models' undiscounted investment estimates and averaging them over the full time period. Investment estimates include two aspects: first, supply-side investments in renewable electricity and hydrogen production, bioenergy extraction and conversion, uranium mining and nuclear power, fossil energy equipped with CCS, and the portion of electricity T&D and storage investments that can be attributed to low-carbon electricity generation; and second, demand-side investments in energy efficiency and conservation. Comparable value for 2015 denoted by vertical line (about US$680 billion per year). Cumulative carbon emissions include FF&I CO_2 between 2016 and 2100.

Low-carbon energy investment shares

Professionals engaged in the business of 'green financing' (that is, those responsible for mobilizing capital to launch low-carbon energy and efficiency projects) should be aware of the stepped-up investment effort required to lay the groundwork for a future consistent with 2 °C, and even more so 1.5 °C. The NDC pledges made by countries over the past 2 years are certainly a move in the right direction, but they are clearly insufficient for incentivizing the deeper, structural changes in the energy investment portfolio required for reaching the lower temperature targets of the Paris Agreement[32] (see previous sections). By our calculations, full implementation of the NDCs by countries throughout the world would require that low-carbon supply-side investment shares grow over the next decades to levels higher than today, yet remaining below 50% up to mid-century (Fig. 5; multi-model means shown; individual model results vary as exhibited in Supplementary Fig. 3).

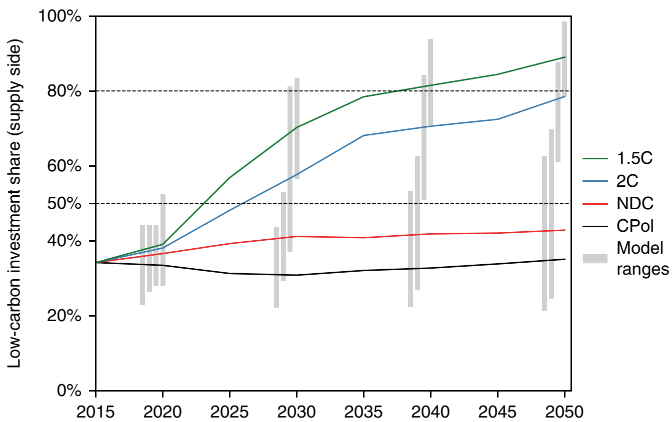

Fig. 5 | Projected global-average annual low-carbon energy supply-side investments as a share of total supply-side investments. Solid lines represent multi-model means; floating bars give the minimum–maximum ranges across the models. Estimates shown here include supply-side investments in renewable electricity and hydrogen production, bioenergy extraction and conversion, uranium mining and nuclear power, fossil energy equipped with CCS, and the portion of electricity T&D and storage investments that can be attributed to low-carbon electricity generation. Dashed lines denote important thresholds for low-carbon energy investment.

In other words, total low-carbon investments would continue to remain smaller than fossil investments for the foreseeable future. The 2C and 1.5C pathways offer a marked departure from these trends, with low-carbon supply-side investments already overtaking fossil investments by around 2025 or before. Then, some years later low-carbon supply-side investments would need to reach and/or surpass the 80% threshold, a mark that is projected to occur close to mid-century in the 2C pathway and much sooner (around 2035) in the 1.5C case. Unabated fossil investments (without CCS) never drop fully to 0% during the first half of the century, even in the 1.5C pathway—a finding of particular note considering that many scenarios point to the need for fossil fuel and industrial (FF&I) CO_2 emissions to cross the threshold of zero $GtCO_2$ per year during the 2050–2065 timeframe, consistent with the emissions trends implied by Article 4 of the Paris Agreement[9].

