Project No 282846

LIMITS

Low climate IMpact scenarios and the Implications of required Tight emission control Strategies

FP7-Cooperation-ENV
Collaborative project
Small or medium-scale focused research project

DELIVERABLE No 2.2
Report that analyses the economic resources needed to achieve 2°C and to adapt to it

Due date of deliverable: 30/09/2013
Actual submission date: 24/10/2013

Start date of project: 01/10/2011 Duration: 36 months

Organisation name of lead contractor for this deliverable: FEEM

Revision: 0

Project co-funded by the European Commission within the Seventh Framework Programme		
Dissemination level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

DELIVERABLE NO. 2.2

Report that analyses the economic resources needed to achieve 2°C and to adapt to it

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1. Introduction

This document summarizes the outcome of the LIMITS project under task 2.1, "A quantitative assessment of the economic resources required to achieve 2 C". The task foresees to assess the results of IAMs scenarios of WP1 with respect to the rates of investments and financing which is needed to achieve the transition to a low carbon world. It is composed of two main parts.

- The first and most important one, which relies on the paper by McCollum et. al to appear in the LIMITS special issue, presents the first multi model comparison in the literature which quantifies the global and regional investment requirements for achieving 2°C.
- The second addresses the specific issue of R&D and innovation investments, and is based the one single model in the project which projects innovation investments. It relies on the paper of Marangoni and Tavoni, also to appear in the special issue.

Adaptation investments are not included in this report, since the WP1 study protocol specified policies in terms of cost effectiveness rather than cost benefit, as a way to harmonize the probabilities of achieving 2°C across models. Currently, additional scenarios are being simulated by the 2 models which can generate adaptation patterns. Results regarding adaptation investments will be included either in D3.1 or by –if possible- an update of this deliverable.

2. Executive summary

Ten robust insights emerge from this deliverable, many of which are new to the literature, which as noted is extremely thin, and mostly relies on reports from international agencies or private banks.

a. Meeting the future energy service demands of a growing number of consumers worldwide will require a significant upscaling of investments irrespective of the type of climate policy. Supply-side investments into the global energy system could increase by at least 50%, if not double, compared to today's level of about $1000 billion/yr.

b. Stringent climate policies consistent with the 2°C target may lead to a further increase in total energy investments, but this is uncertain and probably moderate, and depends on how demand side reduction will occur (e-g- more via technology or behavioral change).

c. 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.

d. Investments into renewables will see the most dramatic upscaling, on average between $100 and $750 billion/yr globally over the 2010-2050 timeframe compared to a reference scenario. A sizeable upscaling of demand-side investments into energy efficiency and conservation also appears to be critical (+$200-650 billion/yr), and stepped-up investments into nuclear power and electricity infrastructure (power grid, storage, etc.) may also be needed.

e. 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.

f. 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.

g. There also exists an important ‘clean-energy R&D investment gap’ of approximately $50 billion/yr. Though smaller than the general one, it is key to fill it up given the long term dynamics of innovation.

h. The investments would be initially concentrated in the industrialized countries, but would balance off with those of developing economies after 2030. The largest share of investments would be concentrated for the development of low carbon alternative fuels, though energy efficiency investments would also play an important (and growing) role.

i. Focusing on an international clean energy R&D effort slightly underperforms a continuation of the fragmented mitigation effort outlined by the Copenhagen pledges for the sake of climate stabilization.

j. An exclusive focus on R&D at the expenses of mitigation is incompatible with climate stabilization if maintained for too long. Specifically, R&D agreements to 2030 and 2040 do not attain 2°C with likely (e.g. 450ppm-eq) and as likely as not (e.g. 500ppm-eq) probabilities respectively.

PART I: Energy Investments

1. Energy investments for achieving 2°C: a model based assessment

1.1 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). Scenario results from five different IAMs are analyzed in this paper: IMAGE (van Vuuren 2007), MESSAGE (Riahi et 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.; and for clean-energy research and development investment needs, see Marangoni and Tavoni.) 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. and Tavoni et al..) 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).

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. () 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.

