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

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Supplementary Information

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

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Contents

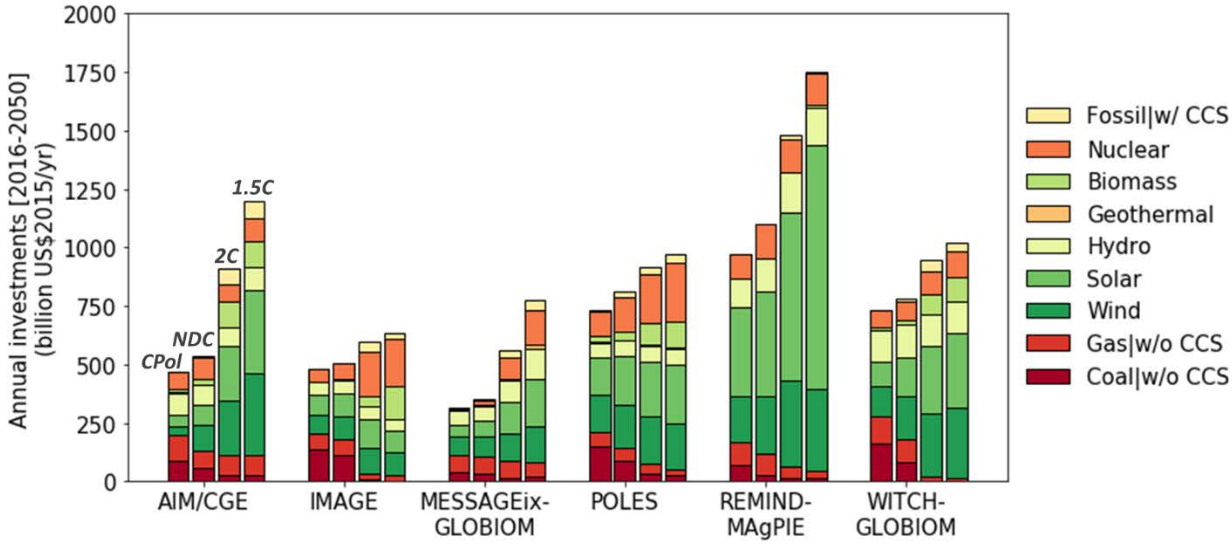
Supplementary Tables

Supplementary Table 1. Projected global, regional, and national average annual low-carbon energy and energy efficiency investment gaps in tightened policy scenarios. Values along top row for each regional classification represent the incremental investment requirements beyond the 'CPol' baseline. They are calculated as average annual investments (in billion US$/yr) over two separate timeframes (undiscounted). Mean values across models are given for each region, with min-max ranges in parentheses; numbers may therefore not add up to global totals. Values along bottom row for each region represent the ratio of the LCEI-Gap in each model's tightened policy scenarios relative to total supply-side and energy efficiency investments in that model's 'CPol' baseline. Based on this calculation method, the shares can potentially exceed 100%. Mean values across models are given for each region, with min-max ranges in parentheses. See Supplementary Methods for regional definitions.

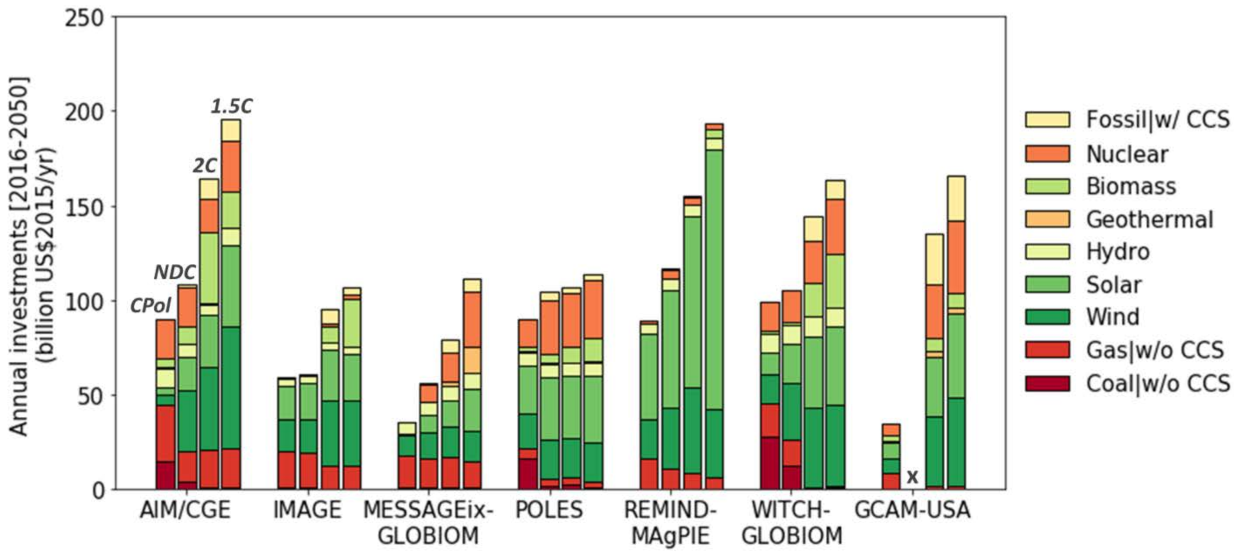
		2016 to 2030			2016 to 2050		
		NDC	**2C**	**1.5C**	**NDC**	**2C**	**1.5C**
	WORLD	$132 ($38 to $273)	$303 ($38 to $554)	$458 ($75 to $822)	$229 ($71 to $373)	$1052 ($590 to $1559)	$1567 ($885 to $2290)
		6% (2% to 11%)	*15% (2% to 32%)*	*22% (5% to 37%)*	*9% (3% to 14%)*	*43% (26% to 80%)*	*65% (41% to 121%)*
5 Regions	**ASIA**	$48 ($10 to $98)	$163 ($56 to $314)	$243 ($85 to $430)	$92 ($14 to $194)	$476 ($241 to $780)	$715 ($380 to $1104)
		8% (3% to 16%)	*30% (9% to 78%)*	*44% (14% to 89%)*	*12% (4% to 25%)*	*72% (45% to 143%)*	*110% (65% to 220%)*
	LAM	$12 ($0 to $50)	$14 ($-3 to $34)	$24 ($-5 to $54)	$18 ($5 to $33)	$77 ($52 to $121)	$102 ($58 to $168)
		6% (0% to 22%)	*10% (-3% to 27%)*	*17% (-4% to 30%)*	*9% (3% to 18%)*	*42% (22% to 80%)*	*56% (29% to 117%)*
	MAF	$5 ($-1 to $19)	$32 ($9 to $59)	$60 ($6 to $125)	$10 ($-1 to $24)	$187 ($95 to $294)	$299 ($96 to $558)
		2% (0% to 4%)	*12% (5% to 35%)*	*21% (3% to 52%)*	*3% (0% to 7%)*	*43% (26% to 91%)*	*67% (28% to 131%)*
	OECD90	$65 ($0 to $132)	$84 ($-11 to $190)	$136 ($12 to $255)	$108 ($33 to $217)	$309 ($157 to $497)	$487 ($288 to $771)
		12% (0% to 31%)	*14% (-3% to 30%)*	*24% (3% to 38%)*	*17% (7% to 44%)*	*51% (21% to 100%)*	*81% (35% to 156%)*
	REF	$1 ($-2 to $7)	$23 ($6 to $58)	$36 ($13 to $73)	$3 ($-3 to $15)	$72 ($36 to $150)	$109 ($56 to $205)
		2% (-1% to 6%)	*20% (4% to 52%)*	*31% (9% to 64%)*	*3% (-1% to 12%)*	*51% (20% to 119%)*	*75% (34% to 163%)*
Major Economies	**China**	$31 ($0 to $87)	$113 ($30 to $236)	$166 ($65 to $268)	$61 ($-3 to $186)	$261 ($116 to $399)	$370 ($159 to $538)
		8% (0% to 22%)	*34% (8% to 95%)*	*49% (17% to 108%)*	*13% (-1% to 40%)*	*69% (41% to 149%)*	*101% (57% to 214%)*
	India	$6 ($1 to $19)	$33 ($10 to $81)	$46 ($17 to $108)	$8 ($0 to $31)	$118 ($64 to $219)	$175 ($75 to $306)
		5% (1% to 13%)	*35% (9% to 84%)*	*47% (16% to 95%)*	*4% (0% to 10%)*	*86% (45% to 159%)*	*137% (53% to 312%)*
	Europe	$17 ($-1 to $38)	$19 ($-8 to $59)	$41 ($-4 to $103)	$22 ($7 to $42)	$70 ($27 to $123)	$119 ($54 to $188)
		8% (-2% to 21%)	*6% (-9% to 21%)*	*16% (-5% to 36%)*	*10% (4% to 21%)*	*33% (14% to 46%)*	*56% (27% to 77%)*
	USA	$31 ($2 to $53)	$38 ($-3 to $85)	$58 ($8 to $132)	$55 ($11 to $96)	$149 ($74 to $236)	$222 ($129 to $328)
		14% (1% to 27%)	*16% (-1% to 34%)*	*25% (4% to 57%)*	*21% (5% to 44%)*	*57% (25% to 109%)*	*85% (41% to 151%)*

Supplementary Figures

Supplementary Figure 1. Projected global average annual power sector investments by category from 2016 to 2050.



Supplementary Figure 2. Projected USA average annual power sector investments by category from 2016 to 2050. Values from the GCAM-USA model are shown here, in order to directly compare results from a nationally-focused model with national-level results from global models. GCAM-USA scenarios analogous to this study's 'CPol', '2C', and '1.5C' cases are comparable; a similar enough 'NDC' case is not available in this particular study.



Supplementary Figure 3. Projected global average annual low-carbon energy investments as a share of total supply-side investments. Numbers shown for each of the different models. Estimates include supply-side investments into 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.

