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Abstract

The levels of investment needed to mobilize an energy system transformation and mitigate climate change are not known with certainty. This paper aims to inform the ongoing dialogue and in so doing to guide public policy and strategic corporate decision making. Within the framework of the LIMITS integrated assessment model comparison exercise, we analyze a multi-IAM ensemble of long-term energy and greenhouse gas emissions scenarios. Our study provides insight into several critical but uncertain areas related to the future investment environment, for example in terms of where capital expenditures may need to flow regionally, into which sectors they might be concentrated, and what policies could be helpful in spurring these financial resources. We find that stringent climate policies consistent with a 2°C climate change target would require a considerable upscaling of investments into low-carbon energy and energy efficiency, reaching approximately $45 trillion (range: $30-75 trillion) cumulative between 2010 and 2050, or about $1.1 trillion annually. This represents an increase of some $30 trillion ($10-55 trillion), or $0.8 trillion per year, beyond what investments might otherwise be in a reference scenario that assumes the continuation of present and planned emissions-reducing policies throughout the world. In other words, a substantial "clean-energy investment gap" of some $800 billion/yr exists – notably on the same order of magnitude as present-day subsidies for fossil energy and electricity worldwide ($523 billion). Unless the gap is filled rather quickly, the 2°C target could potentially become out of reach.

Keywords: integrated assessment, energy scenarios, climate change, policy analysis, carbon financing

1. Introduction and motivation

Mitigating the effects of climate change requires transformative changes in the way society produces and consumes energy (Edenhofer et al. 2010; IEA 2012a; IPCC 2007; Riahi et al. 2012). These changes, in turn, will necessitate a realignment of energy investment portfolios, moving beyond today's fossil-based energy system to one that makes greater use of low-carbon energy forms and highly-efficient end-use technologies. What this mix of investments should look like is very much an open question, however, especially at the national and regional level. Few studies have explored such questions in any detail (examples include Riahi et al. (2012), IEA (2012b), and Carraro et al. (2012)).

In this paper we analyze a multi-model ensemble of long-term energy and emissions scenarios that were developed within the framework of the LIMITS (Low climate IMpact scenarios and the Implications of required Tight emission control Strategies) model inter-comparison exercise. The diverse nature of these integrated assessment models (IAM) highlights large ranges in the potential development of the energy system (at both the global and regional levels) over the course of the twenty-first century, particularly in pathways that aim to keep the maximum rise in average global temperature to 2°C above the pre-industrial level with a high degree of likelihood (>70% probability).[1] Scenario results from five different IAMs are analyzed in this paper: IMAGE (van Vuuren 2007), MESSAGE (Riahi et

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[1] The 2°C target is currently supported by over 190 countries in the context of the United Nations Framework Convention on Climate Change (UNFCCC) as a limit to avoid dangerous anthropogenic climate change.

al. 2007), REMIND (Luderer et al. 2012b), TIAM-ECN (Keppo and Zwaan 2012), and WITCH (Bosetti et al. 2009). (The GCAM model (Calvin 2011) is also included for a specific analysis relating to electric sector investments; see supplementary material.)

One of the critical uncertainties on the path to 2°C relates to the required levels of future investment into energy-supply and demand technologies: how much is needed, where should the capital flow, into which sectors, and what policies are needed. Each of these questions is taken up in this paper. In so doing, we necessarily explore and explain some of the differences amongst the models. The overarching aim, however, is not to delve deeply into the particulars of the models themselves, but rather to focus on the robust findings across the models, in order to provide insights that may be useful for public policy and corporate strategy. (For an analysis of *total* investment flows across all sectors of the macro-economy, not only energy, see Bowen et al. (this issue); and for clean-energy research and development investment needs, see Marangoni and Tavoni (this issue).) Moreover, it should be noted that while the scenario pathways discussed in this paper allow for a systematic exploration of a wide range of energy investment strategies going forward, they do not span all possible future states of the world. Hence, uncertainties in investments might be larger than those assessed here.

In carrying out the analyses discussed above, we focus primarily on a subset of the twelve LIMITS scenarios. These scenarios are briefly described in Table 1 and then referred to throughout the paper. (A more detailed description of the overall study design and models employed can be found in the two LIMITS overview papers: Kriegler et al. (this issue) and Tavoni et al. (this issue).) We note, in particular, that RefPol, which already includes a certain amount of climate and clean-energy policy, is used as the reference policy scenario here. While this choice makes direct comparison with previous integrated assessment studies a bit more of a challenge, the added value is that RefPol takes into account those climate-related policies that are already "on the books" (e.g., the European Union's "20-20-20" targets; see supplementary material for a full listing). The RefPol scenario therefore reflects the early bridges to the green economy that policy makers have implemented in various countries and regions throughout the world. That said, it is entirely conceivable that actual outcomes could fall below the marks that have been set, particularly in those countries with ambitious plans for renewable energy (e.g., Europe) or nuclear power (e.g., China).

Table 1. Brief descriptions of the subset of LIMITS scenarios used in this study (see Kriegler et al. (this issue) and Tavoni et al. (this issue) for further details).

Scenario	***Description***
Base	Scenario with no climate change mitigation policies of any kind. This "no-policy baseline" is used for comparative purposes in the paper.
RefPol	Scenario with present and planned climate-related policies and regulations implemented in those regions where they exist. Examples include greenhouse gas (GHG) emissions reduction targets, GHG intensity reduction targets, and nuclear power and renewable energy targets (see supplementary material for specific targets by region). Policies with a time horizon to 2020 are extended to 2100 assuming efforts continue at a similar level of stringency. This "reference policy scenario" is considered a more representative baseline than the Base scenario and is therefore used primarily as the reference case for comparison in this analysis. See Kriegler et al. (this issue) and Tavoni et al. (this issue) for further information on the policies assumed in this scenario.
RefPol-450	Climate change mitigation scenario that leads to radiative forcing of 2.8 W/m^2 in 2100 (overshoot allowed in the interim), not including direct forcing from land use albedo changes, mineral dust aerosols, and nitrate aerosols. Such a forcing target would yield a 'likely to very likely' (>70%) chance of staying below the 2°C target over the century. Mitigation commences immediately after 2020; the RefPol reference policy pathway is followed up until that point. Mitigation occurs where and when (after 2020) it is most cost-optimal (thus, globally-harmonized carbon prices). No burden-sharing regimes are in place.

Figure 1 gives an initial indication of how these scenarios are interpreted by the various LIMITS models by showing global carbon dioxide (CO_2) emissions from fossil fuel combustion and industrial processes over the next several decades. The implementation of current and planned climate policies (RefPol) is seen to have a marked impact on emissions, relative to a hypothetical no-policy counterfactual scenario (Base). However, far deeper cuts in emissions are needed if the 2°C target is to be successfully achieved (RefPol-450). Model outcomes diverge for a number of reasons, including, but not limited to, assumptions on resources (availability and cost) and technological parameters (efficiencies, unit investment costs, growth rates, learning rates), as well as future energy demand assumptions (which typically derive from population and gross domestic product projections). Models also differ from a structural perspective. Some utilize linear programming algorithms with perfect foresight; others are built on simulation approaches operating within a recursive-dynamic framework; still more make use of decision making algorithms that build upon other concepts, such as game-theory or agent-based approaches. Both the parametric assumptions and the methodological and conceptual differences across models have an important impact on how the energy investments story plays out at the regional level, as this paper shows.

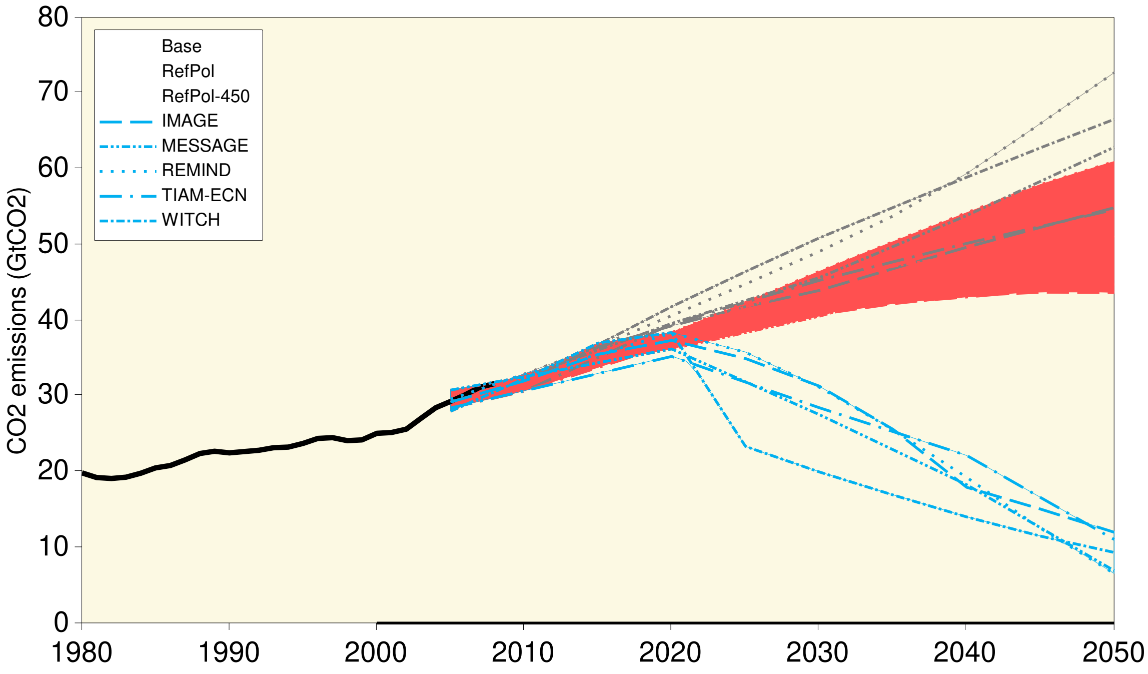

Figure 1. Global CO_2 emissions from fossil fuel combustion and industrial processes across the various models in the Base, RefPol, and RefPol-450 scenarios.

2. Nature and composition of the current energy investment portfolio

Energy is big business: in 2010 supply-side investments into the global energy system amounted to roughly $1000 billion/yr (Figure 2)[2], or approximately 2% of world gross domestic product (GDP). About half of that investment flowed to the developing world and half to currently industrialized countries (see Table 2 for a regional breakdown). Relative to GDP, the average investment intensity of developing economies was around 3.5%, while it was a much lower 1.3% in industrialized countries. According to the Global Energy Assessment (Riahi et al. 2012), fossil-related investments (including coal, oil, and natural gas extraction; fossil electricity generation; oil and gas pipelines; liquefied natural gas terminals; oil refineries; and synthetic fuel plants) are currently the single most dominant investment category on the supply-side, accounting for $500 billion/yr worldwide (Riahi et al. 2012).[3] Investments into electricity transmission and distribution ($260 billion/yr), renewable electricity ($160 billion/yr), nuclear energy ($40 billion/yr), bioenergy extraction and biofuels production ($35 billion/yr), and heating plants ($24 billion/yr) make up the remainder of the investment pie. Interestingly, electricity transmission and distribution (T&D) investments are of roughly the same magnitude as total investments into electricity generation ($270 billion/yr). (See Table 2 and Section 3.2 for further details of the investment breakdown by sector, both at present and in the future.)

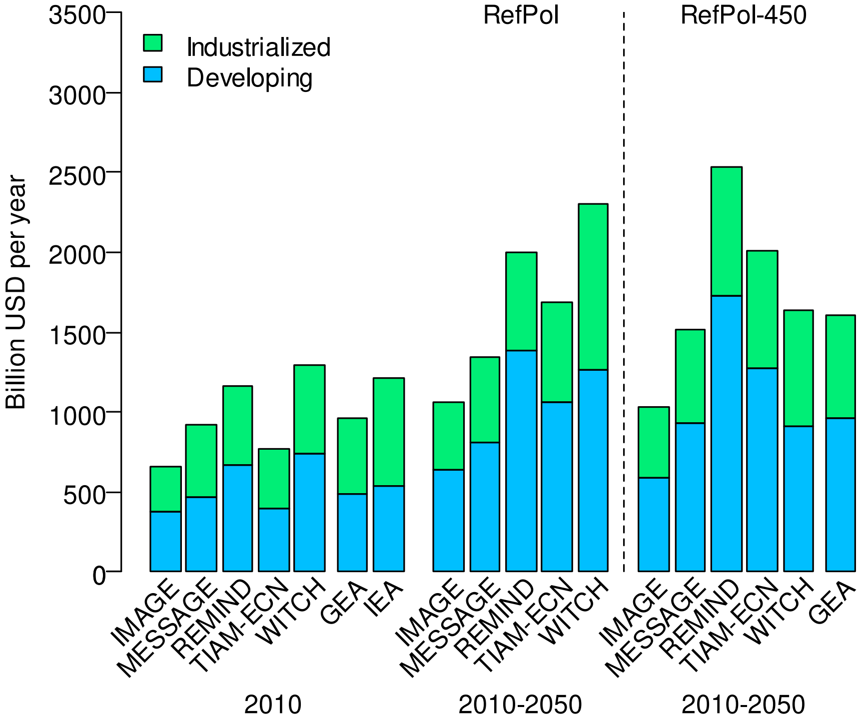

Figure 2. Global annual energy investments (supply-side only) across the various models in 2010 and average annual investments from 2010 to 2050 in the RefPol and RefPol-450 scenarios, in both industrialized and developing countries. See Box 1 for regional definitions. For comparison, estimates from the International Energy Agency (IEA 2012b) and Global Energy Assessment (Riahi et al. 2012) are also shown, where applicable.