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

Figure 1 gives an initial indication of how these scenarios are interpreted by the various LIMITS models by showing global carbon dioxide (CO2) 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.

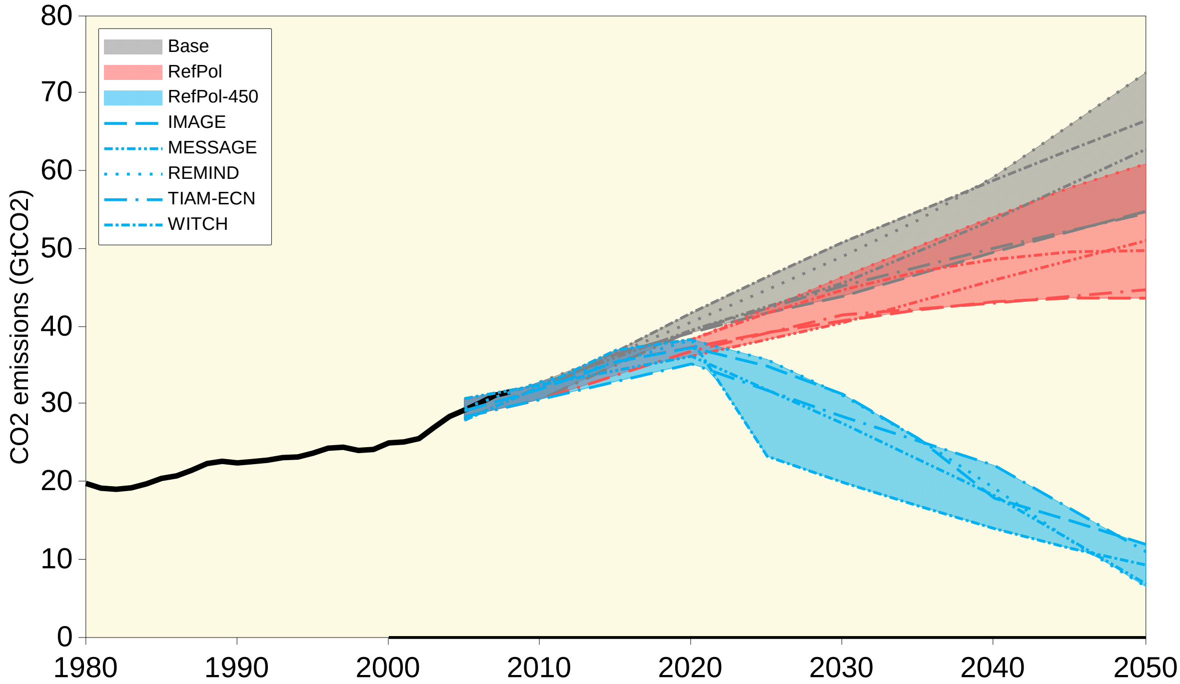

Figure 1. Global CO_2 emissions from fossil fuel combustion and industrial processes across the various models in the Base, RefPol, and RefPol-450 scenarios.

1.2 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)[1], 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

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

billion/yr worldwide (Riahi et al. 2012)[2]. 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 **Errore. L'origine riferimento non è stata trovata.** for further details of the investment breakdown by sector, both at present and in the future.)