Low-carbon energy investment gaps

Another way to illustrate the upscaling requirements for low-carbon energy and energy efficiency in the NDC-achieving future and transformational 2C and 1.5C pathways is to assess their 'investment gaps'—that is, the total incremental investment needs for these cleaner options beyond those likely to happen anyway based on a continuation of today's trends, assuming no future tightening of energy and climate policies worldwide, as is envisaged in the CPol reference case. Gap metrics of this type offer an alternative to the commonly used 'emissions gap' concept[33]. Because investments represent a lever that policymakers and investors can use to affect emissions, quantifying such gaps is important. As presented in Supplementary Table 1, achieving the current NDC pledges of countries implies that a global near-term (to 2030) low-carbon energy and energy efficiency investment gap (LCEI-Gap) of approximately US$130 billion per year (model mean), accounting for around 7% of all energy investments worldwide in 2015, needs to be filled over the next several years. If the aim is instead to keep global temperatures below 2 °C or 1.5 °C in the long term, then this near-term LCEI-Gap quickly escalates to US$300 billion or US$460 billion per year, respectively (or 17–26% of 2015 investments). Looking toward mid-century, the global LCEI-Gap reaches far higher levels in each scenario, with the relative upscaling of investment effort being particularly strong in the 2 °C and 1.5 °C futures.

From a regional and national perspective, the largest LCEI-Gaps are identified for the countries of Asia and those comprising the OECD (Organisation for Economic Co-operation and Development), specifically China, India, Europe and the United States. That said, it is noteworthy that the near-term LCEI-Gaps for the United States, Europe and Latin America are only marginally greater in the 2C pathway than in the NDC case, indicating that the level of low-carbon energy and energy efficiency investment needed to fulfil the Nationally Determined Contributions of those countries would already put them on track for achieving the 2 °C target in the longer term. (That is not to say, however, that the portfolio of projects invested in would look the same in these two diverging futures.) The 1.5C pathway, in contrast, demands a considerably stepped-up investment effort in all regions and countries: put differently, the level of low-carbon investment required for achieving the NDCs is insufficient for setting the world on course for achieving the 1.5 °C target. This is even truer when looking beyond 2030 toward mid-century. Furthermore, we note that though the LCEI-Gap for some regions or countries may seem to be fairly low in absolute dollar terms, it could be large in relative terms—that is, as a share of a particular economy's future investment needs in the CPol baseline. India is a prime example.

Energy sector investments and financing needs for other SDGs

The 2C and 1.5C transformation pathways depicted by the models are in all cases consistent with two of the three targets underlying SDG7 (focused on energy), namely a substantial increase in the share of renewables (Target 7.2) and a doubling of the rate of energy efficiency improvement (7.3), both by 2030[10]. They are also in keeping with SDG13 (Climate action), which refers to the Paris Agreement's aim of limiting global temperature increase to 'well below 2 degrees' during the twenty-first century. Thus, the energy investment needs presented above for the transformational pathways reflect the achievement of critical parts of SDG7 and SDG13.

Other questions worth posing include how the scale of these energy investments relates to those for making progress on other SDG targets, and whether the investment needs for these other SDGs might be affected by the energy and climate policies required for achieving SDG7 and SDG13. Figure 6 summarizes our answers to these questions. First, we see that the total capital needs consistent with an energy system that is fundamentally transformed (or at least on that path by 2030) are an order of magnitude larger than the needs quantified here for most other SDG targets: a couple of trillion dollars versus a few hundred billion (or less). The values presented reflect, in most instances, total sectoral investments in a world in which the various SDG targets are met, as opposed to incremental investments relative to today or to some reference case. (Food security is an exception in that it represents the policy costs to compensate the poor for any increases in food costs beyond the CPol baseline.) Second, our calculations indicate that the financial requirements for achieving or making substantial progress on the SDG7 energy access and SDG2 food security targets would necessitate greater financial flows in a world in which energy and climate policies are tightened considerably, whereas those needs would be roughly the same or lower (thus saving costs) in the case of the SDG3 air pollution and SDG6 clean water and sanitation targets. With respect to the former (SDG7 energy access and SDG2 food security), this is because the higher energy prices brought about by an energy system transformation (and the accompanying carbon pricing, whether explicit or implicit) would have feedbacks on other sectors of the economy; hence, policies (such as subsidies, fuel price support or food aid) would be needed to protect certain consumers from being worse off than otherwise. For air pollution (SDG3), this is because the replacement of fossil fuel combustion activities