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[2] All monetary values in this paper are given in 2005 US dollars using market exchange rates. All cumulative values are undiscounted, unless otherwise specified.

[3] Note that these estimates exclude investments for fossil fuel exploration, which totals ~$50 billion/yr at present (Riahi et al. 2012).

The LIMITS models show some uncertainty surrounding the $1000 billion/yr supply-side investment number reported above from the Global Energy Assessment (GEA): some are higher, others are lower (Figure 2). These base-year differences are noteworthy since they extend into the future as well. To be sure, tracking investments into the energy system – in all countries and at all stages of the supply chain – is by no means an exact science. Variations can be explained by the different ways in which historical (2010 and before) capital stocks are tracked and accounted for within models. This also includes estimates reported by the International Energy Agency (IEA 2012b)[4], which like the GEA numbers[5], are shown in Figure 2 in order to place both the base-year and future investment estimates of the LIMITS models in the wider context of the published literature. The IEA and GEA studies are both independent and data-driven. The former uses publicly available investment data reported by energy companies to arrive at its estimates, while the latter utilizes a systems engineering modeling approach (including a detailed vintage structure of historical energy-supply capacities), the first step of which requires benchmarking with published energy statistics from multiple sources (e.g., IEA and the Platts World Electric Power Plants Database).

Not shown in Figure 2 are demand-side investments for 2010, estimates of which are subject to considerable uncertainty, owing to a lack of reliable statistics and definitional issues (i.e., what exactly is a purely energy-related investment on the demand side?). According to the most comprehensive external analysis of such investments to date (Grubler et al. 2012), it has been estimated that around $300 billion/yr (range: $100-700 billion/yr) is spent annually on energy components at the service level, such as on engines in cars, boilers in building heating systems, and compressors, fans, and heating elements in large household appliances. If, instead, the full costs of demand-side technologies were to be considered (e.g., all parts of the car or refrigerator), then total demand-side investments (as well as their corresponding uncertainty range) would increase by almost an order of magnitude: $1700 billion/yr (range: $1000-3500 billion/yr). According to the authors of the Grubler et al. (2012) study (see Case Study 20 of their appendix), end-use technology volume data (production, delivery, sales, and installations) and price estimates were used to approximate these investment figures globally.

The current global investment picture masks large differences between regions, in terms of the nature and composition of the portfolio. Capital expenditures in regions with relatively low fossil resource endowments (e.g., Europe, India, China, and the Pacific OECD countries, excluding Australia) are dominated overwhelmingly by electricity generation and T&D investments. On the other side are fossil-rich regions, such as Africa and the Middle East, whose investment portfolios center almost exclusively around fossil fuel extraction. North America and Latin America can be found somewhere between these two extremes. Moreover, at approximately $200 billion/yr each, total supply-side investments are at present roughly the same in both China and North America. Meanwhile, investments in Europe are approximately $150 billion/yr, whereas all other regions see less than $100 billion/yr in investment today. Much lower are total supply-side investments in Sub-Saharan Africa, amounting to just $30 billion/yr at present despite the large size of the continent and its considerable population. Such a disparity illustrates the close tie between energy investment and economic development. For a detailed summary of the investment picture by region, see Table 2. (Box 1 provides an explanation of the regional definitions used in this paper.)

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[4] IEA numbers are actually for 2012, not 2010, as suggested in Figure 2. Because the IEA does not report all investment categories for historical years, focusing instead on cumulative future estimates to 2035, we have reconstructed the IEA numbers for 2012 here, using sector- and region-specific energy activity levels (from other parts of their report) as proxies. Therefore, the IEA investment levels we show for 2010 are only an approximation and, if anything, lead to somewhat of an overestimate.

[5] The GEA scenario referred to here is the MESSAGE interpretation of the illustrative GEA-Mix pathway, which is similar to the RefPol-450 scenario in that it achieves the 2°C target with >50% probability. See Riahi et al. (2012) for more details.

Box 1. Regional definitions used in this paper

This paper adopts the same regional definitions as used in the overall LIMITS project, namely the ten “super regions” (plus a Rest of World region). Each of these regions is comprised of a number of geographically- and/or culturally-similar countries (thus with relatively similar energy system structures and requirements). The harmonized set of regions has been chosen so that comparisons can be performed across the suite of LIMITS models. Because the native regions in these models all differ, it would otherwise be difficult, if not impossible, to carry out such regional comparisons. The 10+1 super regions offer a kind of “least common denominator” for this purpose: they represent the most disaggregated set of harmonized regions that could be attained. Nevertheless, not even this set provides a perfect match across the LIMITS models; notable discrepancies are marked below, where applicable. The full list of the super regions is given below, along with a sampling of countries that are included in each (the country lists are meant to be representative, not exhaustive).

AFRICA	*countries of Sub-Saharan Africa; some models also include North African countries, others do not; for REMIND and WITCH South Africa is included in the REST_WORLD region*
CHINA+	*countries of centrally-planned Asia; primarily China; for some models this may also include Cambodia, Vietnam, North Korea, Mongolia, etc.*
EUROPE	*countries of Eastern and Western Europe (i.e., the EU27); some models (except REMIND and WITCH) also include Turkey*
INDIA+	*countries of South Asia; primarily India; for some models this may also include Nepal, Pakistan, Bangladesh, Afghanistan, etc.*
LATIN_AM	*countries of Latin America and the Caribbean; Mexico, Brazil, Argentina, and other countries of Central and South America*
MIDDLE_EAST	*countries of the Middle East; Iran, Iraq, Israel, Saudi Arabia, Qatar, etc.; for some models this may also include countries of North Africa (e.g., Algeria, Egypt, Morocco, Tunisia); for REMIND the former Soviet states of Central Asia are included*
NORTH_AM	*countries of North America; primarily the United States of America and Canada; for REMIND Canada is included in the REST_WORLD region, for WITCH it is included in the PAC_OECD region*
PAC_OECD	*countries of the Pacific OECD (Organisation for Economic Co-operation and Development); for most models this primarily includes Japan, Australia, and New Zealand; for REMIND only Japan is included, Australia and New Zealand are included in the REST_WORLD region; WITCH does not include Australia, which is instead part of the REST_WORLD region; WITCH also includes Canada in the PAC_OECD*
REF_ECON	*countries from the Reforming Economies of Eastern Europe and the Former Soviet Union; primarily Russia, Ukraine, Kazakhstan, Azerbaijan, etc.; for WITCH Turkey is also included; for REMIND this region only includes Russia*
REST_ASIA	*other countries of Asia; South Korea, Malaysia, Philippines, Singapore, Thailand, Indonesia, etc.; for WITCH South Korea is included in the REST_WORLD region*
REST_WORLD	*only consists of countries for REMIND and WITCH that are not categorized elsewhere; for REMIND this includes Australia, Canada, Iceland, Norway, New Zealand, Moldova, Serbia, South Africa, Switzerland, Turkey, Ukraine, and some other smaller countries; for WITCH this includes Australia, South Africa, and South Korea*

Note that when we refer to “Industrialized” countries in this paper, we are referring to those countries that comprise the following regions: EUROPE, NORTH_AM, PAC_OECD, REF_ECON, and REST_WORLD. All other regions are then a part of the “Developing” world. We recognize that this grouping creates some non-trivial inconsistencies for the REMIND and WITCH models, though they are not enough to alter the overall results and conclusions of this paper.

Table 2. Annual energy investments in 2010 (GEA and IEA data) and averages for 2010-2050 (across LIMITS models) in the RefPol and RefPol-450 scenarios, by energy sector and region. Units: billions of US$/yr. Uncertainty bands span the range of (i) GEA and IEA data for 2010, and (ii) output from LIMITS models for 2010-2050. ‘NA’ (not applicable) refers to categories for which model estimates are unavailable. Totals may not add because of the heterogeneous “REST_WORLD” region (not shown here; see Box 1 for explanation).

2010

	Extraction		Electricity				Liquids		Others	Efficiency	TOTAL
	Fossil Fuels	Others	Fossil Fuels	Renewables	Nuclear	TD and Storage	Fossil Fuels	Biofuels	Others	Efficiency	Total
AFRICA	17 - 87	1	2 - 6	1 - 3	0 - 0	6 - 9	0.8 - 2	0 - 0	0.2 - 8	NA	28 - 115
CHINA+	25 - 48	0	14 - 36	14 - 48	1 - 1	41 - 66	1.0 - 10	0.2 - 0	4.6 - 16	NA	133 - 193
EUROPE	38 - 58	6	16 - 20	28 - 39	0 - 6	37 - 47	2.4 - 6	1.5 - 2	0.5 - 20	NA	151 - 177
INDIA+	8 - 10	2	7 - 12	6 - 7	0 - 1	13 - 15	2.2 - 8	0 - 0	0.3 - 3	NA	42 - 51
LATIN_AM	30 - 69	4	2 - 4	8 - 19	0 - 0	11 - 16	2.0 - 2	1.3 - 4	0 - 3	NA	76 - 99
MIDDLE_EAST	43 - 76	0	5 - 6	1 - 3	0 - 0	6 - 13	4.3 - 5	0 - 0	0 - 8	NA	69 - 101
NORTH_AM	77 - 157	7	26 - 28	17 - 23	0 - 5	49 - 56	1.7 - 4	3.0 - 6	0.9 - 21	NA	199 - 283
PAC_OECD	8 - 12	1	4 - 13	5 - 12	1 - 5	10 - 15	0.9 - 2	0.0 - 0	0.0 - 5	NA	42 - 51
REF_ECON	64 - 86	0	6 - 24	0 - 3	1 - 6	10 - 19	2.9 - 4	0.1 - 0	5.4 - 17	NA	90 - 159
REST_ASIA	13 - 30	1	6 - 9	2 - 6	0 - 1	16 - 18	3.1 - 5	0.1 - 1	1.3 - 6	NA	44 - 74
Developing	168 - 286	8	51 - 58	38 - 80	1 - 4	98 - 133	13.4 - 32	1.6 - 5	17.6 - 32	NA	484 - 542
Industrialized	187 - 313	14	53 - 84	52 - 75	2 - 22	115 - 128	7.8 - 16	4.7 - 9	6.8 - 62	NA	482 - 670
World	355 - 599	22	111 - 135	90 - 155	3 - 26	213 - 261	21.2 - 48	6.3 - 14	24.4 - 94	NA	965 - 1212