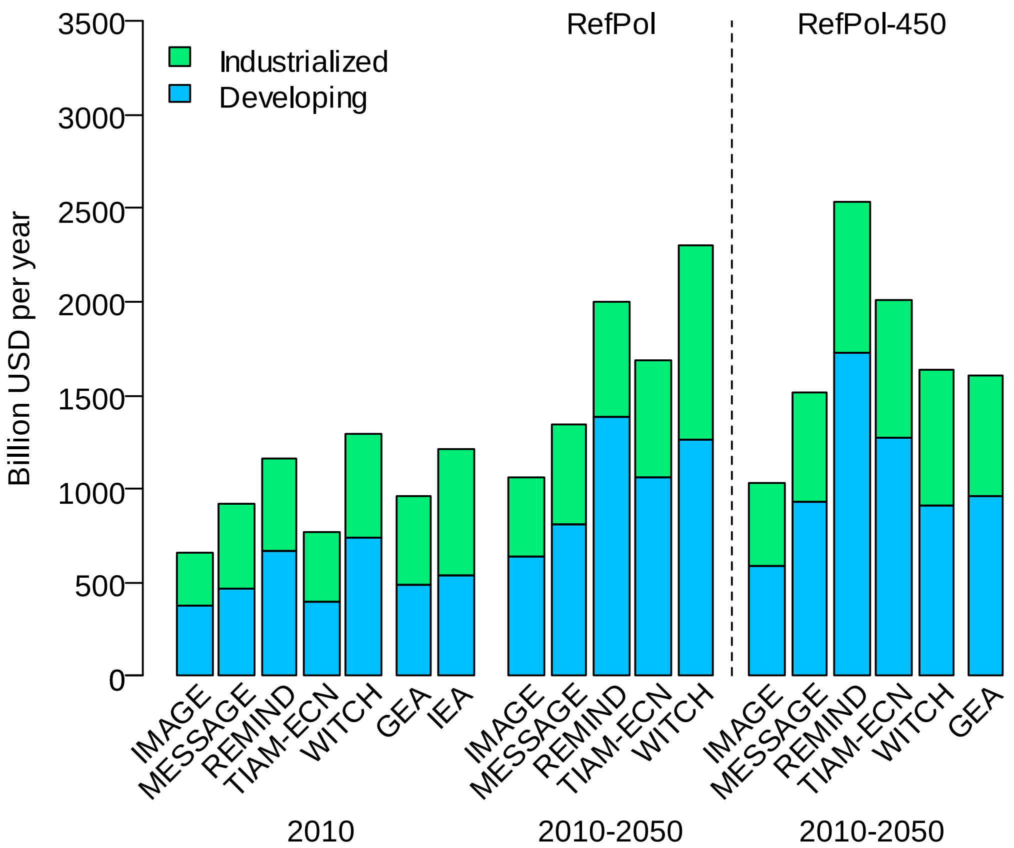

Figure 2. Global annual energy investments (supply-side only) across the various models in 2010 and average annual investments from 2010 to 2050 in the RefPol and RefPol-450 scenarios, in both industrialized and developing countries. See Box 1 for regional definitions. For comparison, estimates from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

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

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

accounted for within models. This also includes estimates reported by the International Energy Agency (IEA 2012b)[3], which like the GEA numbers[4], 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.)

[3] 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.

[4] 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

1.3 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).

1.4 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[5], 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

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

level as in industrialized countries (Figure 2; see GEA (2012) for historical investment figures[6]). 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 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)[7]. 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

[6] 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.

[7] 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.

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[8]. 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 **Errore. L'origine riferimento non è stata trovata.** 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.

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[9]. This required, for a single model and region, calculating the ratio

[8] 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.

[9] 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

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).

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

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.

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.

1.5 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.