Supplementary Notes

Supplementary Note 1: Additional information about base-year energy investments and the inherent challenges in estimating them

The International Energy Agency (IEA) estimates that in 2015 total investments in the global energy system were approximately 1800 billion US$2015/yr (including both supply-side and demand-side energy efficiency investments; excluding fuel and operations and maintenance costs)[1,2]. Between 2000 and 2012, global energy investments grew almost continuously (approximately a three times increase); they then leveled off for three years before declining in 2015. As illustrated in the main text, investments made to extract fossil fuel resources (coal, natural gas, and crude oil) and to transport and convert those resources to finished products (excluding electricity) accounted for roughly half of the total investment pie in 2015 (~900 billion US$/yr). The power sector, including both fossil and non-fossil electricity generation as well as transmission and distribution (T&D), also amounted to significant share (~680 billion US$/yr). Notably, renewable electricity generation investments (principally solar, wind, hydro, geothermal and biomass) have been consistently greater than fossil electricity investments since the early-2000s (by more than double in 2015), owing to the rapid capacity growth (in gigawatts) and relatively higher unit capital costs (in $ per gigawatt) of the former.

Tracking energy investments is by no means an exact science. This is because not all entities making those investments (e.g., private or publicly-traded companies, governments, stated-owned enterprises, and households) are required to report such information to authorities or statistical agencies. Hence, no fully comprehensive database of investment flows exist, meaning the values must be estimated. There are different ways this can be done, and ultimately historical estimates of investments will always be subject to some amount of uncertainty. End-use sector (or demand-side) efficiency investments pose a particular challenge and are therefore the most uncertain. The IEA defines these as the incremental spending needed to acquire equipment that consumes lower energy than would otherwise have been used to provide the same service but with a less efficient device. For estimating supply-side investments, the models utilize essentially the same calculation methodology as the IEA: multiplying known capacity installations by assumed unit capital costs. While these differences between the base-year energy investment estimates of the models and IEA are not the express focus of our study, it is nevertheless important to draw attention to them, given that base-year uncertainties can contribute to model differences in future years.

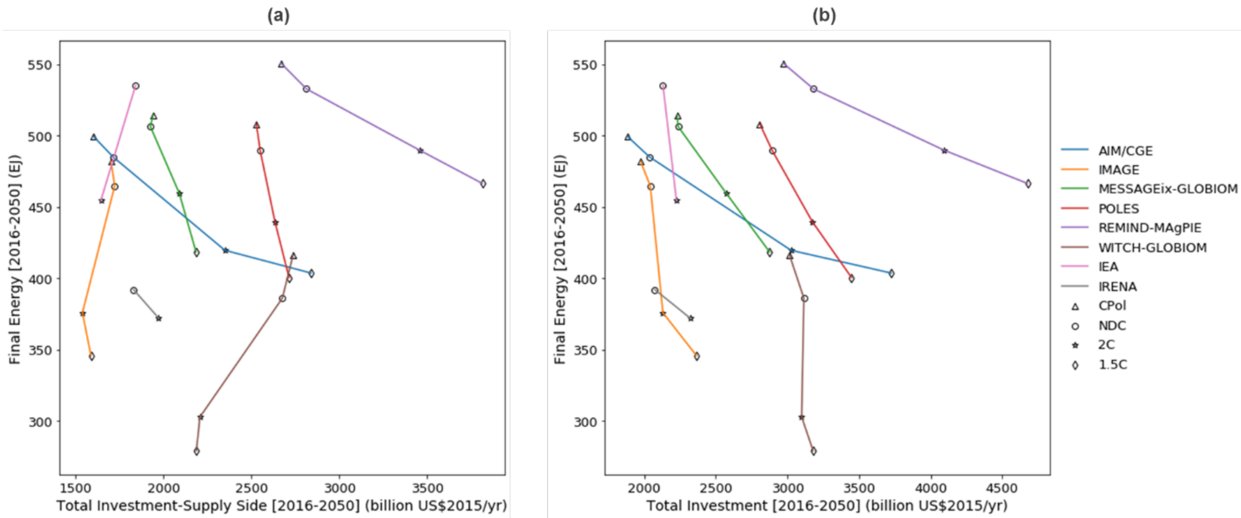
Supplementary Note 2: Additional discussion on future investment needs across the models

The two scenarios depicting either a continuation of current trends ('CPol') or countries' most recent energy and climate policy pledges ('NDC') show a significant future increase in supply-side investments beyond today in some models (POLES, REMIND-MAgPIE, WITCH-GLOBIOM) while relatively small in others (AIM/CGE, IMAGE, MESSAGEix-GLOBIOM). In the scenarios envisioning considerably more aggressive energy and climate policies post-2020 ('2C' and '1.5C'), greater divergences between the models are observed. Either the models anticipate that the two transformational pathways would lead to a sizeable increase in total supply-side investment needs beyond the 'CPol' and 'NDC' cases (AIM/CGE, MESSAGEix-GLOBIOM, POLES, REMIND-MAgPIE) or they depict a future with stagnant or reduced investments (IMAGE, WITCH-GLOBIOM). Additionally, the dichotomy in supply-side investment needs that we see between the two groups of models (increasing versus stagnant/reduced) is mirrored by the IEA and IRENA results for their '2C'-type scenarios: IEA shows a decrease, IRENA an increase. Given these similar findings from multiple studies, our conclusion is that it is not entirely clear whether pursuing the more ambitious targets of the Paris Agreement will ultimately necessitate larger capital flows into the supply side of the global energy system (namely resource extraction, power generation, electricity T&D, fuel conversion, pipelines, and energy storage) relative to a reference case future.

One of the principal reasons for why supply-side investments do not increase more than one might expect in the '2C' and '1.5C' pathways, or why they could even decline, is because of the rapid acceleration in demand-side energy efficiency and conservation foreseen across nearly all models, relative to the 'CPol' and 'NDC' cases. These actions also require investments, and while there is no generally accepted methodology for calculating such costs, our estimate of them shows they could potentially be quite significant going forward. In fact, addition of these demand-side efficiency investments to the supply-side investments shows that, across all models and scenarios, total investments in the '2C' and '1.5C' pathways are always greater than in 2015 and when compared to the 'CPol' and 'NDC' cases, either by a little or by a lot (Supplementary Figure 4).

Three categories of model-scenario behavior can be distinguished when relating investments and final energy demand. The first group is comprised of IMAGE, WITCH-GLOBIOM, and IEA, each of which exhibits a decrease in total supply-side energy investments (Supplementary Figure 4, panel 'a') and only a mild increase in total energy investments (supply-side + energy efficiency; Supplementary Figure 4, panel 'b') when moving from the 'CPol' and/or 'NDC' baselines to the more transformational '2C' and/or '1.5C' pathways. Among the six global integrated assessment models, the demand reductions calculated by IMAGE and WITCH-GLOBIOM are the largest. The second group is comprised of MESSAGEix-GLOBIOM, POLES, and IRENA. The scenarios from these models show moderate increases in supply-side investments and somewhat more significant increases in total investments when moving from the 'CPol' and/or 'NDC' baselines to the more transformational '2C' and/or '1.5C' pathways. The third group is comprised of AIM/CGE and REMIND-MAgPIE, models that show large increases in both supply-side and total energy investments as climate mitigation efforts become stronger. The conclusion from this comparison among model-scenario results is that while it is entirely possible that end-use demand reductions could be so strong in deep decarbonisation futures ('2C' and '1.5C') that supply-side energy investments decline and total investments remain roughly similar (relative to baseline scenarios like 'CPol' and 'NDC'), it is also very possible that deep decarbonisation efforts will ultimately lead to a more capital-intensive energy system, perhaps significantly so.

Supplementary Figure 4. Projected global average annual supply-side energy investments (panel 'a') and total supply-side and energy efficiency investments (panel 'b') related to total final energy demand for different models and scenarios. Both the investment and final energy aalues are calculated by cumulating the models' estimates and averaging them over the full 2016-2050 period. Source of IEA and IRENA supply-side investment numbers is ref [3]. Analogous versions of the 'CPol' and '1.5C' scenarios are not available from IEA and IRENA (hence the missing data points). 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. abc.



As a share of global GDP (measured at market exchange rates), the total energy investments foreseen by the models do not change markedly from today (just over 2%) in either the 'CPol' baseline or 'NDC' scenarios. In other words, global GDP grows just as fast as energy investments, due in part to saturating demands for energy in today's emerging economies and also to ever-lower per-unit capital costs for energy technologies (at least as assumed by the models). The more transformational '2C' and '1.5C' pathways do see global energy investment shares increasing beyond today, but only marginally. Regional disparities are present in these estimates, with currently wealthy economies (e.g., USA, Europe) approximately 1 %-point lower than the global averages and currently emerging economies (e.g., China, India) around 1-2 %-points higher. Meanwhile, major energy-exporting countries, such as Russia and those in the Middle East and North Africa, tend to see energy investment shares above 5% of GDP in our scenarios.