RefPol

	Extraction		Electricity				Liquids		Others	Efficiency	TOTAL
	Fossil Fuels	Others	Fossil Fuels	Renewables	Nuclear	TD and Storage	Fossil Fuels	Biofuels	Others	Efficiency	Total
AFRICA	20 - 55	0 - 12	6 - 22	3 - 13	0 - 1	6 - 28	2.1 - 25	0.2 - 14	0.0 - 19	0 - 2	72 - 129
CHINA+	23 - 102	3 - 8	33 - 70	29 - 94	4 - 35	63 - 95	5.5 - 33	0.0 - 6	0.0 - 33	1 - 31	204 - 403
EUROPE	16 - 59	3 - 11	5 - 16	27 - 47	0 - 28	32 - 67	2.4 - 13	0.2 - 16	1.2 - 14	5 - 27	143 - 266
INDIA+	7 - 29	1 - 5	26 - 46	13 - 27	2 - 28	30 - 57	2.3 - 9	0.0 - 9	0.0 - 25	0 - 8	129 - 198
LATIN_AM	28 - 148	1 - 9	4 - 20	11 - 37	0 - 3	20 - 31	2.1 - 15	0.3 - 17	0.0 - 16	0 - 7	117 - 233
MIDDLE_EAST	30 - 326	0 - 1	7 - 36	2 - 3	0 - 3	14 - 36	3.6 - 22	0.0 - 1	0.0 - 24	0 - 0	59 - 393
NORTH_AM	36 - 157	3 - 6	12 - 45	20 - 29	0 - 37	43 - 58	1.4 - 12	1.5 - 10	0.3 - 17	3 - 21	170 - 333
PAC_OECD	5 - 84	0 - 2	2 - 7	4 - 20	0 - 20	9 - 23	0.8 - 2	0.0 - 5	0.0 - 2	0 - 16	37 - 176
REF_ECON	40 - 151	0 - 2	6 - 26	1 - 8	4 - 32	10 - 49	2.1 - 9	0.3 - 11	0.0 - 8	0 - 2	86 - 272
REST_ASIA	10 - 56	1 - 6	6 - 40	7 - 13	0 - 8	13 - 46	1.5 - 31	0.1 - 6	0.0 - 19	1 - 5	62 - 192
Developing	124 - 644	10 - 39	85 - 205	86 - 169	7 - 66	197 - 289	20.8 - 135	1.2 - 38	0.0 - 135	8 - 38	667 - 1393
Industrialized	97 - 494	10 - 18	33 - 77	59 - 93	5 - 128	108 - 183	7.8 - 37	6.5 - 29	3.0 - 55	17 - 76	438 - 1119
World	222 - 1138	25 - 56	118 - 282	146 - 256	12 - 172	306 - 422	28.5 - 164	9.4 - 62	5.9 - 190	30 - 114	1105 - 2425

RefPol-450

	Extraction		Electricity				Liquids		Others	Efficiency	TOTAL
	Fossil Fuels	Others	Fossil Fuels	Renewables	Nuclear	TD and Storage	Fossil Fuels	Biofuels	Others	Efficiency	Total
AFRICA	6 - 58	4 - 19	2 - 26	13 - 72	0 - 3	5 - 40	0.3 - 4	0.1 - 16	0.1 - 19	9 - 72	59 - 243
CHINA+	12 - 91	8 - 16	13 - 69	43 - 171	9 - 107	60 - 142	4.5 - 9	0.1 - 41	0.0 - 26	29 - 146	202 - 674
EUROPE	9 - 29	8 - 15	3 - 14	39 - 69	4 - 38	35 - 67	2.3 - 11	0.6 - 20	5.2 - 20	18 - 68	177 - 272
INDIA+	1 - 27	5 - 9	13 - 43	32 - 94	6 - 54	32 - 78	1.6 - 4	0.1 - 20	0.8 - 18	23 - 93	171 - 392
LATIN_AM	15 - 52	5 - 15	4 - 13	17 - 77	0 - 5	18 - 51	2.0 - 3	0.6 - 27	0.9 - 14	22 - 50	132 - 275
MIDDLE_EAST	19 - 121	1 - 5	6 - 41	5 - 36	0 - 5	12 - 38	1.8 - 8	0.0 - 18	0.2 - 17	13 - 69	63 - 330
NORTH_AM	20 - 142	7 - 17	11 - 29	35 - 92	0 - 61	43 - 63	0.8 - 8	0.6 - 36	4.6 - 12	38 - 96	212 - 417
PAC_OECD	3 - 10	1 - 7	1 - 7	8 - 30	2 - 27	8 - 21	0.4 - 2	0.7 - 7	0.9 - 3	6 - 31	48 - 116
REF_ECON	26 - 79	2 - 11	4 - 20	7 - 16	4 - 47	10 - 37	0.5 - 6	0.0 - 15	0.7 - 12	8 - 77	105 - 243
REST_ASIA	4 - 60	6 - 10	5 - 34	10 - 70	0 - 33	12 - 63	1.5 - 5	0.1 - 19	2.5 - 14	17 - 75	83 - 314
Developing	83 - 351	37 - 56	64 - 196	121 - 509	22 - 161	165 - 411	14.9 - 24	1.2 - 132	7.1 - 108	144 - 497	750 - 2228
Industrialized	61 - 238	20 - 39	25 - 63	91 - 220	10 - 183	102 - 183	7.1 - 26	5.9 - 76	12.8 - 56	82 - 287	542 - 1011
World	143 - 590	62 - 104	94 - 259	212 - 729	55 - 312	267 - 594	22.1 - 50	7.1 - 208	26.7 - 164	226 - 704	1292 - 3202

3. Aligning the investment portfolio with the 2°C target

Achieving deep cuts in GHG emissions necessitates a pronounced reallocation of investment flows compared to the status quo. This section discusses where future investments could potentially need to flow (into which world regions and energy sectors), if global temperature increase is to be kept to less than 2°C above the pre-industrial level with a high degree of likelihood (>70% probability).

3.1 Future investment requirements: where, when, and how much?

Meeting the future energy service demands of a growing number of consumers will require a significant upscaling of investments over the next several decades, regardless of the presence or absence of climate policy. On the current path – with only the reference set of emissions-reducing policies in place in a subset of countries – average annual supply-side investments into the global energy system (between 2010 and 2050) could increase by at least 50%, if not double, compared to today. This is shown by the RefPol scenario in Figure 2. Implementation of even more stringent climate policies after 2020, in the context of concerted, global action to achieve the 2°C target (as envisioned in the RefPol-450 scenario), would for most models lead to a further increase in investments on the supply side. On this point, and for later discussions in the paper, it is important to note that the investment differences between the RefPol and RefPol-450 scenarios emerge entirely from the period 2020-2050. By definition, the scenarios are the same until 2020 (following the reference policy case); hence; they have the same investment requirements over the 2010-2020 period.

As with the current investment picture, Figure 2 indicates a considerable spread in future investments across the different models, though not always for the same reasons. For a given model, investment requirements depend on the evolution of the energy system foreseen in a particular scenario. Models naturally differ in how the energy-supply mix changes over time: as discussed previously, potential sources of variation can be explained by differences in both parametric assumptions and methodological/conceptual frameworks. A sweeping discussion of these issues, and of model outcomes more generally, is outside the scope of this paper. For more information, the interested reader is referred to the other cross-comparison papers of the LIMITS special issue (e.g., Calvin et al. (this issue), Jewell et al. (this issue), Kriegler et al. (this issue), Sluisveld et al. (this issue), Tavoni et al. (this issue), van der Zwaan et al. (this issue)), as well as the publicly-available LIMITS Scenario Database[6], which provides all scenario results for all models involved in the inter-comparison exercise.

Notwithstanding the variation in future supply-side investment estimates across models, certain trends appear to be fairly robust. The first has to do with the geographic concentration of future investments. Today marks a watershed moment in the historical development of the global energy system, with investments in developing countries now having grown to roughly the same level as in industrialized countries (Figure 2; see GEA (2012) for historical investment figures[7]). Perhaps not surprisingly, owing to their rapidly growing economies and populations, the developing world will see a greater share of investment going forward. (Although not shown here, this trend is even truer after 2050.) According to the models, in the reference policy scenario average annual (undiscounted) supply-side investments could reach approximately $1000 billion/yr (range: $650-1400 billion/yr) in developing countries in the years between now and 2050 (see also Table 2). China (CHINA+) and India (INDIA+) will be responsible for a considerable share of the dramatic growth, but not all of it: Latin America (LATIN_AM) and Africa (AFRICA) could see substantially increased investments as well. Energy demand growth, which differs across the models, will drive the need for investments in the countries of these regions. But that energy has to come from somewhere, and to the extent that fossil fuels continue to play a dominant role in the energy system (as they do in the RefPol reference policy scenario), then substantial investments could also be needed in the Middle East (MIDDLE_EAST) and in the reforming economies (REF_ECON). The latter region is part of the industrialized category, which helps to explain why those countries' collective investments are also seen to increase in Figure 2 – up to approximately $650 billion/yr (range: $400-1050 billion/yr) on average to 2050. Generally speaking, this increase is not the result of dramatically increased investments in Europe (EUROPE) or the Pacific OECD countries (PAC_OECD, and partially

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[6] URL: https://secure.iiasa.ac.at/web-apps/ene/LIMITSDB/

[7] According to the GEA, total supply-side investments in industrialized countries were approximately $475 billion/yr in the year 2000, or about 1.7x greater than those in developing countries ($275 billion/yr). By 2005, that gap had closed to just 1.2x ($475 billion/yr industrialized vs. $390 billion/yr developing); and by 2010, investments were essentially the same in these two parts of the world.

REST_WORLD for the REMIND and WITCH models); though, it does appear that investments may continue to scale up in North America (NORTH_AM) over the next decades as the region's fossil fuel industry continues to grow.

The regional investment estimates of the LIMITS models can be benchmarked against recent studies that have been carried out for China and the European Union toward the achievement of their respective 2020 energy goals. Firstly, according to the Chinese Government's National Development and Reform Commission – Energy Research Institute (NDRC-ERI), based on a review of existing government planning scenarios, the country will need to spend $80-112 billion per year through 2020 on renewable energy investments in order to achieve the country's 2015 and 2020 emission intensity targets (a 17% cut vs. 2010 levels and a 40-45% cut vs. 2005 levels, respectively) (The Climate Group 2013).[8] These investment requirements are consistent with the range of estimates from the LIMITS models for RefPol and CHINA+ ($32-108 billion/yr on average from 2010 to 2050; see Table 2), the scenario and region of this study that are most directly comparable to those analyzed by NDRC-ERI. Secondly, according to a recent UK House of Lords study – which took evidence from a range of parties including the European Commission, power companies and environmental campaigners – total energy-supply investments (across all types of infrastructure) of roughly $1300 billion (€1000 billion) are required cumulatively from now to 2020 if the European Union is "to stave off an energy crisis" (House of Lords 2013). This implies average annual investments of ~$185 billion per year, an estimate that is very much in line with the investment range calculated by the LIMITS models ($138-239 billion/yr from 2010 to 2050; see EUROPE region and RefPol scenario in Table 2).

In the stringent climate policy scenario (RefPol-450), the supply-side investment picture continues to vary markedly across models. For starters, it is not entirely clear whether climate policies will lead to a further increase in investments on the supply side, on top of the investments already expected in the reference policy scenario (RefPol). For models that do see an increase (MESSAGE, REMIND, TIAM-ECN), the relative change is on the order of 10-20%. However, one model (IMAGE) shows roughly similar levels of supply-side investments, while another (WITCH) actually shows a large decrease (approximately -30%). The primary explanation for the down-scaling of supply-side investments in the latter case is that energy demands are significantly reduced (through aggressive energy efficiency and conservation measures, which themselves incur costs) as a result of stringent climate policy. To be sure, large demand reductions also take place in the other models' interpretations of the RefPol-450 scenario, but supply-side investments in those models are still found to be higher than in the reference scenario, due to the generally higher cost of low-carbon technologies compared to conventional fossil fuel alternatives.[9] Accounting also for investments into energy efficiency and conservation (see Box 2), and then adding these investments on top of supply-side investments (Figure 3), has an important effect on the investment picture: in this case, all but one model indicate that the overall impact of stringent climate policies would lead to a net increase in *total* investments compared to the reference scenario. (See Section 3.2 for an elaboration of this point.) Partially offsetting this increase is the fact that, in general across the models, stringent climate policies lead to a slight contraction of the global economy (varying regionally but typically in the low single-digits in terms of percentage loss of consumption or GDP; see Kriegler et al. (this issue) and Tavoni et al. (this issue) for further discussion). This, in turn, has a non-trivial (reducing) effect on energy demands and, thus, investment needs.

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[8] NRDC-ERI calculates that China will need to invest a total of $353-385 billion/yr by 2020 on mitigation action: $273 billion/yr on the demand side to promote energy efficiency, in addition to the $80-112 billion/yr on renewable energy mentioned in the text. Because of differing accounting methods used in the NRDC-ERI study and in this paper, however, the demand-side energy efficiency investments cannot be directly compared.

[9] In the WITCH model, reducing energy demand is, to a certain extent, a far less costly strategy for mitigating emissions than investing in low-carbon energy-supply options. Another reason that supply-side investments are lower in WITCH in the climate policy scenario than in the reference case has to do with the considerable amount of spending on research and development (R&D) for improving low-carbon technologies and making them more affordable. These R&D investments are not reflected in the numbers shown here. See Carraro et al. (2012) and Marangoni and Tavoni (this issue) for further information on the investment dynamics in WITCH.