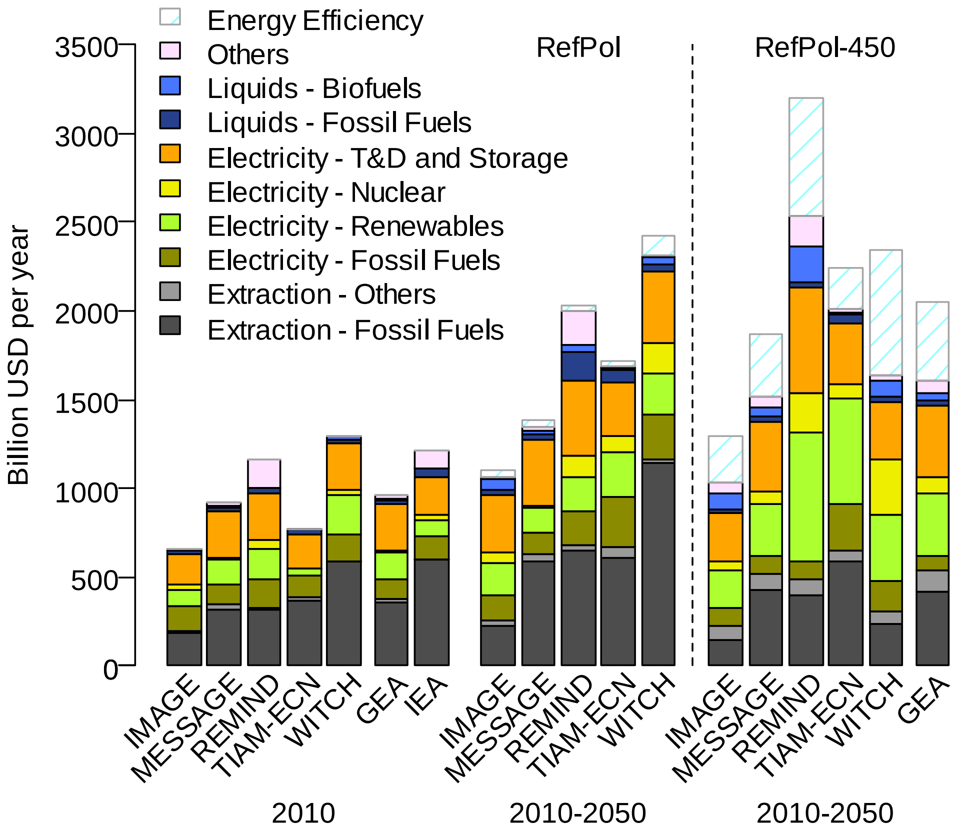

Figure 3. Global annual energy investments (both supply- and demand-side) across the various models in 2010 and average annual investments from 2010 to 2050 in the RefPol and RefPol-450 scenarios, by energy sector. For comparison, estimates from the International Energy Agency (IEA 2012b) and Global 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 CO2 transport and storage, among other things[10].

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 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

[10] 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).

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.