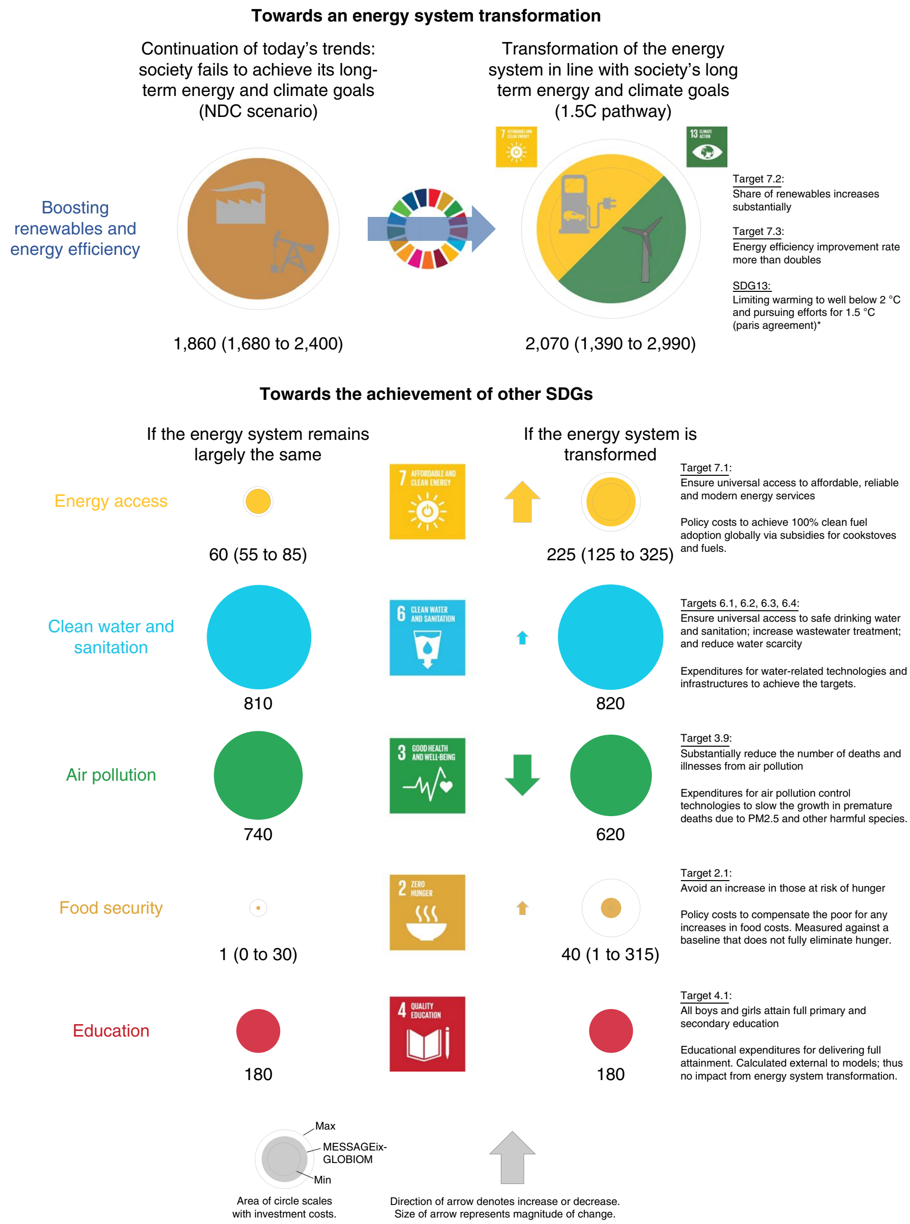

Fig. 6 | Projected investment needs, to 2030, for achieving or making progress on a subset of SDG targets relevant for energy systems planning. Values in top section of diagram are derived directly from the global IAM energy investment results discussed previously. Values in bottom section ('other' SDGs) are calculated separately via diverse approaches. The starting point for analyses of the latter is that their targets must be achieved by 2030, or substantial progress must be made on them, whether the energy system is transformed (right side) or not (left side). We then assess the impacts that an energy transformation would have on these other SDG investment needs. Units: global average annual investments (billion US$ (2015 values) per year). All investment values are undiscounted. Timeframe: 2016 to 2030. MESSAGEix-GLOBIOM values are enumerated below circles; model ranges (if available) in parentheses. PM2.5: particulate matter under 2.5 µm diameter. *Avoided damages due to climate change (mainly for health, hunger and water) are not considered here. SDG icons and colour wheel are the property of the United Nations.

with clean and efficient alternatives (such as solar and wind power, or electric vehicles) obviates the need for investing in expensive technologies for air pollution control. Water infrastructure (SDG6) costs are found to be little affected by an energy system transformation, at least when focusing on the industry and households/municipal sectors, as we do.

Conclusions

This paper summarizes findings and insights from a systematic attempt to evaluate future energy-related investment needs in multiple, plausible scenarios for climate change mitigation, from a continuation of today's trends to achieving the 2 °C and 1.5 °C targets, and to relate those investments to the financial requirements for making major progress on several other SDG targets. The entire exercise is carried out with a multi-model perspective, thereby lending some robustness to the insights derived. Nevertheless, our analysis points to clear uncertainties in the energy investment landscape going forward. Importantly, underpinning all of the models' scenarios are population and socioeconomic development assumptions in line with the 'middle-of-the-road' storyline of the Shared Socioeconomic Pathways, SSP2. The fact that there is little variance along this dimension is one potential caveat to our work, though in practice we find that alternate assumptions do not have much impact on the insights that we derive, at least for one model. In other words, the multi-model means and ranges we report are not expected to differ greatly in those alternative cases. The ranges would widen, but not much, and one could expect SSP3 investment needs to be greater than those for SSP1 and SSP2 (see Supplementary Note 4).