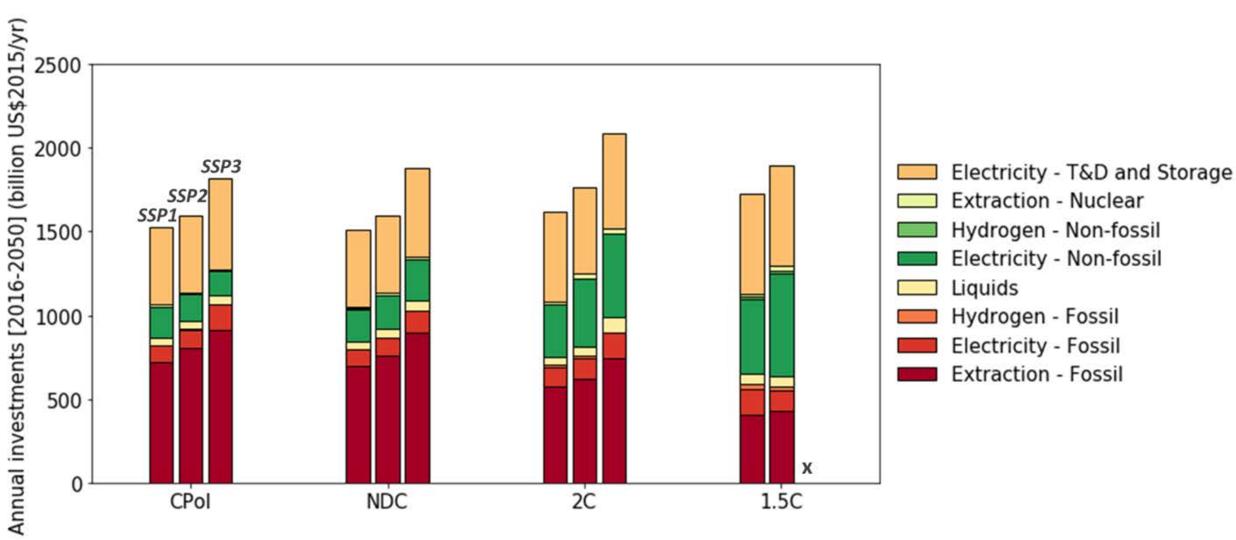
Supplementary Note 3: Fossil energy investments in scenarios

The time period between now and 2030 is particularly critical for investing in energy infrastructure, owing to the fact that such infrastructure is typically long-lived (20-40 years, if not more). Hence, the portfolio shifts envisioned in the more transformational pathways ('2C' and '1.5C') for the medium-to-long term necessitate a readjustment of global capital flows already in the near term. This is illustrated quite clearly in the main text, where the focus is on fossil fuel supply investments and the reductions in them that are foreseen by the models in the 'NDC', '2C', and '1.5C' scenarios relative to the 'CPol' case. By all indications, the industry most impacted by increasingly stringent energy and climate policies appears to be coal: the NDCs could lead to a 20% decrease in coal-related investment dollars within just a few years, while the Paris Agreement targets could necessitate that those investments are cut in half. Coal power plants witness the biggest reductions of all, as there is very little room for these technologies in a low-carbon world, especially those not equipped with carbon capture and storage (CCS). (Note that investments in fossil plants equipped with CCS are negligible in the near term due to either their relatively higher capital costs or modeler assumptions that these technologies will not be available at commercial scale before the late-2020s.) This is true to a lesser extent for natural gas, which of all the fossil fuels sees the smallest reductions in investment intensity as a result of the NDCs and Paris Agreement targets, given its standing as the least carbon-intensive fossil option. Also noteworthy is the finding that whether society aspires to limit global warming to 2 °C or 1.5 °C matters very little for the magnitude of the phase-out in coal investments, whereas it does have an important impact for oil and natural gas (near-term investment reductions that are up to 10 %-points higher in the 1.5 °C pathway). We note that for the MESSAGEix-GLOBIOM model, non-CCS related investments (everything but CO_2 capture and compression) are included in the corresponding fossil energy w/o CCS investment categories (e.g., coal power plants without CCS). In other words, fossil energy w/ CCS investments only account for CO_2 capture and compression equipment.

Supplementary Note 4: Impact of alternate population and socio-economic development assumptions on scenario results

Sensitivity analyses varying assumptions for future population and socio-economic development indicate that the magnitude of supply-side investments as well as the investment portfolio do not change a great deal across the SSPs for a given level of climate policy stringency. Comparing these sensitivities to the results shown in the main text, we conclude that the uncertainties in investments arising from different population and socio-economic development futures (for a single model, MESSAGEix-GLOBIOM) are smaller than the uncertainties stemming from the use of different models (for a single development future).

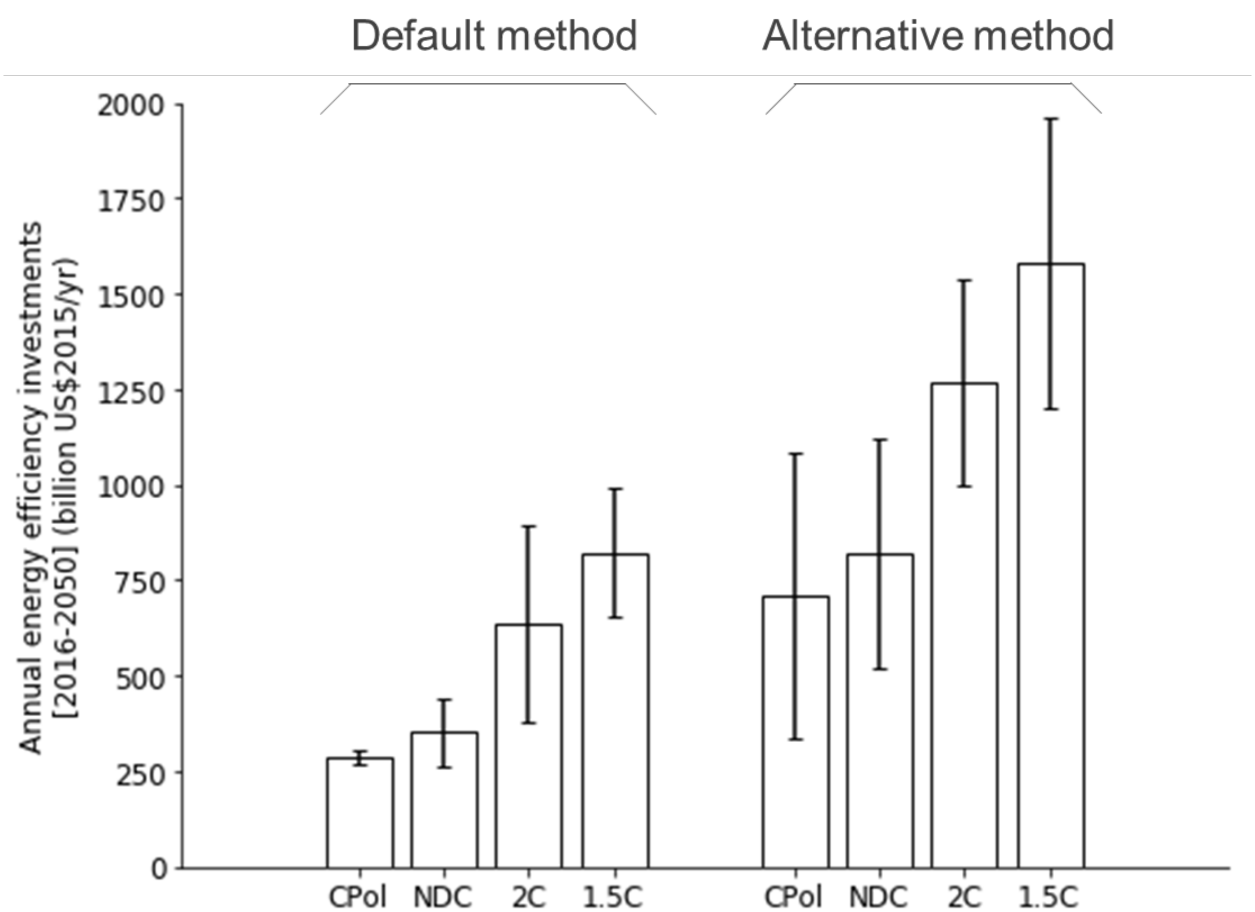
Supplementary Figure 5. Projected global average annual energy investments (supply side) by category from 2016 to 2050 in SSP1, SSP2, and SSP3 variants of the CD-LINKS scenarios. Only the MESSAGEix-GLOBIOM model was part of this sensitivity analysis. Results for the '1.5C' case under the SSP3 storyline are not available because it was not found to be feasible with MESSAGEix-GLOBIOM.



Supplementary Note 5: Alternative methodology for calculating demand-side energy efficiency investments

The alternative methodology for calculating energy efficiency investments applies the 'supply-side offset' approach described elsewhere to hypothetical levels of final energy demand reduction in future years. By hypothetical, we are referring to the differential between the final energy demand (across all end-use sectors) projected by a given model and the hypothetical demand that would have been realized had the energy intensity (FE/GDP) seen in the base-year remained constant indefinitely (thus, $FE_{hypo} = FE_{2015}/GDP_{2015} * GDP_{future}$). This differential in a given year is then multiplied by the supply-side investment intensity ($= INV_{supply,future}/FE_{future}$) in that same year, thereby resulting in a measure of the energy efficiency investments necessary for improving energy intensity over time. The future values are then cumulated and divided by the number of years over that specific timeframe, in order to arrive at annual averages.

Supplementary Figure 6. Projected global average annual energy efficiency investments based on different calculation methodologies used for this paper. Bar values from represent multi-model means; bar whiskers represent min-max ranges across the models.



Supplementary Note 6: Relationship between capital cost inputs and resulting deployment levels and investment magnitudes for different electricity generation technologies by model

Technology investment choices within a given global energy-economy models, or integrated assessment (IAM), model are made based on a variety of considerations, including capital costs, non-fuel O&M costs, and fuel costs, as well as any explicit constraints that have been assumed (e.g., to represent policies, to allow for smooth up-/down-scaling, and so on). Owing to the whole-systems nature of these models, trying to pinpoint one single reason for a model's behavior is often a fruitless task. A combination of factors is always at play. Nevertheless, the act of connecting model inputs to outputs can yield useful insights, especially if assumptions and results from multiple models are compared. The following paragraphs and figures attempt to do this, specifically for electricity generation technologies, which, in addition to comprising a large and growing share of the total energy investment portfolio, are able to be compared across models in a fairly straightforward way (i.e., all models represent comparable versions of each technology). More specifically, here we relate capital cost inputs of different electricity generation technologies to their resulting cumulative deployment levels (capacity additions) and investment magnitudes. We focus our analysis on this paper's stringent climate policy '2C' pathway. Findings are presented in Supplementary Figure 7 and Supplementary Figure 8 (see also Supplementary Figure 1 and Supplementary Figure 2, which provide detailed breakdowns of electricity sector investments by model and scenario). Below we distill some of the main insights, keeping in mind that each of the cost and constraint considerations highlighted above may weigh more or less heavily in the decision to deploy this or that technology. (Though, in the '2C' pathway, all models have a strong preference for low-carbon generation technologies, and all of these are more capital-intensive than they are fuel-cost-intensive.)