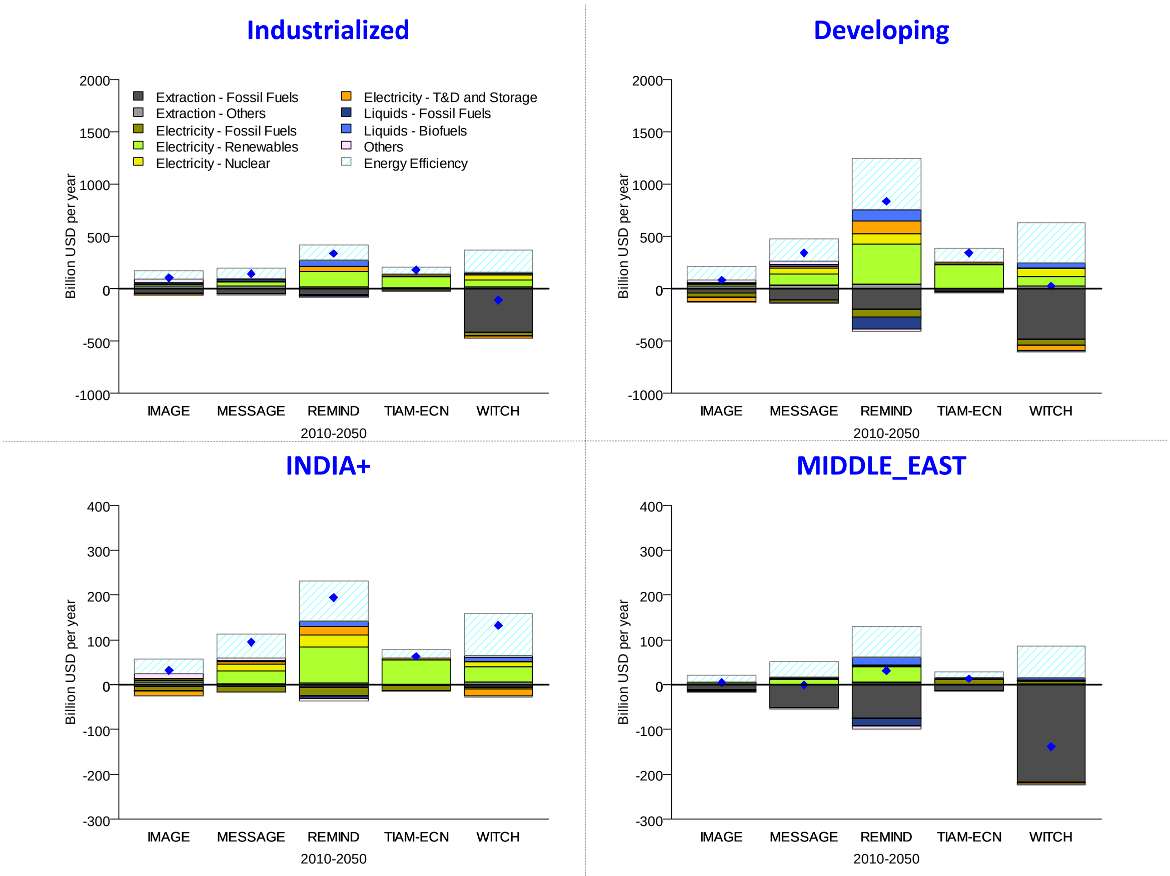

Figure 4. Incremental energy investments (both supply- and demand-side) across the models in the RefPol-450 scenario relative to the RefPol scenario. Investment and disinvestment are shown for each energy sector and for a subset of regions. Values represent annual averages from 2010 to 2050. "Others" category includes investments into hydrogen production and distribution, refined petroleum product transport, heat generation, and CO2 transport and storage, among other things[11]. "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).

1.6 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

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

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 GtCO2 (range: 700-1100 GtCO2) 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.