Box 2. Description of how energy efficiency investments are calculated in this study

For the purposes of this study, efficiency-related investments are calculated in a standardized way for each LIMITS model, building upon a methodology that was developed for the Global Energy Assessment (Riahi et al. 2012). Specifically, we compared final energy demands in the two policy scenarios (RefPol and RefPol-450) to those in a hypothetical no-policy scenario (Base) and assumed that, in equilibrium, the investments made to reduce energy demand could be equated to the investments that have been simultaneously offset on the supply side.[10] This required, for a single model and region, calculating the ratio of supply-side investments to total final energy demand in the policy scenario and then multiplying this ratio (in $ per exajoule) by the final energy demand reductions (in exajoules) foreseen in that scenario as well as by the share of total GDP in the policy scenario to that in the Base scenario (in %). The result is our approximation of a given 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). Calculated efficiency investments thus do not represent all demand-side investments, including, for example, the component costs of appliances, which would be an order of magnitude larger (see Grubler et al. (2012)), nor do they exactly match the demand-side investment numbers submitted by the individual modeling teams as part of the LIMITS exercise, as varying methodologies were used in each case. To be sure, our methodology only provides a zero-order assessment of efficiency-related investments on the demand side. It is not without its shortcomings, and future work should consider improving upon the approach.

With regard to where exactly supply-side investments would need to be made in a low-carbon world (RefPol-450), the situation is actually not so much different than in the reference case (RefPol). More specifically, the LIMITS models reveal that a majority share of available financial capital will need to flow to the developing world (increasing from today's 50/50 percent split to roughly 60/40 on average between 2010 and 2050; see Figure 2). The fast-growing countries of developing Asia (CHINA+, INDIA+, and REST_ASIA) appear poised to experience the largest upscaling of total investments from the reference scenario, but so too do sub-Saharan Africa (AFRICA+) and Latin America (LATIN_AM). Meanwhile, the models agree that the fossil-rich countries of MIDDLE_EAST and REF_ECON may see only a marginal increase, if not a decrease, in total investments. Furthermore, as discussed in the following section, scenario results indicate sizeable disinvestments in fossil energy infrastructure from the RefPol to RefPol-450 scenario, particularly fossil electricity generation in CHINA+, INDIA+, and NORTH_AM, and fossil resource extraction in LATIN_AM, MIDDLE_EAST, NORTH_AM, and REF_ECON). Offsetting these reductions are stepped-up investments in solar and wind power in nearly all regions, and possibly in nuclear power in CHINA+ and INDIA+. Some, but not all, models also show significant investment increases in biofuels production in the Americas (NORTH_AM and LATIN_AM); however, no region appears to experience a significant investment increase in bioenergy production (e.g., agriculture), perhaps because its costs are relatively small compared to downstream conversion. Importantly, the origin of all of these investment dollars is still very much an open question, as it will depend, to a large extent, on the architecture of the international burden-sharing agreements involved, a point that is taken up explicitly by Tavoni et al. (this issue). Interestingly, roughly one-third of all climate mitigation-related investments globally in 2011 were located in three of the largest developing countries – China, India, and Brazil – with a significant share of that capital having been raised domestically in pursuit of national development mandates (CPI 2012).

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[10] A key difference between the methodology employed in our study and that of the GEA is that the latter utilized useful energy demands as a proxy. The distinction between useful and final energy demands is undoubtedly important, and although it does indeed affect the efficiency investment calculations described here, a comparison of MESSAGE model results in the contexts of LIMITS and the GEA reveals that the utilization of final energy demands leads, if anything, to higher estimates of the efficiency investment figures compared to the useful energy demand calculation method. So all things considered, the efficiency investment estimates shown in this paper are somewhere in the middle of what they could potentially be: higher than a similarly derived supply-side investment offset measure based on useful energy demands, but lower than a measure that takes the full costs of energy end-use devices into account.

The timing of the investment profile is also important. We restrict our analysis in this paper to the time period between 2010 and 2050 because it is most relevant for current policy and decision making; yet, this is not to say the dynamics in the second half of the century are not also important. Our analysis of the LIMITS models shows that while some models indicate an exponential increase in annual investment needs over time, others envision a more linearly-increasing trajectory (see supplementary material). In stringent climate mitigation scenarios, such behavior can be partly explained by variations in the timing of emissions mitigation (Figure 1); other key factors include future energy-demand levels and the costs assumed for individual energy technologies in the models. Another paper that has looked at investment timing globally is Carraro et al. (2012), who by conducting an analysis using a single IAM (WITCH), find future investment needs to be linearly-increasing. Kober et al. (this issue) instead focus on total energy system costs using the TIAM-ECN model; and in contrast, they find that exponential increases are to be expected.

3.2 Into which sectors might future investments be concentrated?

In addition to the need to scale up total supply- and demand-side investments in both the developing and industrialized world if the 2°C target is to be successfully achieved, the LIMITS models also collectively suggest that major changes will be needed in the structure of the energy investment portfolio (Figure 3 and Table 2). In particular, the energy transformation will require pronounced shifts away from upstream investments in the fossil fuel sector (e.g., coal, oil, and gas extraction; oil refining) and more toward downstream investments in electricity generation (especially renewable and nuclear electricity) and transmission, distribution, and storage. This tendency is amplified by the increasing electrification of the end-use sectors (buildings, industry, and transport), which the models foresee to be a robust, cost-effective strategy for achieving deep cuts in greenhouse gas emissions (van der Zwaan et al. this issue). The models do tend to disagree somewhat considerably, however, about future investment requirements for certain categories, such as nuclear power. As mentioned previously, this results directly from the varying energy-supply mixes foreseen by the models, which are themselves a function of the models' varying assumptions and structures.

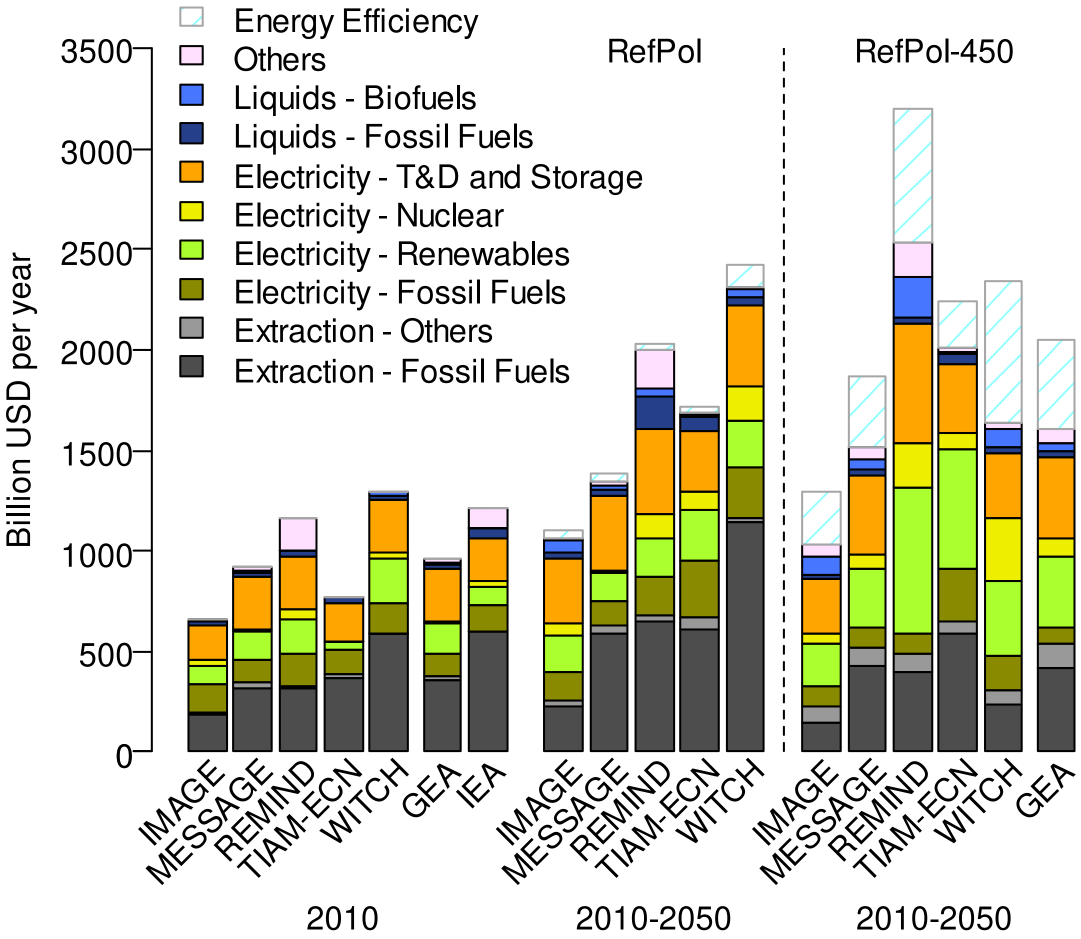

Figure 3. Global annual energy investments (both supply- and demand-side) across the various models in 2010 and average annual investments from 2010 to 2050 in the RefPol and RefPol-450 scenarios, by energy sector. For comparison, estimates from the International Energy Agency (IEA 2012b) and Global Energy Assessment (Riahi et al. 2012) are also shown, where applicable. "Others" category includes investments into hydrogen production and distribution, refined petroleum product transport, heat generation, and CO_2 transport and storage, among other things.[11]

On the supply side, most models indicate that the renewable electricity sector could potentially require the largest increase in investments compared to the reference policy scenario: up to $150 billion/yr (average between 2010 and 2050) in industrialized countries and up to $400 billion/yr in developing countries (Figure 4). Three of the models also foresee a sizeable upscaling of investments into nuclear power (while remaining flat in the other two), particularly in

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[11] Certain investment figures for REMIND and WITCH have been reconstructed because the particular categories are not explicitly tracked in the models (i.e., the technology vintage structure, turnover of capital stock, etc.). This includes biomass production, electricity T&D, fossil liquids production, and biofuels production in WITCH, and biomass production and fossil fuel extraction in REMIND. To estimate these investment figures ex-post, we used a variety of activity variables as proxies (e.g., electricity generation, fossil fuel extraction, biomass energy, etc.) and then scaled these activities to the corresponding investment categories in the Global Energy Assessment (namely the MESSAGE interpretation of the illustrative GEA-Mix pathway).

the developing world; for WITCH these additional nuclear investments approach those for renewable electricity. Additional investments into biofuels production also increase in another three models (remaining flat in the other two), though generally not to the same degree as for renewable or nuclear power, except in the case of REMIND. Meanwhile, the IMAGE model exhibits unique behavior: not only are total investments quite similar across the RefPol and RefPol-450 scenarios, the investment portfolio does not substantially change as a result of stringent climate policies. In sum, the models tend to agree on the additional investment requirements for certain categories, but not for others. This is shown quite clearly by the detailed breakdown of electric sector investments by model, found in the supplementary material (which also includes a sixth model, GCAM). For example, except in GCAM and IMAGE, solar power investments are seen to rise quite sharply in the RefPol-450 case, whereas investments into biomass power with CCS scale up in all models but MESSAGE.

The potential impact of climate policy on electricity T&D and storage investments (the latter being necessary for integrating intermittent renewables) is also not entirely clear. In the industrialized world, net investments into new or expanded grid infrastructure could be negligible, as a result of two countervailing forces: on one hand there is the increased demand for electricity and the necessity for high-voltage power lines to bring remote renewable supplies to market, while on the other hand energy efficiency and conservation temper overall energy demand growth. Similar forces will be at play in developing countries as well; though because their power grids are not as widely built out at present and because it is not yet clear where those grids will need to be located, climate policy represents a bigger uncertainty here (some models show an increase in T&D/storage investments, others do not).

A more robust finding is that in the RefPol-450 scenario investments into low-carbon options on the supply side will be partly offset by disinvestments into fossil fuel extraction, fossil liquids production, and fossil electricity generation (Figure 4), the latter of which includes power plants equipped with carbon capture and storage for the purposes of this analysis. Resource-rich regions like the MIDDLE_EAST are seen to be most directly affected, thanks to lower demand for their fossil energy exports, whereas disinvestments in resource-poor regions like INDIA+ may be restricted to the fossil electricity sector and to electricity T&D/storage infrastructure.

In addition to the required increase into low-carbon investments on the supply side, the LIMITS models also make clear that stringent climate mitigation will also necessitate a dramatic upscaling of demand-side investments into energy efficiency and conservation (over and above the efficiency investments already foreseen in the RefPol scenario). The magnitude of these additional investments appears to be on the order of $50-200 billion/yr in industrialized countries and $150-500 billion/yr in developing countries (Figure 4). Note that our estimates of efficiency-related investments can be interpreted as investments made to enhance the efficiency of demand in order to offset supply-side investments. To arrive at these figures, as described in Box 2, we use a top-down approach that only considers the efficiency-increasing part of an investment, as opposed to the full investment into a given end-use device.