Of all the models, REMIND-MAgPIE sees the largest expansion of non-biomass renewable electricity investments in its stringent climate policy scenarios. This is dominated by solar power, with significant contributions from wind and hydro as well. Solar power is the least capital-intensive electricity generation technology in REMIND-MAgPIE (on average over the 2016-2050 timeframe), at least half the cost assumed in the other models. Capital costs for wind power, in contrast, are on the higher end of the model range, even though in REMIND-MAgPIE they are still one of the least capital-intensive options. Hydro and nuclear power investments are also substantial in the REMIND-MAgPIE '2C' pathway, a result that is mostly a function of the high capital costs that are assumed, relative to other models.

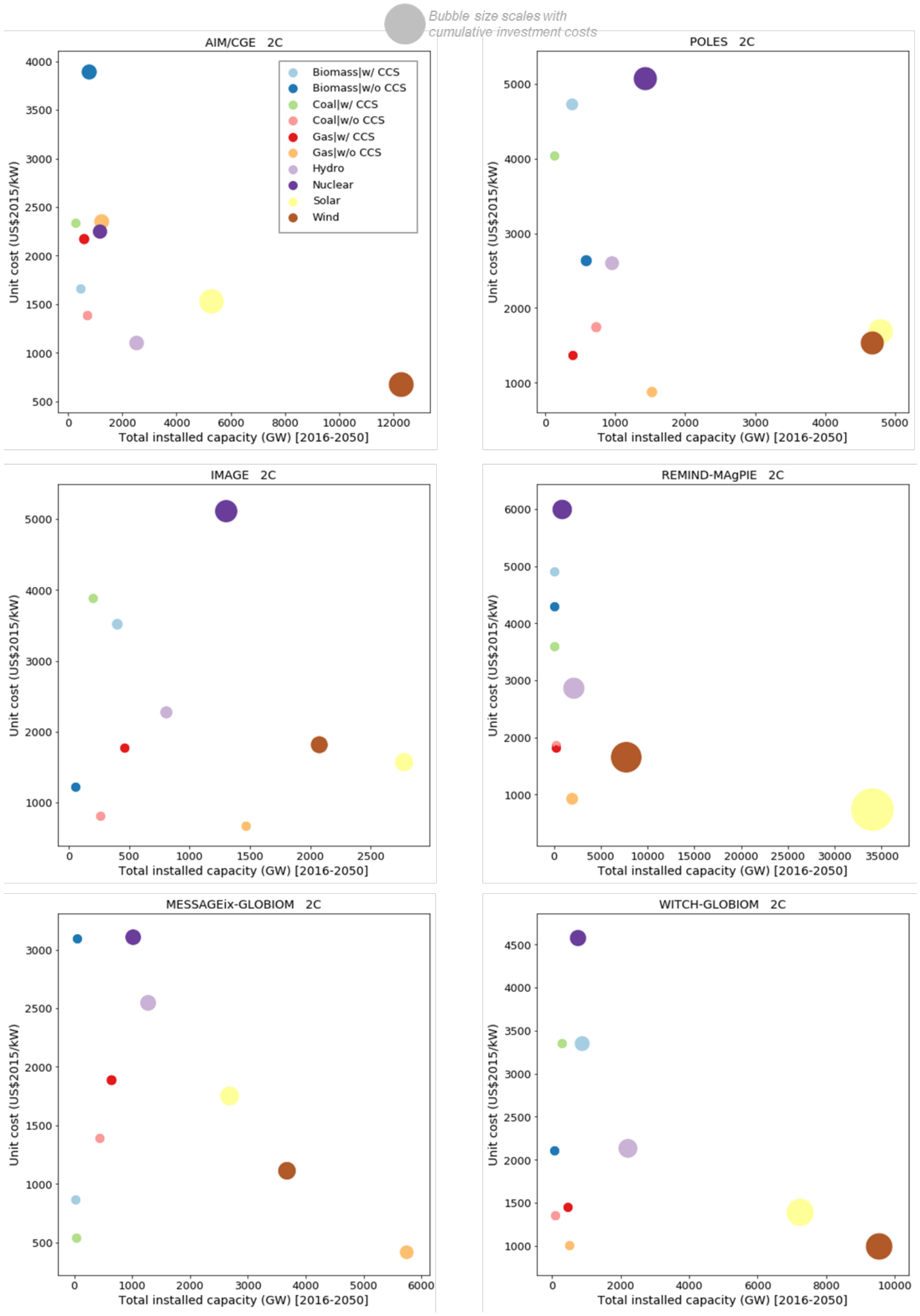
AIM/CGE exhibits similar results to REMIND-MAgPIE in the sense that a single technology, in this case wind, is significantly less expensive than others. For this reason, wind power deployment dominates compared to other technologies, and also relative to other models. Total wind investments are moderate, however, thanks to the low capital costs that are assumed. Solar power, on the other hand, is assumed to have much higher capital costs in AIM/CGE. While this contributes to its lower deployment levels, it also leads to total investment levels for solar that are actually on par with wind. Interestingly, despite the significantly lower costs for nuclear and hydro power in AIM/CGE compared to other models, total deployment levels, and therefore investments, remain relatively modest.

WITCH-GLOBIOM displays a more balanced picture than REMIND-MAgPIE and AIM/CGE in terms of its low-carbon electricity investment portfolio under a '2C' pathway. Solar and wind are two of the least capital-intensive technologies in the model, and the model does deploy these substantially. But nuclear, biomass and hydro power investments are also significant, owing to moderate deployment of these technologies and their intermediate-to-high capital costs.

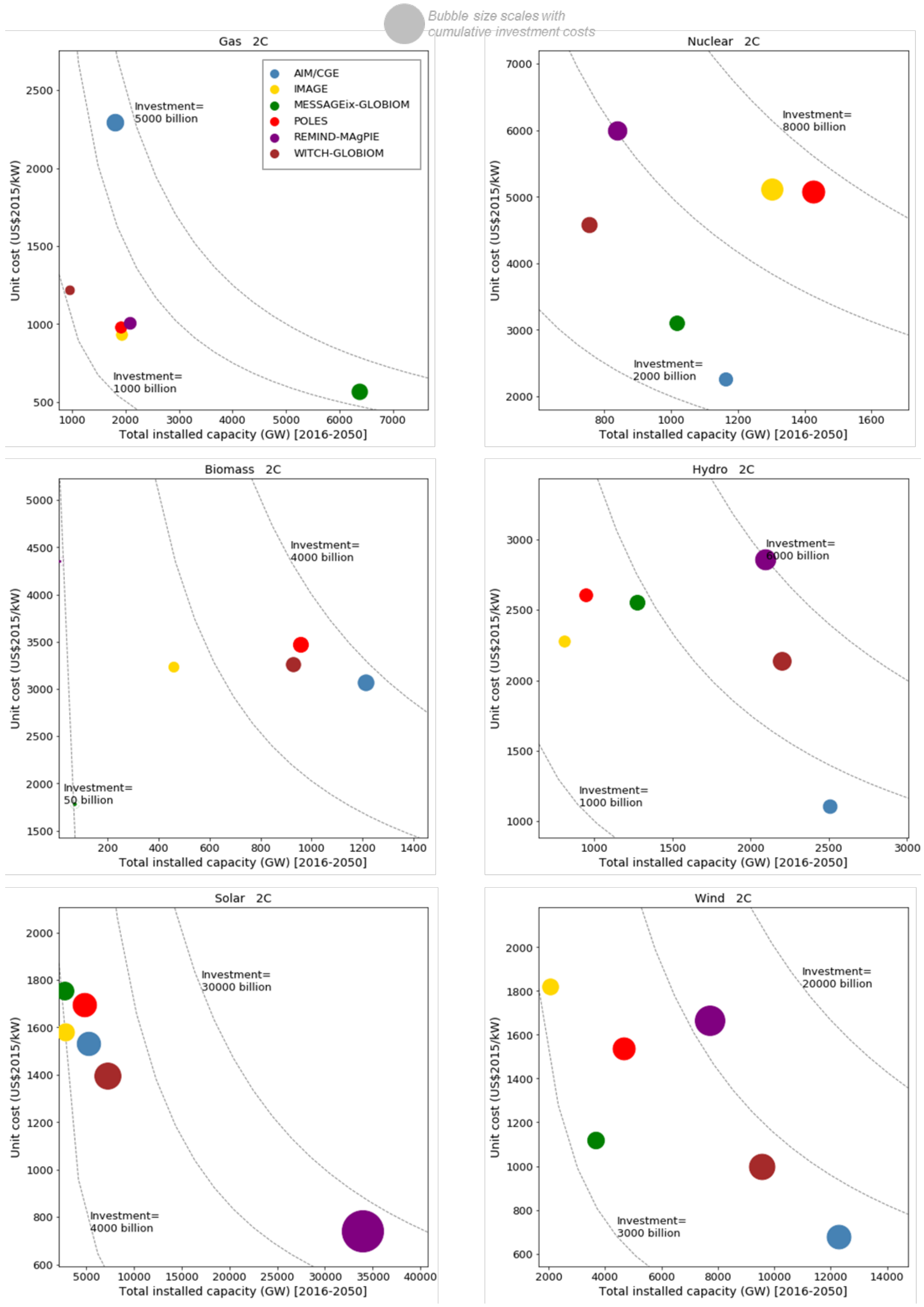
The dynamics exhibited by the POLES and IMAGE models are similar to WITCH-GLOBIOM in many respects. One notable difference is that these models, in comparison to all others, see stronger deployment and investment levels for nuclear power. This happens despite nuclear being much more capital-intensive than other technologies in these models.