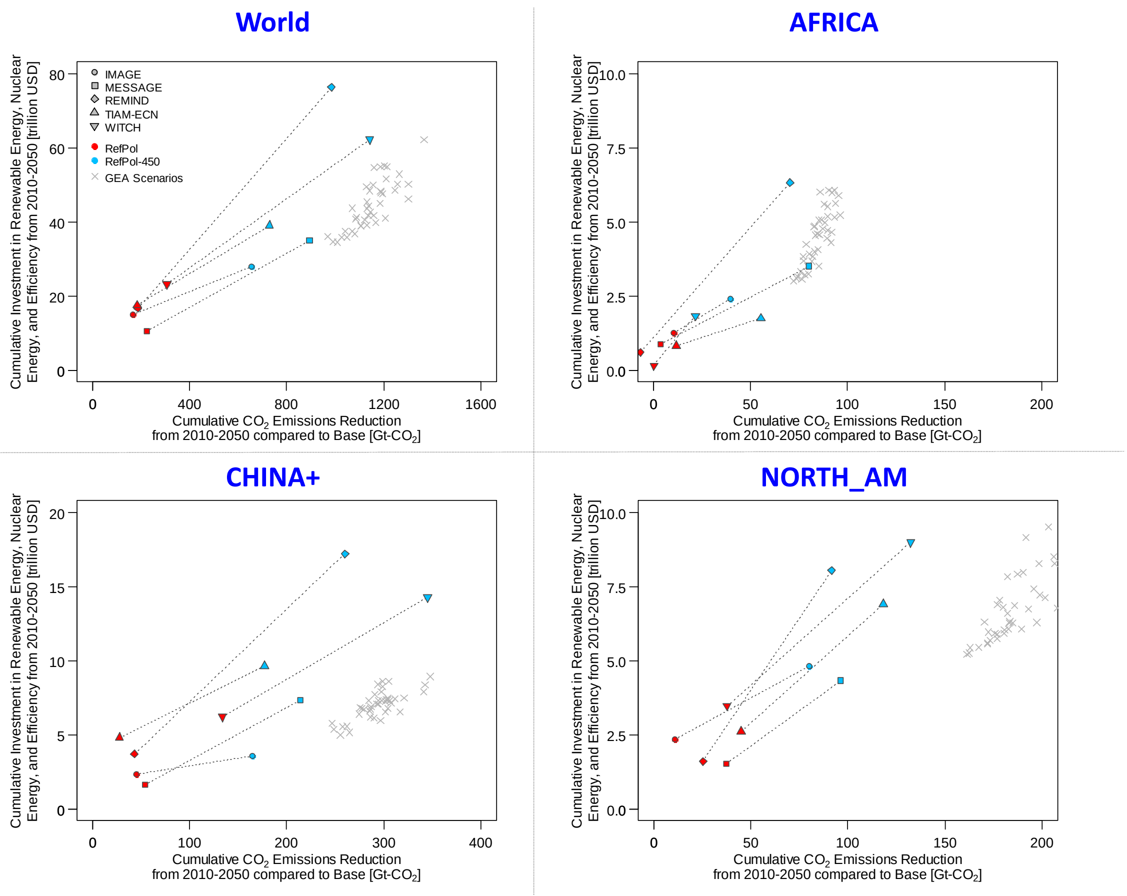

Figure 5. Cumulative clean-energy investments (renewables, nuclear, and efficiency) as a function of cumulative CO2 emission reductions (relative to a hypothetical no-policy scenario, Base) across the models in the RefPol and RefPol-450 scenarios. Also shown for comparison are the 2°C scenarios of the 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 GtCO2 (range: 150-350 GtCO2) 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 GtCO2 (range: 80-140 GtCO2) demanding investments of some $6 trillion (range: $4-9 trillion). Climate mitigation needs in Sub-Saharan Africa (AFRICA+) could be lower still: ~50 GtCO2 (range: 20-80 GtCO2) 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[12].

1.7 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)[13]. 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.

[12] 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.

[13] 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).

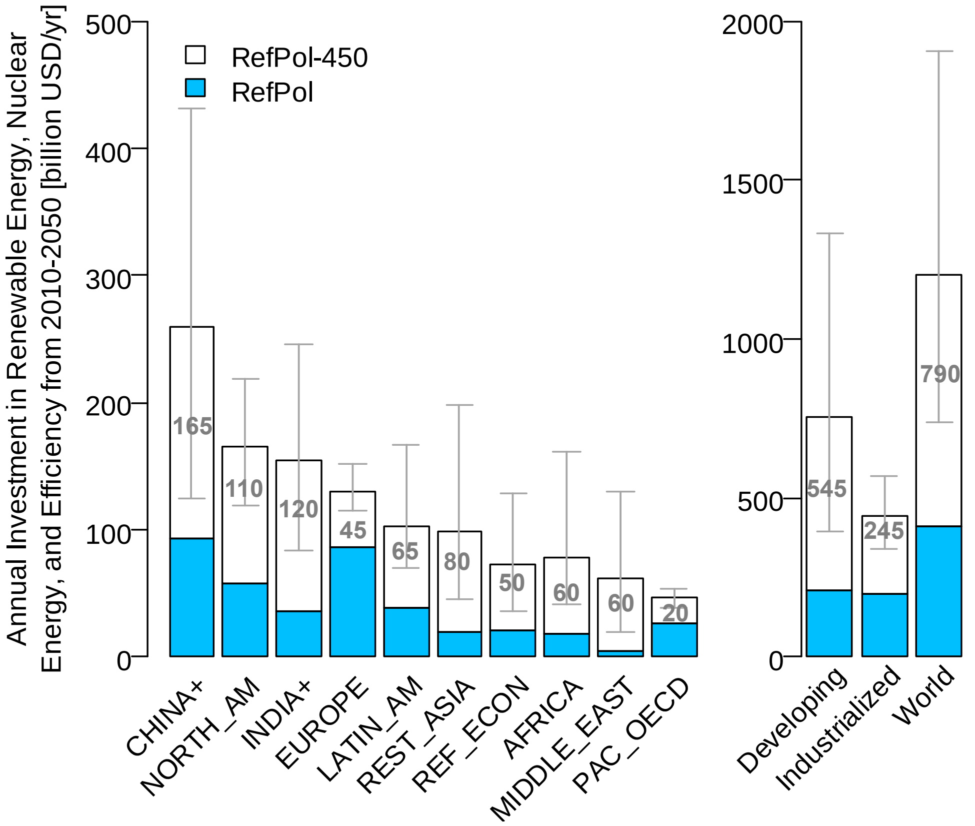

Figure 6. Clean-energy investment requirements in the reference policy (RefPol) and stringent climate policy (RefPol-450) scenarios. Investments include renewables and nuclear on the supply side and energy efficiency on the demand side. RefPol investments shown here for each region are the averages across 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.