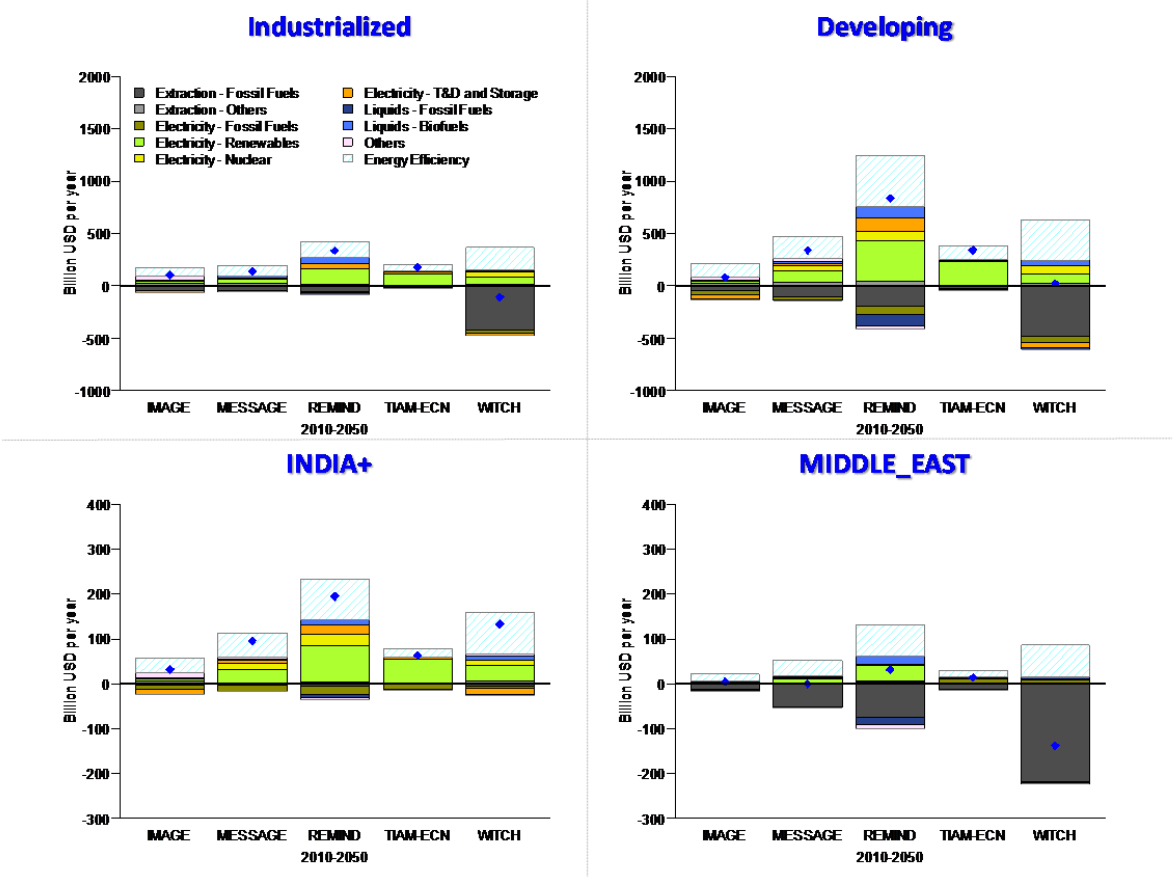

Figure 4. Incremental energy investments (both supply- and demand-side) across the models in the RefPol-450 scenario relative to the RefPol scenario. Investment and disinvestment are shown for each energy sector and for a subset of regions. Values represent annual averages from 2010 to 2050. "Others" category includes investments into hydrogen production and distribution, refined petroleum product transport, heat generation, and CO_2 transport and storage, among other things.[12] "Energy Efficiency" category includes only those investments that have been made to enhance the efficiency of demand in order to offset supply-side investments (see text).

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[12] Certain investment figures for REMIND and WITCH have been reconstructed using alternative data; see earlier footnote for more details.

3.3 Low-carbon energy and energy efficiency investments and their impact on emissions

As is clear from the previous discussion, achieving the 2°C target in the long term requires a significant upscaling of investments into low-carbon energy-supply sources (e.g., renewables and nuclear) complemented by energy efficiency and conservation investments on the demand side (see Table 2). Figure 5 compares cumulative investments (2010-2050; undiscounted) into low-carbon energy and energy efficiency with cumulative CO_2 emission reductions (relative to a hypothetical no-policy scenario, Base) across the models in the RefPol and RefPol-450 scenarios. This is done at four different levels of regional aggregation, including countries at different stages of economic development and with varying potentials for emissions mitigation.

A robust finding across the LIMITS models is that in most parts of the world low-carbon energy and energy efficiency investments will need to increase considerably, relative to a reference policy scenario (RefPol), if the 2°C target is to be successfully achieved (RefPol-450). Despite some disagreement in the estimates across models, it appears that the requisite reduction of ~900 $GtCO_2$ (range: 700-1100 $GtCO_2$) globally over the first half of this century could necessitate cumulative investments on the order of $45 trillion (range: $30-75 trillion) – see top-left panel of Figure 5. Model outcomes tend to diverge in the stringent climate policy scenario for a variety of reasons, a key one being how much mitigation a given model foresees as necessary by 2050 versus how much could more cost-effectively be done in the second half of the century (see also Figure 1).

It is important to put the results of the LIMITS scenarios into wider context of the energy investment literature by comparing them to findings from the suite of Global Energy Assessment scenario pathways. As in LIMITS, the GEA pathways all focus on achieving the 2°C target (with >50% probability); but unlike LIMITS, the GEA pathways span a wide range of futures for energy demand and technology availability (Riahi et al. 2012) – hence the cloud of dots exhibited by the 41 GEA pathways in Figure 5. Because the MESSAGE model was used to develop these GEA pathways, it should not be entirely surprising that the MESSAGE scenario results in LIMITS tend to fall within the GEA ranges. However, one key point of divergence between the GEA and LIMITS contexts is that the reference scenario used to calculate cumulative emission reductions and low-carbon energy/efficiency investments in the former is a much higher energy demand baseline than that being used in LIMITS. Precisely for this reason, emission reductions and investments (namely energy efficiency investments) are generally larger in GEA than in LIMITS.

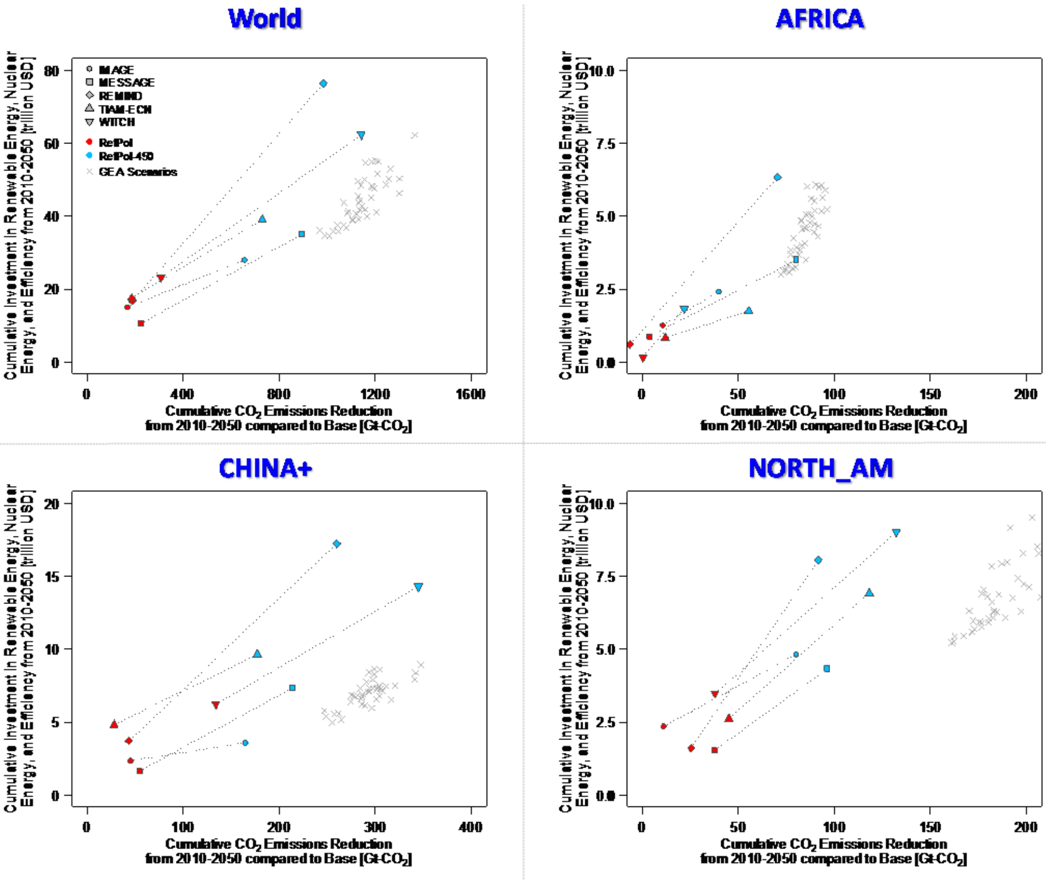

Figure 5. Cumulative clean-energy investments (renewables, nuclear, and efficiency) as a function of cumulative CO_2 emission reductions (relative to a hypothetical no-policy scenario, Base) across the models in the RefPol and RefPol-450 scenarios. Also shown for comparison are the 2°C scenarios of the Global Energy Assessment. Cumulation is done over the time period from 2010 to 2050 without discounting. Investments in trillions of dollars; emissions in gigatonnes (Gt). See Box 1 for regional definitions.

Moving from the global to regional level, the LIMITS models tell a slightly more complicated story. For starters, there tends to be somewhat closer agreement across the models regarding investments and emission reduction requirements in North America (see Figure 5), which has much to do with the fact that the energy infrastructure of this industrialized region is, more or less, fully built-out at present. While a considerable portion of that long-lived infrastructure will need to be overhauled on the path to 2°C, much of it will still remain in 2050. And in any case it is a more straightforward exercise for models to simulate which existing fossil technologies (power plants, oil refineries, etc.) in North America (or Europe, Japan, Australia, etc.) will need to be replaced by low-carbon alternatives (solar, wind, biofuels, etc.) over the next decades, at least compared to doing the same exercise for the developing regions of the world, including China and Africa (Figure 5), where the energy system could potentially evolve in any number of directions. Adding to this uncertainty are model assumptions for future population and GDP, which diverge more widely for developing regions. Varying regional definitions are also at play in certain cases, Africa being a prime example.

As shown in Figure 5, a reduction of ~220 $GtCO_2$ (range: 150-350 $GtCO_2$) in China (CHINA+) between 2010 and 2050 could necessitate cumulative clean-energy investments on the order of $10 trillion (range: $3-17 trillion). In North America (NORTH_AM), the necessary emission reductions might be half this level but so too would be the investment requirements: reductions of ~100 $GtCO_2$ (range: 80-140 $GtCO_2$) demanding investments of some $6 trillion (range: $4-9 trillion). Climate mitigation needs in Sub-Saharan Africa (AFRICA+) could be lower still: ~50 $GtCO_2$ (range: 20-80 $GtCO_2$) reduced for $3 trillion (range: $2-6 trillion) invested. Considering that Sub-Saharan Africa currently lags behind other world regions in terms of economic and energy system development (though the general assumption in the models is that this gap considerably closes by 2050), total emissions in the reference scenario are projected to be relatively low compared to the other world regions. Hence, cumulative emission reductions are lower as well.[13]

3.4 How big is the clean-energy investment gap?

Investments into renewables have been hovering at around $200–250 billion/yr globally over the past several years (BNEF 2012; REN21 2013)[14]. Going forward, our analysis indicates that on society's current path (i.e., the RefPol reference policy scenario), total investments into low-carbon, or "clean", energy (renewables, nuclear, and efficiency) could grow to about $400 billion/yr (range: $250–600 billion/yr) on average between 2010 and 2050 (based on the data shown in Figure 5). This represents an upscaling of efforts compared to what they might otherwise be in the absence of any climate policies whatsoever throughout the world (i.e., the Base no-policy scenario). A further upscaling of clean-energy investments may be required, however, if the 2°C goal is to be achieved with high likelihood (i.e., the RefPol-450 scenario) – to about $1200 billion/yr (range: $700–1900 billion/yr) globally. Hence, there exists a "clean-energy investment gap" of about $800 billion/yr worldwide. Figure 6 shows the size of the gap – and its range across models – for each region, for industrialized and developing countries, and for the world as a whole. Perhaps not surprisingly, the gap is largest for developing countries, particularly in Asia and Africa.