MESSAGEix-GLOBIOM also has a fairly balanced electricity generation investment portfolio in the '2C' pathway. A unique feature, compared other models, is strong natural gas (mostly w/o CCS) deployment, yet gas-related investments that remain relatively limited over the time horizon to 2050. This is due to relatively low capital costs that are assumed for gas plants (both w/o and w/ CCS) in MESSAGEix-GLOBIOM, at least compared to the costs for solar, wind, hydro and nuclear power. The latter technologies see far lower deployment levels than gas, but at the same time similar investment magnitudes, owing to their significantly higher capital costs.

Supplementary Figure 7. Projected capital costs, deployment levels, and investment magnitudes of various electricity generation technologies by model. Panels organized by model. Data comes from the stringent climate policy '2C' pathway. Total deployment levels (capacity additions) from 2016-2050 are shown on the horizontal axis. Overnight capital costs (average over the same time period) are shown on the vertical axis. The third dimension, total cumulative investments, is the product of these two variables and is shown by bubbles of different sizes.



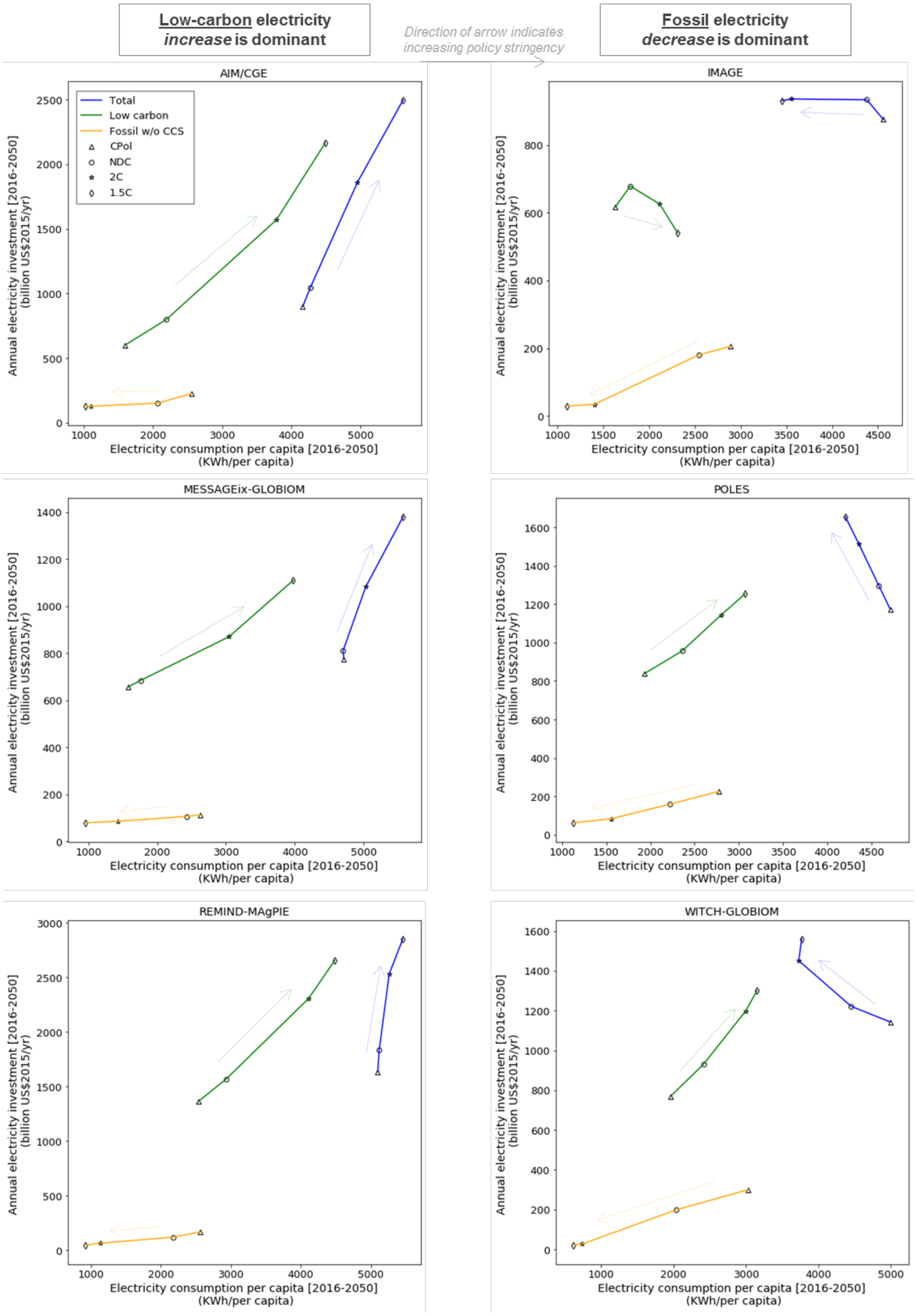
Supplementary Figure 8. Projected capital costs, deployment levels, and investment magnitudes of various electricity generation technologies by model. Panels organized by technology. Data comes from the stringent climate policy '2C' pathway. Total deployment levels (capacity additions) from 2016-2050 are shown on the horizontal axis. Overnight capital costs (average over the same time period) are shown on the vertical axis. The third dimension, total cumulative investments, is the product of these two variables and is shown by bubbles of different sizes.



Supplementary Note 7: Relationship between electricity sector investments and electricity consumption across the end-use sectors, broken down by fossil and low-carbon electricity generation and comparing different scenarios

The models utilized for this study provide evidence of greater electricity sector investment needs in the stringent climate policy scenarios ('2C' and '1.5C') than in the baseline ('CPol'). This results from increased electrification of the end-use sectors in relative terms, as has been shown in other studies[4]. Simply put, as the fossil share of electricity generation declines, the low-carbon share rises. How this works out in terms of absolute electricity generation/consumption and investments is, however, model-dependent. The AIM/CGE, MESSAGEix-GLOBIOM, and REMIND-MAgPIE models exhibit the somewhat intuitive finding of low-carbon electricity generation/consumption and investments both increasing more in the stringent climate policy scenarios than fossil electricity generation/consumption and investments decrease (left panels of Supplementary Figure 9). Because of this, total electricity generation/consumption rises along with total electricity sector investments (i.e., the 'Total' curves in the figure point up and to the right). In contrast, the IMAGE, POLES, and WITCH-GLOBIOM models tell a different story (right panels of the figure). For these three, the decrease in fossil electricity generation/consumption outweighs the increase in that from low-carbon sources. Hence, while total electricity sector investment rises, total electricity generation/consumption actually declines (i.e., the 'Total' curves in the figure point up and to the left). The reason for this is substantial demand reduction (energy efficiency) across the end-use sectors, which helps to temper the total amount of electricity (indeed energy from all fuels/carriers) that is needed in the scenarios.

Supplementary Figure 9. Relationship between projected global average annual electricity sector investments and electricity consumption across the end-use sectors, broken down by fossil and low-carbon electricity generation and comparing different scenarios. Timeframe of 2016-2050.



Supplementary Methods

Regional definitions used in this paper

Each of the global models employed in this study possesses a unique set of regions and regional definitions. Aggregation of these native model regions to the World, five macro-regions, and certain major economies aids in the model inter-comparison exercise. These regions/countries, which are commonly used in the research community's scenario analyses are defined below:

Aggregation on the five-region level

- **OECD90+EU** = Includes the OECD 1990 countries as well as EU members and candidates.
  Albania, Australia, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Fiji, Finland, France, French Polynesia, Germany, Greece, Guam, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Macedonia, Montenegro, Netherlands, New Caledonia, New Zealand, Norway, Poland, Portugal, Romania, Samoa, Serbia, Slovakia, Slovenia, Solomon Islands, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States of America, Vanuatu
- **REF** = Countries from the Reforming Ecomonies of the Former Soviet Union.
  Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
- **ASIA** = The region includes most Asian countries with the exception of the Middle East, Japan and Former Soviet Union states.
  Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China, China Hong Kong SAR, China Macao SAR, Democratic People's Republic of Korea, East Timor, India, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Singapore, Sri Lanka, Taiwan, Thailand, Viet Nam
- **MAF** = This region includes the countries of the Middle East and Africa.
  Algeria, Angola, Bahrain, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Cote d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Oman, Qatar, Reunion, Rwanda, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Syrian Arab Republic, Togo, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Western Sahara, Yemen, Zambia, Zimbabwe
- **LAM** = This region includes the countries of Latin America and the Caribbean.
  Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guadeloupe, Guatemala, Guyana, Haiti,

Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela

Several individual major economies (countries / groups of countries) commonly used in scenario analysis:

ARG = Argentine Republic
AUS = Commonwealth of Australia
BRA = Federative Republic of Brazil
CAN = Canada
CHN = People's Repulic of China
EU = European Union (28 member countries)
IND = Republic of India
IDN = Republic of Indonesia
JPN = State of Japan
MEX = United Mexican States
RUS = Russian Federation
SAU = Kingdom of Saudi Arabia
SAF = = Republic of South Africa
ROK = Republic of Korea (South Korea)
TUR = Republic of Turkey
USA = United States of America

Detailed descriptions of the policy scenarios depicted by the models

The four scenarios focused upon in the main text of the paper, and described there in brief, have been given different names than those originally used when run by the models in the context of the European Union Horizon-2020 'CD-LINKS' project (www.cd-links.org). Supplementary Table 2 provides a mapping between the two naming conventions. The original modeling protocol used to guide CD-LINKS modeling teams when running their scenarios as well as a spreadsheet file containing all the numerical assumptions corresponding to policy constraints in individual countries and regions are available as separate supplementary information files on the journal website.

Supplementary Table 2. Mapping between the original CD-LINKS project scenario names and those used in this paper.