2. 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 Errore. L'origine riferimento non è stata trovata., 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).

2.1 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[14] 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

[14] 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.

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.

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*		*Essential* (security	*Uncertain* (neutral	*Essential* (customers	*Essential* (expertise

	scenario: 305–420		regulation critical for some aspects of reliability)	effect)	must pay for reliability levels they value)	needed for new technologies)
	LIMITS 2°C scenario: 265–595	*GEA 2°C pathways:* 310–500				

i. 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 **Errore. L'origine riferimento non è stata trovata.**.)

ii. Estimate includes efficiency investments on the demand side that offset supply-side investments (see Section **Errore. L'origine riferimento non è stata trovata.**).

iii. 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.

iv. 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.

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

vi. 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 CO2 capture are grouped into the fossil fuel categories, while CO2 transport and storage investments are grouped into the "Other" category.

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

2.2 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 **Errore. L'origine riferimento non è stata trovata.**) – 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. forthcoming; 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 CO2 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 **Errore. L'origine riferimento non è stata trovata.**) – 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.

2.3 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 (CO2-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[15]; full details, as well as an extended discussion of model outcomes within the context of the LIMITS project,

[15] 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 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).

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.

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 **Errore. L'origine riferimento non è stata trovata.**) 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.

3. 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 GtCO2 (range: 700-1100 GtCO2) 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[16].

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

[16] 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.

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).

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.

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PART II: Energy R&D the clean energy R&D investment gap to achieve 2°C

1. Introduction

The purpose of this paper is to assess the role of R&D investments in clean energy technologies under the objective of limiting the average global surface temperature increase of 2°C above the pre-industrial average by the end of this century with sufficient probability. 2°C is considered an important signpost for the scientific community as well as for the climate policy debate. The international community has recognized this threshold as the long term goal for the negotiation process which was initiated in Durban, and more recently moved forward in Doha, and which is supposed to lead to a global agreement after 2020. While governments started to acknowledge anthropogenic climate change and the need for action 20 years ago with the first Earth Summit conference, several obstacles have made implementing such a goal very challenging. One of the most important concerns for action is that mitigating emissions, especially at the deep levels required to meet the 2°C objective, could have serious economic repercussions, given that currently available low carbon technologies are costlier than fossil fuel alternatives. A successful climate policy will thus require significant improvement of existing technologies, and invention of new alternatives which can help to reduce energy consumption and emissions at contained costs. Although the innovation component of the climate agenda has been emphasized by many governments, especially in Europe, the literature that has assessed the clean energy R&D gap remains limited.

The objective of this paper is in line with the main purpose of the LIMITS special issue it belongs to: contributing to a better understanding of the implications of a 2°C stabilization. In order to provide quantitative answers to the problem at hand, this and most of the other works of the special issue rely on so-called Integrated Assessment Models (IAMs). This family of models is increasingly common in the field of climate policy analysis, since they provide fairly complete descriptions of the problems that climate policy makers are called to decide upon, and present them with sets of possible least-cost solutions. Further information on the broader results obtained with the models involved in the LIMITS comparison exercise can be found in the overview papers of this same special issue (Kriegler et al., and Tavoni et al., this issue). For a focus on how investments related to clean energy technologies are expected to be allocated under a 2°C target, the reader is invited to refer to McCollum et al. in this special issue.

The literature based on multi-model ensembles has indicated that a huge transformation on the way we produce and demand energy, as well as we use and manage land resources, will be required if we want to meet the climatic constraint of 2°C (Calvin et al., 2012; Clarke et al., 2009; Kriegler et al., this issue). This transformation would require emission reductions rates which exceed by far what has been observed historically. Currently available technologies have the potential to initiate the road towards decarbonization (Pacala and Socolow, 2004). Yet, ultimately, groundbreaking technological innovation will be needed to avoid excessive economic losses. Integrated assessment models have indeed shown that technology availability plays a major role on the feasibility and costs of facing the challenge of 2°C (Krey and Clarke, 2011;

Kriegler et al., Submitted). The literature thus confirms a deep link between the chances of achieving a low carbon world and the ability to improve the performance of currently known technologies, as well as to create new technologies altogether.