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[13] A further interesting result for Sub-Saharan Africa is that the models foresee only limited emission reductions taking place in the reference policy scenario (RefPol), as compared to a hypothetical no-policy scenario (Base). Some models actually show an increase in emissions in the former case. The primary reason for this is "leakage": because the reference set of climate policies of industrialized countries, as well as of certain developing countries (e.g., China), in the RefPol scenario motivates somewhat sizeable reductions in fossil fuel demands in those regions, fossil prices become slightly depressed on the global market. Since such policies are absent in Sub-Saharan Africa in the RefPol scenario, the countries of that region seize on the lower fossil prices opportunity by utilizing more of these types of fuels to satisfy their growing demands for energy. This, in turn, leads to higher emissions than in the case where there are no policies instituted in the other regions, or in the case where all regions, including Sub-Saharan Africa, simultaneously make a concerted, global effort to reduce greenhouse gas emissions, as is the storyline embedded in the RefPol-450 scenario.

[14] The Climate Policy Initiative (CPI) estimates that *total* "climate finance" from all sources (public and private) reached approximately $364 billion/yr globally in 2011 (CPI 2012). This includes $217–243 billion/yr in private sector investments, $16–23 billion/yr in public sector support, and $110–120 billion/yr from public-private partnerships (e.g., funds raised and channeled by national development banks and commercial banks).

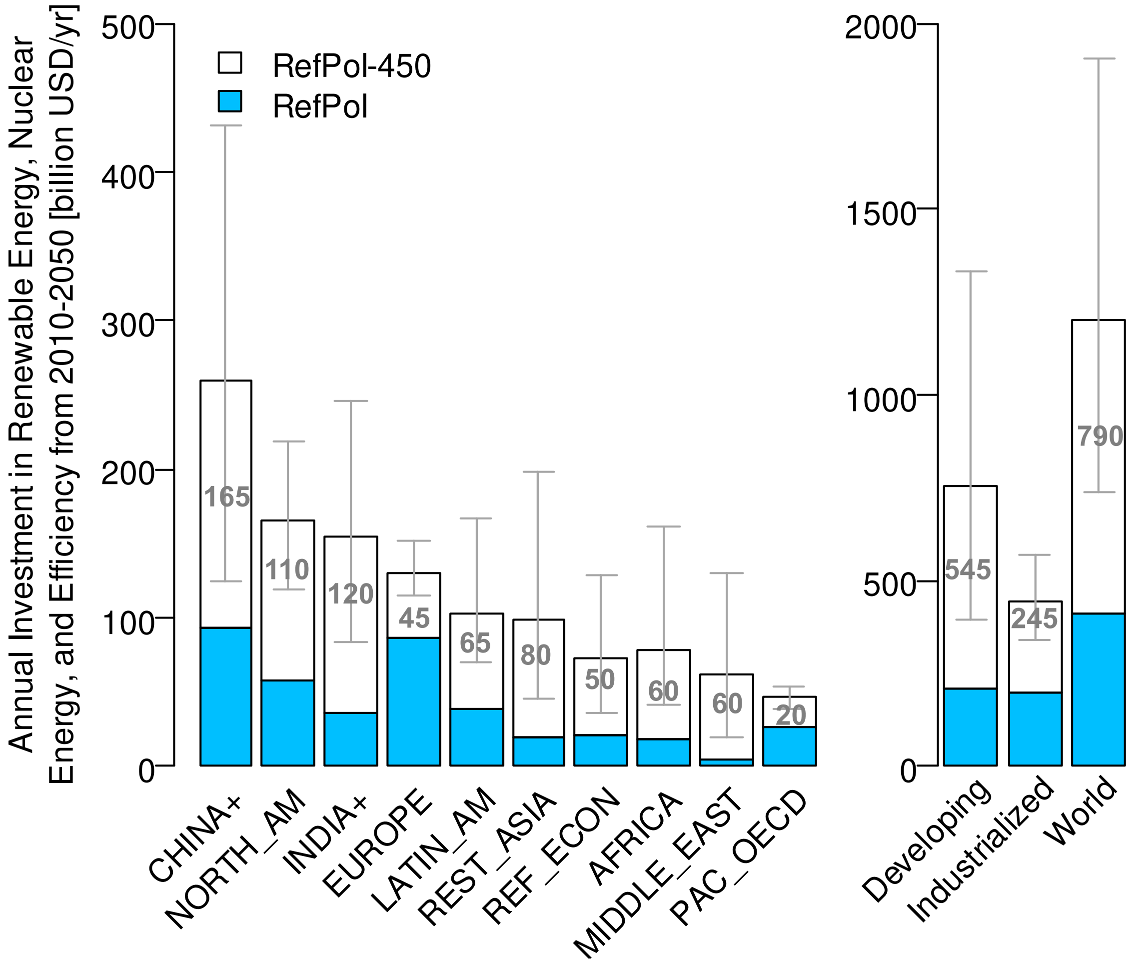

Figure 6. Clean-energy investment requirements in the reference policy (RefPol) and stringent climate policy (RefPol-450) scenarios. Investments include renewables and nuclear on the supply side and energy efficiency on the demand side. RefPol investments shown here for each region are the averages across the models (see Figure 3 for individual model results). The increase from the RefPol to the RefPol-450 scenario (white bar) represents a region's "clean-energy investment gap"; also indicated by the number in grey. The gap is calculated as an average across all models while the uncertainty bands depict the min/max gap estimated by individual models. Note that due to rounding, regional numbers may not sum exactly to Developing, Industrialized, and World totals. See Box 1 for regional definitions.

While the clean-energy investment gaps (globally and by region) may indeed appear quite sizeable at first glance, a comparison to present-day energy subsidy levels helps to put them into context. According to estimates by the International Monetary Fund and International Energy Agency, global "pre-tax" (or direct) subsidies for fossil energy and fossil electricity totaled $480–523 billion/yr in 2011 (IEA 2012b; IMF 2013). This corresponds to an increase of almost 30% from 2010 and was six times more than the total amount of subsidies for renewables at that time. Oil-exporting countries were responsible for approximately two-thirds of total fossil subsidies, while greater than 95% of all direct subsidies occurred in developing countries. Subsidies handed out in the Middle East and North Africa (essentially the LIMITS MIDDLE_EAST region) and Central and Eastern Europe and the Commonwealth of Independent States (essentially REF_ECON) are found to be quite a bit higher than the average annual clean-energy investment needs identified for these two regions going forward (see Figure 6): $240 billion and $72 billion in subsidies, respectively. For the other regions, future investment needs are found to be higher than today's subsidies, though still on the same order of magnitude. Interestingly, on a "post-tax" (or indirect) basis – which also factors in tax breaks and the failure to account for negative externalities from energy consumption – the IMF's estimate of global subsidies swells to $1900 billion. Advanced economies accounted for about 40% of this amount, with the U.S. taking the top spot at $502 billion. The second and third positions were occupied by China and Russia at $279 billion and $116 billion, respectively.

4. Mobilizing the required levels of investment

One of the biggest hurdles to overcome on the path to energy system transformation and the 2°C target will be to mobilize the necessary investment flows, particularly in light of competing demands for capital within the energy sector and, more generally, across all other sectors of the rapidly globalizing economy. This is where policy makers can potentially play a critical role, incentivizing consumers, entrepreneurs, and established energy firms to adopt clean energy on a larger scale. For this to happen, however, new perspectives may be needed, among them a deeper appreciation for the externalities (or social costs) inherent in energy services provision. Policies of both the "carrot" and "stick" variety can be effective at pushing the energy system in a certain direction (Kalkuhl et al. 2012), so long as policy makers value climate change mitigation and the synergies that it can create (Bollen et al. 2010; McCollum et al. 2011). This could open up new business opportunities (on both the energy-supply and –demand sides) and spawn new markets (e.g., for low-carbon energy and energy efficiency technologies). Our investments analysis indicates that such markets could increasingly find themselves centered in what is today the developing world. After all, as is apparent from Section 3, this is where the bulk of investment dollars will need to flow over the next several decades. Yet, developing countries have only contributed to a fraction of the greenhouse gas emissions that have been emitted since the beginning of the industrial revolution. Hence, just because the investment needs of the developing world may be greater than in the currently industrialized world going forward does not automatically imply that the former will be responsible for bearing the full costs of mitigation. This will depend, to a large extent, on the architecture of the international burden-sharing agreements involved (Tavoni et al. this issue).

4.1 Policies to incentivize the energy system transformation

Spurring low-carbon energy and energy efficiency innovation and investments may require the targeted implementation of a portfolio of policies and measures so that the necessary incentives are in place. Although not the explicit focus of this paper, or the LIMITS scenarios more generally, this section draws heavily from other, more focused studies on policy incentives (e.g., Riahi et al. (2012), Grubler et al. (2012), Jaccard et al. (2012), Mytelka et al. (2012), and Wilson et al. (2012)) to understand how various measures might be used to incentivize clean-energy investments. Such a policy portfolio could include, for instance, externality pricing (e.g., for greenhouse gases and other air pollutants), technology standards and regulations in sectors with relatively low price elasticity and/or high transaction costs (e.g., stricter appliance, building, and vehicle efficiency standards), increased research and development funding for both energy-supply and -demand technologies, and/or quotas and subsidies to support the initial market penetration phase of low-carbon technologies. In addition, the forging of an enabling institutional, financial, technical, and legal environment could be important, especially in developing countries, in order to complement traditional deployment policies. It is by no means clear what the most efficient mix of policies and measures could, or should, be for mitigating climate change through an energy system transformation (e.g., see the discussions contained in Nordhaus (2011) and Kalkuhl et al. (2012)), and this paper makes no attempt to assemble its own list. After all, as with many policy choices that are highly context-dependent, what is effective in one jurisdiction may not be suitable in another.

An important finding from the policy literature is that different energy technologies could require different combinations of policy mechanisms to attract the necessary investment capital. Because a rigorous analysis of these policies is beyond the scope of the current paper, we reproduce below a table from the Global Energy Assessment (Riahi et al. 2012). This table concisely summarizes an illustrative set of policies and measures that could help to mobilize critical financial resources. The GEA evaluates these various mechanisms with an eye toward a sustainable energy transformation – including normative targets to stay below 2°C (as in LIMITS) and to achieve near-universal energy access by 2030, among other goals – and then groups them into four categories (see Table 3): "essential" policy mechanisms are those that must be included in order to achieve the 2°C target; "desired" policy mechanisms are those that would help but are not entirely necessary; "uncertain" policy mechanisms are those where the outcome will depend on the policy emphasis and thus may or may not favor a specific option; and "complementary" policy mechanisms are those that are inadequate on their own but could complement other essential policies. This categorization derives in part from historical case studies of policy effectiveness, which were conducted in the GEA context and which are helpful in thinking forward to the future policy and investment environment. That said, we imply no endorsement for (or against) any of the policies, or a particular mix of policies, contained in Table 3. We simply reproduce the GEA analysis here in order to highlight that (i) a range of policies exist to incentivize a clean, sustainable energy transformation, and (ii) a combination of these policies (i.e., a portfolio approach) could be needed to mobilize the transition. Specific policy choices ultimately depend on local and national circumstances. For far more elaborate discussions on the topic of energy and climate policy, see Grubler et al. (2012), Jaccard et al. (2012), Mytelka et al. (2012), and Kalkuhl et al. (2012).

The LIMITS models collectively identify several areas where policy can help to mobilize key financial resources. Table 3 summarizes the investment needs for several specific energy sectors in both the reference policy and 2°C scenarios. In the latter case, investments into renewables (both electricity and fuels) see the most dramatic upscaling, on average between \$100 and \$750 billion/yr globally over the 2010-2050 timeframe[15] compared to a reference policy future (one that assumes implementation of the reference set of clean energy policies in place throughout the world). A sizeable upscaling of demand-side investments into energy efficiency and conservation also appears to be critical for the energy system transformation: \$200-650 billion/yr over and above the efficiency investments already foreseen in the reference case. Stepped-up investments into nuclear power and electricity infrastructure (power grid, storage, etc.) may also be needed, though it should be noted that the capital needs for these two sectors, especially the latter, are foreseen by the models to already be quite sizeable in the reference scenario. For comparison purposes, we also add to Table 3 the corresponding sectoral investment estimates deriving from the GEA (Riahi et al. 2012). (Note that only the GEA investments for achieving the 2°C target are shown here; the energy access investments are not.) This serves to embed the current analysis within the broader context of the energy investments literature. The key difference between the two studies is that in LIMITS the same scenarios were run with several different models, whereas in the GEA the same model was used to run many different scenarios. Hence, the LIMITS analysis provides an indication of the size of the investment uncertainty range in light of cross-model differences (both structural and parametric), whereas the GEA pathways show how sensitive investments are to assumptions about the available technology portfolio and energy demand growth. In this sense, the fact that the sectoral investment ranges are so similar between the two studies is quite remarkable, though it should be noted that the LIMITS and GEA scenarios do not span all possible future states of the world. Uncertainties in investments might therefore be larger than those summarized in Table 3.