Original CD-LINKS project scenario names	Scenario names used in this paper
NPi	CPol
INDCi	NDC
NPi2020_1000	2C
NPi2020_400	1.5C

Brief descriptions of energy-economy and integrated assessment modeling frameworks

What follows are concise overviews of each of the energy-economy and integrated assessment models employed in this study: AIM/CGE, IMAGE, MESSAGEix-GLOBIOM, POLES, REMIND-MAgPIE, WITCH-GLOBIOM, and GCAM-USA. For the global models among these, much lengthier descriptions can be found at The Common Integrated Assessment Model (CIAM) documentation website developed within the context of the ADVANCE project[5]. This site allows for side-by-side comparisons between different modelling frameworks.
http://themasites.pbl.nl/models/advance/index.php/ADVANCE_wiki

AIM/CGE

AIM/CGE is a one-year-step recursive-type dynamic general equilibrium model that covers all regions of the world. The model includes 17 regions and 42 industrial classifications. For appropriate assessment of bioenergy and land use competition, agricultural sectors are also highly disaggregated[6]. Details of the model structure and mathematical formulae are described by ref [7]. The production sectors are assumed to maximize profits under multi-nested constant elasticity substitution (CES) functions and each input price. Energy transformation sectors input energy and value-added are fixed coefficients of output. They are treated in this manner to deal with energy conversion efficiency appropriately in the energy transformation sectors. Power generation values from several energy sources are combined with a Logit function. This functional form was used to ensure energy balance because the CES function does not guarantee an energy balance. Household expenditures on each commodity are described by a linear expenditure system function. The parameters adopted in the linear expenditure system function are recursively updated by income elasticity assumptions. In addition to energy-related CO2, CO2 from other sources, CH4, N2O, and fluorinated gases (F-gases) are treated as GHGs in the model. Energy-related emissions are associated with fossil fuel feedstock use. The non-energy-related CO2 emissions consist of land use change and industrial processes. Land use change emissions are derived from the forest area change relative to the previous year multiplied by the carbon stock density, which is differentiated by AEZs (Global Agro-Ecological Zones). Non-energy-related emissions other than land use change emissions are assumed to be in proportion to the level of each activity (such as output). CH4 has a range of sources, mainly the rice production, livestock, fossil fuel mining, and waste management sectors. N2O is emitted as a result of fertilizer application and livestock manure management and by the chemical industry. F-gases are emitted mainly from refrigerants used in air conditioners and cooling devices in the industry. Air pollutant gases (BC, CO, NH3, NMVOC, NOX, OC, SO2) are also associated with fuel combustion and activity levels. Emissions factors change over time with the implementation of air pollutant removal technologies and relevant legislation.

IMAGE

IMAGE 3.0 is a comprehensive ecological-environmental model framework that simulates the environmental consequences of human activities worldwide. The model is a simulation model, i.e. changes in model variables are calculated based on the information from the previous time-step. The model includes a detailed description of the energy and land-use system and simulates most of the socio-economic variables for 26 regions and most of the environmental variables based on a geographical grid of 30 by 30 minutes or 5 by 5 minutes (depending on the variable). The time horizon of the model is until 2100.

The IMAGE core model comprises most parts of the Human system and the Earth system, including the detailed energy system model TIMER, and the food and agriculture system and plant growth, carbon and water cycle model LPJmL. The IMAGE framework includes soft-linked models, such as the agro-economic model MAGNET, and PBL policy and impact models, such as FAIR (climate policy), GLOBIO (biodiversity), GLOFRIS (flood risks) and GISMO (human development). The IMAGE framework uses exogenous assumptions on population, economic development, lifestyle, policies and technology change.

The IMAGE framework identifies socio-economic pathways, and projects the consequences for energy, land, water and other natural resources, subject to resource availability and quality. Impacts such as air, water and soil emissions, climatic change, and depletion and degradation of remaining stocks (fossil fuels, forests), are calculated and taken into account in future projections. Within the IAM group, different types of models exist, and IMAGE is characterised by relatively detailed biophysical processes and a wide range of environmental indicators.

The IMage Energy Regional model (TIMER) has been developed to explore scenarios for the energy system in the broader context of the IMAGE framework. Similar to other IMAGE components, TIMER is a simulation model. The results obtained depend on a single set of deterministic algorithms, according to which the system state in any future year is derived entirely from previous system states. TIMER includes 12 primary energy carriers in 26 world regions and is used to simulate long-term trends in energy use, issues related to depletion, energy-related greenhouse gas and other air polluting emissions, together with land-use demand for energy crops. The focus is on dynamic relationships in the energy system, such as inertia and learning-by-doing in capital stocks, depletion of the resource base (upward pressure on prices), technology development (downward pressure on prices), and trade between regions. The model includes detailed representations of energy trade and investments in the energy system. IMAGE offers a range of options for introducing climate policies: e.g. carbon pricing, taxes, renewable energy targets, efficiency standards, reduced deforestation, non-CO2 reduction measures.

An extensive description of the IMAGE 3.0 model is provided in book form[8], which can also be found online:
http://themasites.pbl.nl/models/image/index.php/Welcome_to_IMAGE_3.0_Documentation

MESSAGEix-GLOBIOM

MESSAGE*ix*-GLOBIOM 1.0 integrates the energy engineering model MESSAGE with the land-use model GLOBIOM via soft-linkage into a global integrated assessment modeling framework[9,10]. It utilizes the 'ix' platform for integrated and cross-sectoral modeling[11].

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) is a linear programming (LP) energy engineering model with global coverage[4,12]. As a systems engineering optimization model, MESSAGE is primarily used for medium- to long-term energy system planning, energy policy analysis, and scenario development. The model provides a framework for representing an energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation. To assess economic implications and to capture economic feedbacks of climate and energy policies, MESSAGE is linked to the aggregated macro-economic model MACRO[13].

Land-use dynamics are modelled with the GLOBIOM (GLobal BIOsphere Management) model, which is a partial-equilibrium model[14,15]. GLOBIOM represents the competition between different land-use based activities. It includes a detailed representation of the agricultural, forestry and bio-energy sector, which allows for the inclusion of detailed grid-cell information on biophysical constraints and technological costs, as well as a rich set of environmental parameters, incl. comprehensive AFOLU (agriculture, forestry and other land use) GHG emission accounts and irrigation water use. For spatially explicit projections of the change in afforestation, deforestation, forest management, and their related CO2 emissions, GLOBIOM is coupled with the G4M (Global FORest Model) model[16,17]. As outputs, G4M provides estimates of forest area change, carbon uptake and release by forests, and supply of biomass for bioenergy and timber.

MESSAGE*ix*-GLOBIOM covers all greenhouse gas (GHG)-emitting sectors, including energy, industrial processes as well as agriculture and forestry. The emissions of the full basket of greenhouse gases including CO2, CH4, N2O and F-gases (CF4, C2F6, HFC125, HFC134a, HFC143a, HFC227ea, HFC245ca and SF6) as well as other radiatively active substances, such as NOx, volatile organic compounds (VOCs), CO, SO2, and BC/OC is represented in the model. Air pollution implications of the energy system are accounted for in MESSAGE*ix*-GLOBIOM by a linkage to the GAINS (Greenhouse gas and Air pollution INteractions and Synergies) model[18]. MESSAGE*ix*-GLOBIOM is used in conjunction with MAGICC (Model for Greenhouse gas Induced Climate Change) version 6.8 for calculating atmospheric concentrations, radiative forcing, and annual-mean global surface air temperature increase[19].

<u>POLES</u>

The POLES (Prospective Outlook on Long-term Energy Systems) model[20] is a global partial equilibrium simulation model of the energy sector with an annual step, covering 38 regions world-wide (G20, OECD, principal energy consumers) plus the EU. The model covers 15 fuel supply branches, 30 technologies in power production, 6 in transformation, 15 final demand sectors and corresponding greenhouse gas emissions. GDP and population are exogenous inputs of the model. The model can provide insights of the evolution of global and local technology developments. The model can assess the market uptake and development of various new and established energy technologies as a function of changing scenario conditions. The global coverage allows an adequate capture of the learning effects that usually occur in global markets[21]. The model represents the adjustments of energy supply and demand to prices, while accounting for delayed reaction. POLES can also assess the global primary energy markets and the related international and regional fuel prices under different scenario assumptions. To this end, it includes a detailed representation of the costs in primary energy supply (in particular oil, gas and coal supply), for both conventional and unconventional resources. Major countries for the oil, coal and gas markets are represented.

The model can therefore be used to analyse the impacts of energy and climate policies, through the comparison of scenarios concerning possible future developments of world energy consumption and corresponding GHG emissions under different assumed policy frameworks[22]. Policies that can be assessed include: energy efficiency, support to renewables, energy taxation/subsidy, technology push or prohibition, access to energy resources, etc.

Mitigation policies are implemented by introducing carbon prices up to the level where emission reduction targets are met: carbon prices affect the average energy prices, inducing energy efficiency responses on the demand side, and the relative prices of different fuels and technologies, leading to adjustments on both the demand side (e.g. fuel switch) and the supply side (e.g. investments in renewables). Non-CO2 emissions in energy and industry are endogenously modelled with potentials derived from literature (marginal abatement cost curves). Air pollutants are also covered (SO2, NOx, VOCs, CO, BC, OC, PM2.5, PM10, NH3) thanks to a linkage with the specialist GAINS model. Projections for agriculture, LULUCF emissions and food indicators are derived from the GLOBIOM model (dynamic look-up of emissions depending on climate policy and biomass-energy use), calibrated on historical emissions and food demand (from UNFCCC, FAO and EDGAR). Food demand and production is represented with a split between crops and livestock, with an accounting of the land-use occupation. A full documentation of POLES is available at http://ec.europa.eu/jrc/poles.