From where exactly these investment dollars are summoned is outside the scope of our study and for the most part beyond the capability of the models used. Funding for individual projects could come from all manner of sources: businesses, governments, households, banks (private, state-owned, development), multilateral climate finance institutions or other means. And this funding could be sourced domestically or be provided by foreign entities. The ultimate funding portfolio, from the macro- to micro-scale, will be determined by some mixture of the world's financial system, countries' fiscal and monetary policies, and foreign development aid institutions, among others.

The good news, for backers of sustainable energy at least, is that the world's largest economies have already agreed that spurring low-carbon energy investments should be placed high on their collective priority list. One of the stated action items from the recent G20 Hamburg Climate and Energy Action Plan for Growth is "to create an enabling environment that is conducive to making public and private investments consistent with the goals of the Paris Agreement as well as with the national sustainable development priorities and economic growth"[8] (see also Article 2.1c of the Paris Agreement[9]). In support of this effort, G20 countries have re-emphasized the previously agreed commitment of wealthy countries to jointly mobilize US$100 billion per year (during the period 2020–2025) for mitigation actions in developing countries. According to our analysis, this level of support would go a long way towards closing—if not fully covering—the low-carbon energy and energy efficiency investment gap faced by developing countries as they work to fulfil their NDC commitments. Considerably more capital would have to be mobilized, however, to close the investment gap for a 2 °C- or 1.5 °C-consistent future.

Methods

Overview of the policy scenarios run by the models. The following paragraphs provide additional information about the scenarios of this study on top of what is written in the main manuscript. For more details, see the discussion in the Supplementary Methods as well as Supplementary Data 2 and Supplementary Data 3.