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[15] Note that the upscaling requirements discussed here in the text represent the increases seen by individual models (i.e., they represent the lower/upper ends of the range of increases). These increases cannot be directly calculated from the lower/upper ends of the ranges shown in Table 3 because a model exhibiting either minimum or maximum investment costs in one scenario may not be the same in the other.

Table 3. Comparison of low-carbon energy and energy efficiency investment needs globally for achieving the 2°C target (values represent ranges across the LIMITS models and for all Global Energy Assessment pathways) alongside illustrative policy mechanisms for mobilizing those financial resources in a 2°C scenario. Policy mechanisms are reproduced from the GEA (Riahi et al. 2012). 'LIMITS reference scenario' refers to RefPol; 'LIMITS 2°C scenario' refers to RefPol-450; 'GEA 2°C pathways' refer to the 41 feasible pathways of the Global Energy Assessment.

	Average annual investments (billions of US$/yr)			**Policy mechanisms**			
	2010	2010–2050		Regulation, standards	Externality pricing	Carefully designed subsidies	Capacity building
End-use Efficiency	n.a.[a]	*LIMITS reference scenario:* 30–115[b] *LIMITS 2°C scenario:* 225–700[b]	*GEA 2°C pathways:* 290–800	*Essential* (elimination of less efficient technologies every few years through efficiency standards, labeling, etc.)	*Essential* (cannot achieve dramatic efficiency gains without prices that reflect full costs)	*Complementary* (ineffective without price regulation, multiple instruments possible)[c]	*Essential* (expertise needed for new technologies)
Nuclear	5-40[d]	*LIMITS reference scenario:* 10–170 *LIMITS 2°C scenario:* 55–310	*GEA 2°C pathways:* 15–210	*Essential* (regulation of waste disposal and of fuel cycle to prevent weapons proliferation)	*Uncertain* (GHG pricing would provide major assistance to nuclear but prices reflecting nuclear risks could hurt)	*Uncertain* (has been important in the past, but with GHG pricing perhaps not needed)	*Desired* (need to correct the loss of expertise of recent decades)[e]
Renewables	190	*LIMITS reference scenario:* 200–320 *LIMITS 2°C scenario:* 385–1020	*GEA 2°C pathways:* 260–1010	*Complementary* (renewable portfolio standards can complement GHG pricing)	*Essential* (GHG pricing is key to rapid development of renewables)	*Complementary* (feed-in tariff and tax credits for R&D or production can complement GHG pricing)	*Essential* (expertise needed for new technologies)
Carbon Capture and Storage (CCS)	<1	n.a.[f]	*GEA 2°C pathways:* 0–64	*Essential* (CCS requirement for all new coal plants and phase-in with existing)	*Essential* (GHG pricing is essential, but this may not suffice in near term)	*Complementary* (would help with first plants while GHG price is still low)	*Desired* (expertise needed for new technologies)[e]
Electricity Infrastructure[g]	260	*LIMITS reference scenario:* 305–420 *LIMITS 2°C scenario:* 265–595	*GEA 2°C pathways:* 310–500	*Essential* (security regulation critical for some aspects of reliability)	*Uncertain* (neutral effect)	*Essential* (customers must pay for reliability levels they value)	*Essential* (expertise needed for new technologies)

a. Global investments into end-use efficiency improvements for the year 2010 are not available. However, as a point of comparison, the best-guess estimate from Chapter 24 of the Global Energy Assessment (Grubler et al. 2012) indicates that investments into energy components of demand-side devices are about US$300 billion per year. This includes, for example, investments into the engines in cars, boilers in building heating systems, and compressors, fans, and heating elements in large household appliances. The uncertainty range is between US$100 billion/yr and US$700 billion/yr for investments in components. Accounting for the full investment costs of end-use devices would increase demand-side investments by about an order of magnitude. (See Section 2)

b. Estimate includes efficiency investments on the demand side that offset supply-side investments (see Section 3).

c. Efficiency improvements typically require a basket of financing tools in addition to subsidies, including, for example, low- or no-interest loans or, in general, access to capital and financing, guarantee funds, third-party financing, pay-as-you-save schemes, or feebates as well as information and educational instruments such as labeling, disclosure and certification mandates and programs, training and education, and information campaigns.

d. Lower-bound estimate includes only traditional deployment investments in about 2 GW capacity additions in 2010. Upper-bound estimate includes, in addition, investments for plants under construction, fuel reprocessing, and estimated costs for capacity lifetime extensions.

e. Depending on the social and political acceptability of CCS and nuclear, capacity building may become essential for achieving a high level of future investments.

f. Total CCS investments (capture, transport, and storage) are not explicitly broken out in this table. In earlier figures and tables of the paper, investments for electric generation and fuel production facilities equipped with CO_2 capture are grouped into the fossil fuel categories, while CO_2 transport and storage investments are grouped into the "Other" category.

g. Overall electricity grid investments, including investments for operations and capacity reserves, back-up capacity, and power storage.

4.2 Potential implications for private industry: some initial thoughts

The structural changes to the energy system that climate policy will bring about – in terms of which sectors see either increased or decreased investments (see Section 3.2) – will have important implications not only for policymaking but also for private industry. This section intends to think through some of these issues by using the LIMITS scenarios as a springboard for the discussion. To be sure, none of the LIMITS models are disaggregated enough to speak to the dynamics of firm-level competition. Nevertheless, while not supported directly by model results, the discussion here reflects on the higher-level trends foreseen in the LIMITS scenarios to identify potential implications of 2°C-type mitigation efforts for selected classes of companies and technology providers in the energy industry.

If the LIMITS scenarios are any indication of how the future could potentially unfold, then it seems electric utilities, renewable electricity providers and component manufacturers (including producers of solar PV cells and wind turbines, etc.), transmission line and transformer station builders, biofuel refinery operators, and even nuclear engineering firms all stand to gain from a concerted, global push toward achieving the 2°C target. Some of these industries are already well-established, capital-intensive, and therefore well-positioned to expand their operations over the coming decades. By comparison, parts of the renewable energy industry are still in an embryonic state (REN21 2013); hence, a considerable amount of financial support – either from government loans and subsidies, as in Germany (Jacobsson and Lauber 2006), or through venture capital and private equity financing (Moore and Wüstenhagen 2004) – may be needed so that the smaller companies in the field do not find themselves so cash-poor that they are unable to expand their operations rapidly and ubiquitously. The challenge of constrained financial resources could play a particularly important role in the developing world (Ekholm et al.).

The "energy efficiency and conservation industry", to the extent such a categorization can be made, also stands to gain markedly from strong carbon policy. A heterogeneous mix of actors comprises this portion of the energy sector, including everything from engine, battery, light bulb, and refrigerator manufacturers to building energy use consultants and transit providers. Given the disparate, small-scale, and often local nature of these operations, capital support mechanisms will vary widely; and for this reason policy, particularly at the sub-national level, can play a central role (e.g., through incentive mechanisms, institutional and educational support, etc. (Grubler et al. 2012; Jaccard et al. 2012; Wilson et al. 2012)).

One industry that tends to lose out from stringent climate policy, according to the LIMITS models, is the fossil fuel sector: fossil resource exploration and development, coal mining, oil and gas production and transportation, oil refining, and fossil electricity generation. To be sure, natural gas – owing to its relatively low carbon intensity compared to coal and oil – could act as a kind of transitional fuel on the path to 2°C (Kriegler et al. in press; van der Zwaan et al. this issue); hence, that particular part of the industry (both gas producers and electricity providers) may still find space to grow (with consequent capital requirements). Similarly, other fossil fuel industries could benefit from the application of CCS. Yet, this growth may only last for a few decades, as all carbon-containing fuels will need to be reduced substantially in the mid-to-long term if deep cuts in GHG emissions are to be achieved. (The share of total primary energy met by fossils equipped with CCS in 2050 [2100] is 5-23% [0-38%] across the LIMITS models; for non-CCS fossils it is 30-45% [3-12%], in contrast to today's ~85% share.) The fossil fuels industry is extremely well-endowed at present, with annual revenues of some $5 trillion (Koomey 2012); thus, constraints on capital are unlikely to play a defining role in limiting investments for the various multi-national corporations involved. For these actors, the transition toward low-carbon energy might present a number of new business opportunities. Today's oil refiners, for instance, could become heavily engaged in biofuels production, as is now happening in Brazil (Medeiros 2012); oil and gas producers and pipeline companies could eventually capture the market for CO_2 transport and storage, as is partly the case today (Doctor et al. 2005); coal mining companies might begin to focus their operations more on the extraction of rare earth elements and minerals (necessary for some low-carbon technologies, such as batteries and solar PV cells); and fossil electricity generators and product manufacturers (such as Siemens and General Electric (Lewis and Wiser 2007)) may be able to find ways to transfer their skills to the new crop of energy-supply technologies that, despite the many differences, will still rely on some of the same componentry and engineering know-how as their more conventional counterparts (e.g. electric motors, generators, gearboxes, control equipment, and transmission/distribution systems).

In short, owing to the limitations of the LIMITS models, it is difficult to predict where today's key corporate players would figure into the new energy paradigm of a carbon-constrained world. Given the projected magnitude of energy investments going forward (see Section 3) – particularly those in new areas of the economy – and the fact that so much of the world's energy-related capital is currently bound up in established energy companies, the overall, system-wide implications for investment flows are still not entirely clear. So whether it takes place within academia or private industry, a deeper exploration of these issues could prove quite useful for both public policy making and strategic corporate decision making.

4.3 Sharing the mitigation burden and offsetting energy investments through carbon trade

Numerous studies have analyzed the potential impacts of alternative burden-sharing regimes for different regions of the world (see for example Nakicenovic and Riahi (2003), IPCC AR4 (2007), den Elzen et al. (2010), Luderer et al. (2012a), and Tavoni et al. (this issue)). This section goes beyond previous research by putting the financial offsets from carbon trade in the context of the regional energy investment requirements that are consistent with achieving the 2°C target. It does so by focusing on the carbon (CO_2-eq) trade flows realized across the LIMITS models in two scenarios, each of which offers an alternative view of how a global burden-sharing regime could potentially be implemented: equal per-capita emissions rights (RefPol-450-PC) or equalized mitigation efforts (RefPol-450-EE). Both scenarios can be viewed as modified versions of the RefPol-450 storyline, except with carbon trade between regions now being possible. In fact, as a general rule, the evolution of the energy system (including investment needs) foreseen by a given model is the same in the RefPol-450-PC and RefPol-450-EE scenarios as it is in RefPol-450, aside from some small differences owing to macro-economic feedbacks from carbon trade. Further details of the different burden-sharing regimes can be found in the footnote[16]; full details, as well as an extended discussion of

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[16] Both burden-sharing scenarios are similar to the RefPol-450 scenario except that they allow for trade of GHG emission allowances between regions as of 2020. The RefPol-450-PC scenario foresees implementation of a standard per-capita convergence burden-sharing regime, in which the per-capita GHG emissions of all regions converge to a common value by 2050 and then maintain the same per-capita emissions in all subsequent years. The common values are derived from the global per-capita emission levels calculated by each model for 2050 and beyond in a cost-optimal mitigation scenario without burden-sharing (i.e., the RefPol-450 scenario). The purchase or sale of emission allowances allows individual regions to emit either more or less than they do in the RefPol-450 scenario, so long as they achieve the globally-harmonized per-capita level between 2050 and 2100. The RefPol-450-EE scenario foresees implementation of a burden-sharing regime that attempts to equalize mitigation costs throughout the world, i.e., all regions incur the same mitigation costs (formulated as either consumption losses or the area under the marginal abatement cost curve, depending on whether a model is general or partial equilibrium, respectively) as a

model outcomes within the context of the LIMITS project, are given in Tavoni et al. (this issue). The key questions we focus on here are where (in which regions) and how (in terms of cost) might carbon trade re-balance energy investment expenditures on the part of each region.

Table 4 summarizes total energy investments in each region for the reference policy (RefPol) and stringent climate policy (RefPol-450) scenarios. The incremental investment flows to achieve the 2°C target are then compared to the financial flows from carbon trade that could potentially arise under the two different burden-sharing regimes in the context of a 2°C future. Generally speaking, these regimes result in industrialized countries making large financial transfers to developing countries over the first part of the century. (The exception is REF_ECON in the RefPol-450-EE case.) Such capital inflows help compensate the developing world for the incremental investments they may need to make over this time period – which according to some models are actually negative (i.e., lower total investments under stringent climate policy). As Table 4 shows, the annual financial flows from carbon trade are on the same order of magnitude as the incremental investment requirements for many regions, and in certain cases they could be far greater. The reasons why some regions fare better or worse than others under the different burden-sharing regimes is outside the scope of this paper, given the various macro-economic considerations involved. For a detailed analysis of these dynamics, the interested reader is referred to the Tavoni et al. (this issue) paper in the LIMITS special issue.