<u>REMIND-MAgPIE</u>

The coupled REMIND-MAgPIE integrated assessment modeling framework is presented in ref [23], from which the following description is adapted. The framework consists of the energy-economy-climate model REMIND[24] coupled to the land-use model MAgPIE[25]. REMIND (Regional Model of Investment and Development) is an energy-economy general equilibrium model linking a macro-economic growth model with a bottom-up engineering based energy system model. It covers eleven world regions, differentiates various energy carriers and technologies and represents the dynamics of economic growth and international trade. A Ramsey-type growth model with perfect foresight serves as a macro-economic core projecting growth, savings and investments, factor incomes, energy and material demand. The energy system representation differentiates between a variety of fossil, biogenic, nuclear and renewable energy resources. The model accounts for crucial drivers of energy system inertia and path dependencies by representing full capacity vintage structure, technological learning of emergent new technologies, as well as investment mark-ups for rapidly expanding technologies. Several energy sector policies are represented explicitly, including energy-sector fuel taxes and consumer subsidies. The model also represents trade in energy resources. A detailed model description can be found at http://themasites.pbl.nl/models/advance/index.php/Model_Documentation_-_REMIND

MAgPIE (Model of Agricultural Production and its Impacts on the Environment) is a global multi-regional economic land-use optimization model designed for scenario analysis up to the year 2100. It is a partial equilibrium model of the agricultural sector that is solved in recursive dynamic mode. The objective function of MAgPIE is the fulfilment of agricultural demand for ten world regions at minimum global costs under consideration of biophysical and socio-economic constraints. Major cost types in MAgPIE are factor requirement costs (capital, labor, fertilizer), land conversion costs, transportation costs to the closest market, investment costs for yield-increasing technological change (TC) and costs for GHG emissions in mitigation scenarios. Biophysical inputs (0.5° resolution) for MAgPIE, such as agricultural yields, carbon densities and water availability, are derived from a dynamic global vegetation, hydrology and crop growth model, the Lund-Potsdam-Jena model for managed Land (LPJmL). Agricultural demand includes demand for food, feed, bioenergy, material and seed. MAgPIE derives cell specific landuse patterns, rates of future agricultural yield increases, food commodity and bioenergy prices as well as GHG emissions from agricultural production and land-use change.

Emissions in the land-use and energy sectors are interlinked by overarching climate policy objectives and the deployment of bioenergy. REMIND and MAgPIE models are coupled to establish an equilibrium of bioenergy and emissions markets in an iterative procedure.

WITCH-GLOBIOM

WITCH (World Induced Technical Change Hybrid) is an integrated assessment model designed to assess climate change mitigation and adaptation policies. It is developed and maintained at the Fondazione Eni Enrico Mattei and the Centro Euro-Mediterraneo sui Cambiamenti Climatici. It is a global integrated assessment model with two main distinguishing features: a regional game-theoretic setup, and an endogenous treatment of technological innovation for energy conservation and decarbonization. A top-down inter-temporal Ramsey-type optimal growth model is hard linked with a representation of the energy sector described in a bottom-up fashion, hence the hybrid denomination. The regional and intertemporal dimensions of the model make it possible to differentiate and assess the optimal response to several climate and energy policies across regions and over time. The non-cooperative nature of international relationships is explicitly accounted for via an iterative algorithm which yields the open-loop Nash equilibrium between the simultaneous activities of a set of representative regions. Regional strategic actions interrelate through GHG emissions, dependence on exhaustible natural resources, trade of fossil fuels and carbon permits, and technological R&D spillovers. R&D investments are directed towards either energy efficiency improvements or development of carbon-free breakthrough technologies. Such innovation cumulates over time and spills across countries in the form of knowledge stocks and flows.

The competition for land use between agriculture, forestry, and bioenergy, which are the main land-based production sectors, is described through a soft link with a land use and forestry model (GLOBIOM, Global Biosphere Management Model, see ref[15], hence the name WITCH-GLOBIOM). A climate model (MAGICC) is used to compute climate variables from GHG emission levels and an air pollution model (FASST) is linked to compute air pollutant concentrations. While for this exercise WITCH is used for cost-effective mitigation analysis, the model supports climate feedback on the economy to determine the optimal adaptation strategy, accounting for both proactive and reactive adaptation expenditures.

WITCH-GLOBIOM represents the world in a set of a varying number of macro regions – for the present study, the eversion with 14 representative native regions has been used; for each, it generates the optimal mitigation strategy for the long-term (from 2005 to 2100) as a response to external constraints on emissions. A model description is available in ref [26] and [27], and a full documentation can be found at http://doc.witchmodel.org.

<u>GCAM-USA</u>

GCAM is a partial equilibrium integrated assessment model that couples a suite of dynamic-recursive models of the global energy, economy, agriculture and land-use systems with a reduced-form atmosphere-carbon-cycle-climate model[28]. GCAM-USA is a U.S.-focused version of version of the Global Change Assessment Model (GCAM) that breaks the energy and economy components of the U.S. into 50 states and the District of Colombia in addition to modeling the simultaneous interactions of 31 geopolitical regions outside of the U.S.[29,30]. The principle drivers of GCAM-USA are population growth, labor participation rates and labor productivity, along with representations of resources, technologies and policy. The energy system formulation in GCAM-USA consists of detailed representations of extractions of depletable primary resources such as coal, natural gas, oil and uranium along with renewable sources such as bioenergy, solar, wind and geothermal. Wind, solar and geothermal resources are represented at the state-level for the U.S. and at the level of the 31 other GCAM regions. The supply of bioenergy is modeled in the agriculture and land-use component of the model, along with competition for land among alternative uses, at the national level for the U.S. and at the level of the 31 other GCAM regions. GCAM-USA also includes representations of the processes that transform these resources to final energy carriers which are ultimately used to deliver goods and services demanded by end users in buildings, transportation and industrial sectors. Key energy transformation sectors (refining and electric power), and end-use sectors (buildings, transportation and industry) are modeled at the state-level for the U.S. and at the level of 31 other regions. Each technology in the model has a lifetime, and once an investment is made, technologies operate till the end of their lifetime or are shut down if the variable cost exceeds the market price. The deployment of technologies in GCAM depends on relative costs and is achieved using a logit-choice formulation which is designed to represent decision making among competing options when only some characteristics of the options can be observed.

Additional background on SDG investment needs calculations conducted externally to the IAMs

Energy access (SDG7)

Universal access to clean, reliable and modern energy services is one of the three targets underlying SDG7 (Target 7.1). Energy access is unequally distributed across the globe, with low income households in rural areas of developing countries that have inadequate infrastructure to modern energy supplies the most affected. The modelling of energy access calls for accounting for socio-economic heterogeneities, as well as spatial heterogeneities that determine reliance on solid fuels such as fuel wood, charcoal or hard coal for cooking. In this study we rely on the MESSAGE-Access model[31], a separate standalone residential cooking energy choice and demand model that is linked here through prices to scenario results from the different global IAMs. (A public version of the model is available at http://data.ene.iiasa.ac.at/MESSAGE-Access/.)

In the MESSAGE-Access model, population heterogeneity in affordability, access and availability of cooking fuels is accounted for by disaggregating households by income and urban/rural residence. This also allows for evaluating the distributional impacts of policies on different segments of the population. Cooking demands, expenditures, and household characteristics in the base year are calibrated using data derived from several large, nationally representative household surveys, including the following:

Uganda: Uganda National Household Survey (UNHS) 2012-2013
Ghana: Ghana Living Standards Survey (GLSS) 2012-2013
Nigeria: General Household Survey (GHS) 2012-2013
South Africa: Income and Expenditure Survey (IES) 2010-2011
India: National Sample Survey (NSS) 2011-2012

These surveys are combined to create aggregate regional versions of the model. For example, to create a regional version for Sub-Saharan Africa, household surveys from Nigeria and South Africa are scaled using survey household weights and the total population from the respective nation. Additionally, the surveys from Uganda and Ghana are combined and aggregated. These are then scaled to represent the remaining population of Sub-Saharan Africa. For the case of South Asia, the survey from India is considered representative of the entire region and simply scaled to represent the total population of South Asia.

For future scenarios, population and income projections are drawn from the Shared Socioeconomic Pathways (SSP) database (https://tntcat.iiasa.ac.at/SspDb/). Projections of Gini coefficients that measure income inequality within nations are from ref [32], and downscaling methods are applied from ref [33].

Prices for each cooking fuel derived from the IAMs are then run through the MESSAGE-Access model. In general, fuel prices reported by IAMs reflect marginal costs of producing an additional unit of fuel. These are a proxy for the cost to supply the fuel, but usually do not capture market and distribution costs such as retail profits that determine the market prices residential consumers face. To account for these differences, a fixed-margin adjustment is applied to align the IAM prices to those observed in the surveys. The adjustment is estimated as the difference in the shadow price in each model year from either the 2010 or 2020 price. The adjustment is then added to the base-year market price sourced from the surveys to reflect the future trajectory of changes in price under each scenario. In the case of mitigation scenarios, an additional fixed-margin adjustment, estimated as the difference between the IAM prices from the no policy case is calculated for 2020, and also applied to the 2020 price and price in each subsequent time period.

Policy costs of meeting the SDG target 7.1 for universal access to clean cooking by 2030 under each scenario are estimated employing the MESSAGE-Access model. These costs are calculated for the years 2020 and 2030 as the product of the lowest combination of fuel and stove subsidies on clean cooking solutions required to make these affordable universally by 2030 (i.e., ensuring that the entire underserved population transitions to 100% cleaner cooking as a result of these policies). We take these policy costs as investment costs, in the sense that they represent the amount of money that needs to be invested to ensure access via the fuel/stove subsidies. Average annual investment costs between today and 2030 are then derived as the average of the 2020 and 2030 values, assuming that these are gradually ramped up from an initial value of zero in 2010. Since the population without access to clean cooking in South Asia and sub-Saharan Africa represents approximately 64% of those without access globally in 2010, growing to 74% in 2030, we scale up the aggregate estimate of policy costs for South Asia and sub-Saharan Africa by ~40% (= 100% / 70%) to estimate global policy costs for achieving SDG 7.1 under each scenario, thereby accounting for underserved individuals in Southeast Asia, China, and Latin America (i.e., regions that are not explicitly modeled). This global scaling calculation inherently assumes that the per-individual policy costs to achieve universal access in these other parts of the world are the average of the South Asia and sub-Saharan Africa policy costs.