Current Policies (CPol) considers high-impact energy- and climate-related policies implemented in G20 countries as of 2015. These policies are included up to 2030; after this, equivalent effort, in terms of carbon emissions development, is assumed. Examples of policies include greenhouse gas (GHG) emissions reduction targets, GHG intensity reduction targets, and nuclear power and renewable energy targets.

Nationally Determined Contributions (NDC) assumes implementation of all countries' NDCs (conditional commitments) by 2030, the target year of most. Post-2030, an assumption of equivalent effort, in terms of carbon emissions development, is assumed (that is, no intensification). The scenario thus represents a continuation of fragmented and highly diversified climate action worldwide.

Well Below 2 Degrees (2C) aims to hold the maximum increase in global average temperatures to 2.0 °C (above the pre-industrial level) over the course of the twenty-first century with >66% likelihood. Stylized, globally and sectorally comprehensive climate mitigation policies, in the form of carbon budgets, are included immediately after 2020 so as to limit CO_2 emissions from fossil fuel and industrial operations to approximately 1,000 $GtCO_2$ over the 2011–2100 timeframe (actual model results vary). Emissions mitigation (after 2020) occurs where and when it is most cost-effective; no burden-sharing regimes are in place. The pathway of the 'Current Policies' scenario is followed up through 2020.

Toward 1.5 Degrees (1.5C) aims to limit the increase in global average temperatures to 1.5 °C (above the pre-industrial level) in 2100 with >50% likelihood. Stylized, globally and sectorally comprehensive climate mitigation policies, in the form of carbon budgets, are included immediately after 2020 so as to limit CO_2 emissions from fossil fuel and industrial operations to approximately 400 $GtCO_2$ over the 2011–2100 timeframe (actual model results vary). Emissions mitigation (after 2020) occurs where and when it is most cost-effective; no burden-sharing regimes are in place. The pathway of the 'Current Policies' scenario is followed up through 2020.

Technical documentation for the modelling frameworks. Documentation for the six global energy-economy and integrated assessment models used in this study (AIM/CGE[11,12], IMAGE[13], MESSAGEix-GLOBIOM[14,15], POLES[16,17], REMIND-MAgPIE[18,19] and WITCH-GLOBIOM[20,21]), as well as for the nationally focused GCAM-USA[22,23] model, can be found in the Supplementary Methods. For the global models, a particularly useful reference is the Common Integrated Assessment Model (CIAM) documentation website developed within the context of the ADVANCE project[34]. This site allows side-by-side comparisons between different modelling frameworks.

Overview of approaches for calculating SDG investment needs. A diverse set of approaches has been used to calculate investment needs for achieving the other SDG targets by 2030. The following paragraphs summarize these while the Supplementary Methods section goes into further detail. Note that in some of these cases multi-model results are calculated, whereas in other cases results from only the MESSAGEix-GLOBIOM model are available.

For renewable energy and energy efficiency (SDG Targets 7.2, 7.3), detailed energy sector investment results are reported by the full set of global IAMs.

For energy access (SDG Target 7.1), residential fuel price outputs are reported from the global IAMs for their South Asia and Sub-Saharan Africa regions. These prices are then delivered to the MESSAGE-Access fuel choice model as inputs. Investments are calculated as the policy costs for ensuring 100% clean fuel adoption throughout the world by 2030. The policies considered are subsidies for clean cookstoves and price support for modern fuels. Unique results for each of the global IAMs can be generated by MESSAGE-Access. See ref. [24].

For clean water and sanitation (SDG Targets 6.1, 6.2, 6.3, 6.4), a specialized version of the MESSAGEix-GLOBIOM model is used for the analysis. The IAM is enhanced to include a reduced-form representation of the global water supply sector. The approach accounts for the rapid expansion of piped water access and treatment in the developing world, as well as the maintenance and replacement of existing water infrastructure in developed economies. Wastewater recycling and desalination technologies are also enabled as approaches to reduce freshwater withdrawals from rivers and underground aquifers. Water infrastructure investment needs, as well as additional energy and emissions resulting from the water sector development, are accounted for in the IAM explicitly. Results are only available from MESSAGEix-GLOBIOM, not the other global IAMs. See refs [27,28].