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percentage of their gross domestic product after emissions trading has taken place. Allowance allocations for each region and in each year are based on this equalization rule (as of 2020 and then in all subsequent years).

Table 4. Total energy investments in the RefPol and RefPol-450 scenarios compared with financial flows from carbon trade under different burden-sharing regimes in the context of a 2°C future. Units: billions of US$/yr. For investment flows, cumulation and averaging is done over the 2010-2050 time period without discounting; for carbon trade flows, over the 2020-2050 period. Incremental investments solely reflect differences from 2020 to 2050. "PC" refers to the RefPol-450-PC scenario (equal per-capita emissions rights regime), whereas "EE" refers to the RefPol-450-EE scenario (equalized mitigation effort regime). Positive carbon trade flows indicate sales of emissions rights; negative flows indicate purchases. The range of incremental investments shown here represents the min/max increases seen by individual models (i.e., the lower/upper ends of the range of increases). Totals may not add because of the heterogeneous "REST_WORLD" region (not shown here; see Box 1 for regional definitions).

	Reference Scenario Investments (RefPol)	2°C Scenario Investments (RefPol-450)	Incremental Investments (RefPol → RefPol-450)		Financial Flows from Carbon Trade under Different Burden-sharing Regimes in a 2°C Future	
AFRICA	72 - 129	59 - 243	-12 - 114		PC	27 - 612
					EE	8 - 137
CHINA+	204 - 403	202 - 674	-2 - 299		PC	-1069 - 41
					EE	-357 - 149
EUROPE	143 - 266	177 - 272	-5 - 73		PC	-117 - 80
					EE	-741 - -94
INDIA+	129 - 198	171 - 392	32 - 194		PC	35 - 219
					EE	-159 - 75
LATIN_AM	117 - 233	132 - 275	-79 - 74		PC	-198 - 826
					EE	-25 - 19
MIDDLE_EAST	59 - 393	63 - 330	-138 - 32		PC	-127 - -45
					EE	-18 - 765
NORTH_AM	170 - 333	212 - 417	-1 - 144		PC	-197 - -50
					EE	-400 - -8
PAC_OECD	37 - 176	48 - 116	-60 - 23		PC	-111 - 32
					EE	-178 - -10
REF_ECON	86 - 272	105 - 243	-29 - 27		PC	-227 - -1
					EE	11 - 489
REST_ASIA	62 - 192	83 - 314	22 - 121		PC	1 - 355
					EE	-251 - 52
Developing	667 - 1393	750 - 2228	25 - 834		PC	54 - 672
					EE	67 - 801
Industrialized	438 - 1119	542 - 1011	-107 - 335		PC	-672 - -54
					EE	-801 - -67
World	1105 - 2425	1292 - 3202	-82 - 1169		//	

A marked challenge on the path to 2°C, particularly in the early years of the transition before any burden-sharing architectures are in place, will be to ensure that mechanisms exist to encourage investment in regions where capital may be scarce or otherwise hard to pull together. With this in mind, the international community formed the Clean Technology Fund (CTF) in 2008. The CTF provides "middle income countries with resources to explore options to scale up the demonstration, deployment, and transfer of low-carbon, clean technologies" (CTF 2013). Funds are then channeled through multilateral development banks throughout the world, such as the Asian Development Bank. By March 2013, $5.2 billion in funding had already been pledged to the CTF, and $2.3 billion had been approved (for 41 projects). A further $19.2 billion had been attracted in co-financing. While these financial flows are considerable, the LIMITS models indicate they would need to scale up considerably – potentially by an order of magnitude – if the clean-energy investment gap is to be adequately filled (see Section 3.4) or if the total incremental investment needs of developing countries (for achieving 2°C) are to be addressed (see Table 4). An investment vehicle with potentially wider scope for mobilizing capital flows is the Green Climate Fund (GCF), which was initially agreed to in 2010 but, as of mid-2013, is still being set up (GCF 2013). The GCF is organized under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC) and was founded as a way to transfer funds from the industrialized to the developing world, in order to assist the latter group of countries in climate change adaptation and mitigation. The international community's stated objective is to raise $100 billion per year by 2020, a level that would start to approach (but could still be far lower than) the required clean-energy investment levels and total incremental investment needs estimated by the LIMITS models. Whether the GCF funding would come from public or private sources – or a mixture of both – remains an open question.

5. Conclusions

The aim of this paper is to address one of the critical uncertainties facing society on its journey toward achieving the 2°C global warming target: how much investment is needed to mobilize the energy system transformation. To answer this question, we analyze a multi-model ensemble of long-term energy and emissions scenarios that were developed within the framework of the LIMITS model inter-comparison exercise. Results from five different integrated assessment models are considered: IMAGE, MESSAGE, REMIND, TIAM-ECN, and WITCH. (GCAM is also included in a specific instance.) Our study provides insights into several critical areas that relate to the potential future investment picture: (i) where capital expenditures may need to flow, (ii) into which sectors they might be concentrated, and (iii) drawing on other studies, what types of policies could be helpful in spurring the required financial resources. These insights can potentially be useful for public policy making and strategic corporate decision making.

We find that meeting the future energy service demands of a growing number of consumers worldwide will probably require a significant upscaling of investments over the next several decades, regardless of the presence or absence of stringent climate policy. On the current path – with only the reference set of emissions-reducing policies in place in a subset of countries – average annual supply-side investments into the global energy system (between 2010 and 2050; undiscounted) could increase by at least 50%, if not double, compared to today's level of about $1000 billion/yr. Stringent climate policies consistent with the 2°C target may lead to a further increase in total energy investments (both supply- and demand-side), on top of those already expected in the reference policy scenario. Yet, it is not entirely clear how much additional investment that would be: up to a two-thirds increase according to one of the LIMITS models, but less than 25% for most others. It could even be the case that investments remain flat (i.e., no higher than in the reference scenario). The uncertainty on this point hinges mostly on the potential for energy demand reduction foreseen by the models and how that reduction comes about, either through energy efficiency measures on the demand side of the energy system or via structural (economic) and lifestyle (behavioral) changes taking place within society at large (thus necessitating capital expenditures that are not strictly classified as energy investments). Other factors also play a crucial role, such as technology cost reductions over time.

The energy transformation may require pronounced shifts away from upstream investments in the fossil fuel sector (e.g., coal, oil, and gas extraction; oil refining) and more toward downstream investments in electricity generation (especially renewable and nuclear electricity) and transmission, distribution, and storage. Investments into renewables (both electricity and fuels) could see the most dramatic upscaling, on average between $100 and $750 billion/yr globally over the 2010-2050 timeframe compared to a reference scenario that assumes a continuation of present and planned emissions-reducing policies throughout the world. A sizeable upscaling of demand-side investments into energy efficiency and conservation also appears to be critical: $200-650 billion/yr over and above the efficiency investments already foreseen in the reference case. Stepped-up investments into nuclear power and electricity infrastructure (power grid, storage, etc.) may also be needed (up to $140 billion/yr and $170 billion/yr, respectively, relative to the reference), though some models show requirements for nuclear that are close to nil, as well as shrinking electricity infrastructure investments. In sum, we find that in most parts of the world low-carbon energy and energy efficiency investments may need to increase considerably, relative to the reference climate policy scenario, if the 2°C target is to be successfully achieved. Meeting the target could require that some 900 $GtCO_2$ (range: 700-1100 $GtCO_2$) be reduced globally between 2010 and 2050, potentially necessitating cumulative clean-energy investments on the order of $45 trillion (range: $30-75 trillion), or an investment increase from the reference scenario of approximately $30 trillion (range: $10-55 trillion). To put this study's estimates into the context of the literature, note that our figures are roughly in line with those of the Global Energy Assessment (Riahi et al. 2012) and International Energy Agency (2012a). A direct comparison with the latter is not entirely possible, however, owing to differing assumptions for the chosen baseline scenarios (policies in particular, and to a lesser extent socio-economic assumptions and energy demand growth) and because of the way that energy efficiency investments are calculated.[17]

Developing countries – notably those in Central Asia (China), South and Southeast Asia (India, Indonesia, etc.), Sub-Saharan Africa, and Latin America (Brazil) – will require a majority share of the available financial capital going forward. Not all of these investment dollars will originate from within these countries, however, as it will depend, to a large extent, on the architecture of the international burden-sharing agreements involved. Although not discussed at length in this paper, we find that depending on how burden-sharing architectures are set up, the annual financial flows from carbon trade could be on the same order of magnitude as the total incremental investment requirements for achieving 2°C in many regions, and in certain cases they could be far greater.

One of the biggest hurdles to overcome on the path to energy system transformation and the 2°C target will be to mobilize the necessary investment flows, particularly in light of competing demands for capital within the energy sector and, more generally, across all other sectors of the rapidly globalizing economy. This is where policy makers can potentially play a critical role, incentivizing consumers, entrepreneurs, and established energy firms to adopt clean energy on a larger scale. Doing so could open up new business opportunities (on both the energy-supply and demand sides) and spawn new markets (e.g., for low-carbon energy and energy efficiency technologies).

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[17] IEA (2012a) calculates the additional investments of its 2°C scenario ("2DS") relative to its 6°C scenario ("6DS") baseline, which is estimated by Schaeffer and van Vuuren (2012) to reach 3.7°C warming (above pre-industrial levels) by 2100 and 6°C in the much longer term. In contrast, the baseline used in this paper is the RefPol scenario, a reference climate policy scenario that, according to the LIMITS models, leads to between 3.1°C and 3.7°C warming by 2100, generally lower than the IEA's 6DS. A baseline with less warming at the outset translates to less required mitigation and, thus, lower additional investments. A more relevant point of comparison would perhaps be our Base scenario (a no-policy baseline lacking climate policies of any kind), in which global temperatures reach 3.7–4.5°C by 2100 across the models. (Note that the RefPol-450 leads to 1.6–1.8°C warming in 2100.) All of this indicates that differences in socio-economic and energy demand growth assumptions are likely to factor quite prominently in the varying levels of investment between this study and the IEA's, whether in the baseline or a 2°C scenario. Indeed, while *absolute* annual investment needs (all sectors) in the IEA's 2DS scenario are estimated to be $3.5 trillion on average (2010-2050), they range from just $1.3 to a high of $3.2 trillion per year (across models) in the LIMITS RefPol-450 scenario. An additional explanation for the IEA's higher investment estimates is that they consider the full costs of energy components for end-use devices, which leads to much higher investments on the demand side compared to the "avoided-supply-side-investment" method used in this paper.

In conclusion, if society is committed to keeping global temperatures increase to less than 2°C above pre-industrial levels, thereby avoiding dangerous interference with the climate system, then this analysis suggests a transformation of the global energy landscape appears to be unavoidable. Yet, given that energy-supply technologies and infrastructure are characterized by long lifetimes (30-60 years, or even longer), there exists a large amount of technological inertia that can end up impeding a rapid transformation. The energy investment decisions of the next several years are thus of paramount importance, since they will have long-lasting implications and will critically shape the direction of the energy transition path for many years to come. Renewable energy investments have been hovering at around $200–250 billion/yr over the past several years (BNEF 2012); on society's current path, total investments into low-carbon, or "clean", energy (renewables, nuclear, and efficiency) could grow to about $400 billion/yr (range: $250–600 billion/yr) on average between 2010 and 2050. This already represents an upscaling of efforts compared to what they might otherwise be in the absence of any climate policies whatsoever throughout the world. A further upscaling of clean-energy investments may be required, however, if the 2°C goal is to be achieved with high likelihood – to about $1200 billion/yr (range: $700–1900 billion/yr) globally. Hence, the results of this paper lead to one very strong conclusion: a substantial "clean-energy investment gap" of some $800 billion/yr exists – notably on the same order of magnitude as present-day subsidies for fossil energy and fossil electricity worldwide ($523 billion). Unless this gap is filled rather quickly, the 2°C target could potentially become out of reach.

Data availability

All investment data supporting this analysis – including the numbers behind the tables and figures – are available to any interested parties, either as online supplementary material to this paper or through the LIMITS scenario database (https://secure.iiasa.ac.at/web-apps/ene/LIMITSDB/). As discussed earlier in the text, some of the investment estimates differ among these two sources; see the supplementary material for further details.

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