Air pollution (SDG3)

The aim of SDG Target 3.9 is to substantially reduce the number of deaths and illnesses from air pollution. For this we use the GAINS model to estimate the expenditures (capital + O&M + fuel) needed for air pollution control technologies that will limit harmful air pollutant emissions and slow the growth in premature deaths worldwide, particularly due to fine particulate matter (PM2.5).

GAINS (Greenhouse gas and Air pollution INteractions and Synergies) is an integrated policy analysis tool that follows the pathways of atmospheric pollution from driving forces through the key emission sources to the most relevant health and environmental impacts[18]. Within the CD-LINKS project, the focus is placed on the pollutants that contribute directly or act as precursors of fine particles PM2.5 and tropospheric ozone; these include primary particulate matter (predominately fine particles PM2.5), secondary PM precursors (SO2, NOx, NH3), and substances contributing to the ozone formation (NOx and NMVOCs).

In GAINS emissions of the pollutants under examination are calculated as the product of the activity levels, the "uncontrolled" emission factor in absence of any emission control measures, a factor adjusting for the removal efficiency of emission control measures and the application rate of such measures across fuels and sectors. The penetration of specific control technologies defines a “control strategy”, which reflects the level of implementation of emission abatement techniques in order to comply with the legislation and adoption of environmental standards. We note that the GAINS database contains information about hundreds of abatement technologies (or measures) in numerous sectors, applicable to a range of activities or energy carriers.

Projections of economic activities of different types – e.g., energy supply and demand, industrial production, transport, agriculture – are exogenous inputs into the GAINS database and constitute a basis for the emission and impact computation. Activity data are provided to GAINS from MESSAGEix-GLOBIOM. Since these data have in many cases different levels of technological detail or geographical resolution than those of GAINS, it is necessary to perform some form of aggregation in order to relate the inputs and GAINS structures to each other. The scaling algorithm ensures that the resulting energy projections adopted in GAINS correspond to overall primary energy consumption of the main energy carriers as provided by the energy models. The model interface is implemented as a set of database queries that provide a consistent and efficient means of repeating the model linkage whenever required.

More information on the linkage between IAMs and GAINS to carry out air pollution and health impact calculations can be found in ref [34].

Education (SDG4)

SDG4 aims to “ensure inclusive and equitable quality education and promote life-long learning opportunities for all”. Among the most concrete targets is 4.1, which states that “by 2030, ensure that all girls and boys complete free, equitable and quality primary and secondary education leading to relevant and effective learning outcomes.” In our analysis, this goal has been concretely translated into the share of adults across the world who theoretically could be – given the short time horizon – and would have to be educated at each attainment level in order to meet this goal[35]. The data from the Abel et al. study provides the share of adults who have up to primary and up to secondary attainment in each subsequent five year period. This, combined with population projections, provides an estimate of the total person-years of education between now and 2030 that would be required to attain SDG Target 4.1. We apply these attainment shares to population projections for SSP2, the middle-of-the-road SSP, which are largely consistent with the underlying model of the SDG projections in Abel et al. The uncertainty lies in the fact that education attainment in an SSP2 scenario is likely to be lower than the SDGs, but on the other hand, due to this lower attainment, the population projections are likely to be correspondingly higher than population growth under successfully attained SDGs, because of the effect of education on reducing fertility.

Regarding the costs, the premise of the analysis is that a greater policy emphasis on achieving SDG Target 4.1 would be accompanied by a corresponding increase in educational expenditures on primary and secondary school students. Note that these expenditures could ultimately be insufficient to achieve the SDG Target 4.1, since the causes of low educational attainment are many, they vary by context, and are often attributable to non-monetary factors, such as teacher absenteeism.

To estimate per-student expenditures, we use the average primary and secondary education costs per student for countries that have less than 10 percent of the adult population without primary education, which is approximately $1,000 for primary and lower secondary, and $1,500 for upper secondary. The costs of education per student are typically higher by an order of magnitude for tertiary education compared to primary and secondary. Average national expenditure on education, thus, would significantly overestimate education investment costs. We therefore use average costs per student by attainment level from UNESCO's Institute for Statistics (http://uis.unesco.org/en/home). Typically among countries that have full attainment of primary/secondary education, average costs per student increase with income level, reflecting improved facilities and infrastructure. Considering that the countries that have to accelerate education efforts tend to be poor, applying a global average cost would also be unrealistic. Focusing on the lower income countries that have high attainment provides a more conservative and likely realistic estimate of true investment costs.

Combining the above assumptions on the demand gap and related costs, we estimate that achieving SDG Target 4.1 would require investments of around 180 billion US$/year (in constant purchasing power parity dollars) between 2015 and 2030. The costs are dominated by those for secondary education for a number of reasons, namely because the demand gap is much higher for secondary than for primary and because secondary has a longer duration than primary (8 vs. 4).

Note that only those students who begin primary school by 2018 (and secondary by 2022) are included in our estimates of educational expenditures. This is because any student who starts school after these points in time will not be able to achieve secondary-level attainment before 2030, since they would not finish by then. In other words, even though these latter students may be in either primary or secondary school in the year 2030, we do not include their associated educational costs in our estimates of achieving SDG Target 4.1.

Food security (SDG2)

Extreme hunger and malnutrition remain a huge barrier to development in many countries. 795 million people are estimated to be chronically undernourished as of 2014, often as a direct consequence of environmental degradation, drought and loss of biodiversity. Over 90 million children under the age of five are dangerously underweight. And one person in every four still goes hungry in Africa.

SDG Target 2.1 aims to end all forms of hunger and malnutrition by 2030, making sure all people – especially children – have access to sufficient and nutritious food all year round. This involves promoting sustainable agricultural practices: supporting small scale farmers and allowing equal access to land, technology and markets. It also requires international cooperation to ensure investment in infrastructure and technology to improve agricultural productivity.

To be sure, none of the scenarios generated for this study achieve zero hunger by 2030. Instead, SDG Target 2.1 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. These policies can have negative side-effects on food security though increasing agricultural prices – via non-CO2 emissions abatement, GHG tax penalties on residual emissions, bioenergy expansion and afforestation. Therefore, here we define food policy packages which prevent such agricultural demand from such negative side-effects. In other words, the 'investments' we estimate for food security are actually the food policy costs needed to compensate the poor for any increases in food costs.

These policy measures ensure the food consumption as the level of baseline ('CPol'). We computed two illustrative food policy cost metrics; namely 1) food aid to make up for any reductions in food demand, and 2) food subsidies to bring food prices back down to levels seen in the baseline. The subsidy is computed by the agricultural price index (2005=1) and agricultural demand for each scenario. Although these measures could overestimate or underestimate the food policy cost because they can be used for not only the poor but rich people or additional food demand associated aid would upscale the price further, the first order of the magnitude can be captured by them. Ref [36] discuss this methodology in greater detail.

Clean water and sanitation (SDG6)

Universal access to clean water and sanitation, which is the objective underlying SDG6, is unequally distributed across the globe, with low income households in rural areas of water-stressed developing countries most affected[37,38]. Increasingly stringent wastewater treatment standards in line with environmental guidelines can also require energy-intensive processing, with implications for emissions and energy sector investments. Moreover, water conservation strategies aligned with the SDG6 water efficiency indicator can constrain energy supply, as large volumes of water are currently used for energy resource development and electric power generation.

In this work, we assessed future water use and wastewater flows in conjunction with energy transformation across the industry and households/municipal sectors (agriculture irrigation investments are not included) to explore the costs and characteristics of global infrastructure pathways consistent with important elements of the SDG6 objectives. The MESSAGE integrated assessment model (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. Additional investment, energy and emissions resulting from the water sector development are accounted for in the IAM explicitly.

The SDG6 objectives are translated to indicators in MESSAGE by combining spatially-explicit projections of urban, rural and manufacturing water demands with projections of infrastructure connection rates, costs and water scarcity[39,40]. Connection and treatment rates increase with income-level in the model based on a logistic curve fit to harmonized national data for 2010 from ref [37]. The SDG6 objectives for universal clean water and sanitation access are reflected as additional constraints in MESSAGE, and result in accelerated expansion of piped freshwater and wastewater treatment access, towards the levels seen today in western European countries. The analysis estimates, in comparison with a baseline water sector development scenario representing a continuation of existing trends, 2.5 billion more people need piped water infrastructure and 1.3 billion more people need wastewater collection/treatment, in order to meet the SDG6 targets by 2030. Water efficiency and scarcity targets associated with SDG6 are also simulated by constraining freshwater intensity (the amount of freshwater consumed per unit of economic activity) to improve by more than 50% relative to a baseline scenario by 2030. The additional constraints promote shifting to water-efficient energy technologies, investing in water conservation, and expansion of wastewater recycling and desalination.

Incremental SDG policy and infrastructure costs can be estimated as the difference between the costs modeled in the scenario that achieves the SDG6 targets and the costs modeled in the baseline scenario. The baseline scenario includes water sector development projected under the SSP2 (mid-range) income trajectories. Results demonstrate that measures taken to ensure the SDG6 targets are achieved require additional expenditures, mainly because the SDG6 objectives involve a massive upscaling of water infrastructure. Our estimates compare well with previous analysis of the SDG targets for drinking water and sanitation[38]. This work goes further by also quantifying costs associated with the rapid expansion of wastewater recycling and desalination to meet water efficiency and scarcity targets, which is found to comprise a considerable share of global water infrastructure spending to 2030 under the SDG6 pathway.

The water-related expenditures we estimate include investments, fixed, and variable costs (both energy and non-energy in the latter case). The cost categories considered are the following:

- Water storage (excluding reservoirs built for hydropower, which are included in the power sector costs)
- Distribution (pumps and piping that move water from sources to end-users)
- Sewerage (wastewater collection and distribution)
- Wastewater treatment (secondary wastewater treatment)
- Wastewater recycling (wastewater recycling / tertiary treatment)
- Desalination (of sea water)
- Municipal and manufacturing efficiency
- Water cooling technologies for power plants (once-through and closed-loop systems)

Supplementary References

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