For air pollution (SDG Target 3.9), the GAINS model is used to estimate the number of deaths and illnesses that result from air pollution under different air pollutant emissions pathways. The model also estimates the investments needed for air pollution control technologies that will limit air pollutant emissions to certain levels consistent with an extrapolation of current air quality legislation in cities or countries throughout the world. Projections for emissions and economic activities of different types—such as energy supply and demand, industrial production, transport and agriculture—are provided to GAINS from MESSAGEix-GLOBIOM. Results are available only from MESSAGEix-GLOBIOM, not from the other global IAMs. See ref. [25].

For food security (SDG Target 2.1), this target is interpreted for our purposes as avoiding any further increase in those at risk of hunger (over and above the baseline) due to energy and climate mitigation policies that promote a transformation of the global energy system. Unless appropriate safeguards are put in place, such policies can potentially have negative side-effects on food security by increasing agricultural prices, as a result of non-CO_2 emissions abatement, greenhouse gas tax penalties on residual emissions, bioenergy expansion and afforestation. Therefore, in this work we define food policy packages that prevent such negative side-effects. In other words, the 'investments' that we estimate for food security are actually the food policy expenditures needed to compensate the poor for any increases in food costs. These calculations are done externally to the IAMs. Carbon prices are taken from the IAMs, and then these are used to estimate the food policy expenditures (investments) required to limit those at risk of hunger. Unique results for each of the global IAMs can be generated by this methodology.

For education (SDG Target 4.1), attainment shares for those students finishing primary and secondary schooling by 2030 are obtained from educational projections developed externally to the IAMs. These shares are then multiplied by the number of people of school age over this timeframe in the SSP2 scenario. Once the number of individuals in need of primary/secondary education has been calculated, a per-student cost is applied to each, to estimate the educational expenditures over time and by country. Because these investments are calculated externally to the IAMs—and without any input from or feedback on them—the cost estimates do not vary in scenarios with either more or less energy system transformation. See ref.[26].

Calculation of demand-side energy efficiency investments. Demand-side energy efficiency investments across the end-use sectors (buildings, transport, industry) are calculated in a harmonized way for each of the models, by using a methodology that was originally developed for the Global Energy Assessment[3] and then adapted in the LIMITS project[7]. We further refine that methodology here. The methodology makes use of two separate energy efficiency components.

1. **'Base-year efficiency' component**. This is calculated by taking the level of energy efficiency investments estimated globally by IEA in 2015[30], which was US$221 billion per year at 2015 values (relative to a hypothetical counterfactual of a less-efficient world in that year), and then scaling those efficiency investments with total final energy demand in the models' scenarios (relative to 2015 final energy demand) to arrive at future estimates for those same values. Because the IEA publishes only a global number for the year 2015 efficiency investments, we only estimate a global value for the models in their future scenarios (that is, no estimation of regional/national energy efficiency investments for this first component).
2. **'Supply-side offset' component**. More specifically, we compared total final energy demand in each of the model's tightened policy scenarios (NDC, 2C and 1.5C) to that model's demand in the reference case (CPol). We then made an assumption that, in equilibrium, the investments made to reduce energy demand could be equated to the investments that had been simultaneously offset on the supply side. This required, for a single model and region, calculating the ratio of supply-side investments in the policy scenario to total final energy demand in that same scenario and then multiplying this ratio (which is in units of US$ per exajoule) by the reductions in final energy demand calculated separately for that policy scenario (relative to the reference case; units in exajoules). We then multiply that investment value (in US$) by the share of total GDP in the policy scenario to that in the reference case (in %). These calculations are performed for each model time period and then cumulated over the timeframe of interest (for instance, 2016–2050).

The result is our approximation of a given country or region's investment into energy efficiency, taking into account any contraction in the size of its economy (hence economic contraction is not counted toward investment). It is an approximation in that it aims simply to give a sense of the scale of efficiency-related investments on the demand side. Though it is not without its shortcomings, it does allow us to discuss supply-side investments alongside demand-side efficiency investments without completely ignoring the latter. Other demand-side investments could also be included to inflate the figures to larger values, for example by considering the component costs of appliances (more efficient cars, refrigerators, manufacturing equipment and so on). This could lead to demand-side investment estimates that are an order of magnitude higher. As discussed in ref. [35], estimates of demand-side investments are subject to considerable uncertainty, owing to a lack of reliable statistics and definitional issues (what exactly is a purely energy-related investment on the demand side?).

It is worth noting that our default methodology for calculating energy efficiency investments leads to estimates for the 2016–2050 timeframe that are roughly in line with those calculated by IEA[6], even though the latter uses a more 'bottom-up' approach. More specifically, whereas in our 2C pathway we calculate values of US$640 billion per year (model mean; range of US$480 billion to US$890 billion per year), the IEA put the number at around US$1,120 billion per year in their analogous scenario according to their original calculations. Sensitivity analyses using an alternative methodology for calculating the models' efficiency investment estimates lead to values of US$1,270 billion per year (range: US$960 billion to US$1540 billion per year) in the same 2C pathway (see Supplementary Note 5). Thus, our default methodology, although stylized, results in efficiency investments that are consistent with those using other, more bottom-up approaches.

Carbon budgets for achieving the 2 °C and 1.5 °C targets. Carbon dioxide emissions reported in this paper include emissions from FF&I processes but exclude land use. Cumulative emissions globally over the 2016–2100 timeframe range from 880 to 1,074 $GtCO_2$ (mean: 952 $GtCO_2$) in the 2C scenario and from 206 to 525 $GtCO_2$ (mean: 390 $GtCO_2$) in the 1.5C scenario. Cumulative CO_2 emissions (FF&I) over the historical period of 2011–2015 were roughly 165 $GtCO_2$. The cumulative emissions exhibited by the models are thus within the bounds of uncertainty for the 2011–2100 carbon budgets consistent with staying below 2 °C over the twenty-first century with >66% likelihood and with limiting temperature rise to 1.5 °C in 2100 with >50% likelihood[4,36]. And importantly, the cumulative emissions levels in the 1.5C case are markedly lower than other studies in the literature that have looked at long-term energy and climate mitigation investment needs in the context of the Paris Agreement.

Currency conversion for model results. The original investment results provided by the models on which we focused in this study were in units of 2010 US$. Then, for the purposes of this paper, we converted those values to 2015 US$ by using a standardized GDP inflator of 1.087. This value comes from the World Bank Statistical Database[37].

Data availability. All investment data supporting this analysis—including the numbers behind the tables and figures—are available to any interested parties as online supplementary material to this paper (Supplementary Data 1). The CD-LINKS scenario database will also eventually house this information, along with a host of other data describing the various scenarios discussed here (such as energy and emissions time-series by fuel, sector and region). The database will be available here when it is made public: https://db1.ene.iiasa.ac.at/CDLINKSDB/.

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Author Contributions
D.L.M., K.R., J.R., M.F. and C.N. posed the initial research questions to frame the study and then selected the scenarios to analyse. V.K., M.G., O.F., D.H., S.F., M.H., D.v.V., H.-S.d.B., C.B., E.K., J.E., L.D., V.B., J.D., A.S. and G.I. ran the integrated assessment models for obtaining the energy investments. V.K., Si.P., Sh.P., M.P.-C., N.R., P.R., W.S. and S.F. carried out the investment analyses for the other SDGs. W.Z. and D.L.M. compiled and analysed results from all models and analyses. D.L.M. and W.Z. led the writing of the manuscript, with all other authors contributing.

Competing interests
The authors declare no competing interests.

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