Several policies have been put into place in recent years as a way to promote the development of renewables, with the hope that this would have led to the creation of an industry and would have ultimately profited the manufacturing base they supported. However, incentivizing the installation of currently existing technologies does not necessarily provide the best economic answer (Borenstein, 2012); on the other hand, subsidizing research and development is justified by the innovation market failures arising from property rights protection and knowledge spillovers (Geroski, 1995). Thus, a fundamental research question in the field of climate economics is to what extent climate stabilization can be achieved by just focusing on setting the right carbon price, or by considering also policies aimed at fostering innovation (Jaffe et al., 2005, 2003).

A related question to setting the right levels of R&D subsidies is the assessment of the R&D investments gaps that we need to bridge to get to 2°C. Despite the policy relevance of this topic, only a handful of modeling studies have looked into this issue. This can be partly attributed to the complexity of the topic of technical change, an uncertain process which is difficult to model. Surprisingly, however, these studies (Blanford, 2009; Bosetti et al., 2011, 2008; IEA, 2010; Margolis and Kammen, 1999; Nemet and Kammen, 2007; Popp, 2006) tend to agree on a series of important results. First, R&D plays a fundamental role on the costs and feasibility of climate stabilization policies. Second, the gap in R&D investments between a Business as Usual and a climate policy scenario is substantial, in the order of 50 USD Billions per year.

A further research question pertains to the role of innovation policies in case of fragmented cooperation on climate. Given the difficulties in reaching an inclusive agreement on emissions reductions among the major emitters, it is natural to wonder whether focusing on a technology and innovation agreement could offer better prospects and a more efficient outcome than continuing with a set of uncoordinated efforts to reduce CO2 emissions (De Coninck et al., 2008; Newell, 2008).

This paper aims at contributing on the latter two lines of research, and thus improving the understanding of the role of innovation and R&D in the clean energy sector. Our study relies on the integrated assessment model WITCH (see next section). The originality of this article is twofold. First, the clean energy R&D gap is quantified with specific reference to the 2°C objective. To this end, we use the set of scenarios developed in the LIMITS project which combines short term policy realism with two different probabilities of meeting 2°C in 2100. The climate outcome of all scenarios has been tested using the probabilistic version of a medium complexity climate model (MAGICC), ensuring that the exceedance probability remains within specified ranges (see Kriegler et al., this issue). Second, we work out the implications of an alternative climate policy agreement based on a concerted international R&D programme. We refer to this policy setting as the 'RD-deal'. This agreement is meant to replace the current fragmented emission reductions pledges in the near-term with near-term high R&D efforts. International technology innovation policies have been widely discussed as alternatives to binding emission reduction targets, but have been rarely assessed by the IAM community.

The paper is organized as follows. We briefly discuss the main features of the WITCH model, and then present the study design. We show the implications of 2°C policies on the transformation of the energy system, and quantify the size and the regional distribution of the

R&D investments needed to comply with it. We then assess the R&D climate agreement in relation to the feasibility of the 2°C objective. Finally, we summarize our conclusions.

2. Technical change in WITCH

WITCH (World Induced Technical Change Hybrid Model) is an energy-economy-climate model developed within FEEM's Sustainable Development research programme (Bosetti et al. 2006, 2009). The model divides the worldwide economy into 13 regions, whose main macroeconomic variables are represented through a top-down inter-temporal optimal growth structure. This approach is complemented with a compact description of the energy sector, which details the energy production, and provides the energy input for the economic module and the resulting emissions input for the climate module. The endogenous representation of R&D diffusion and innovation processes constitute a distinguishing feature of WITCH, allowing to describe how R&D investments in energy efficiency and carbon free technologies integrate the currently available mitigation options. The different regions can either behave as forward-looking agents optimizing their welfare in a non-cooperative, simultaneous, open membership game with full information, or be subject to a global social welfare planner in order to find a cooperative first-best optimal solution. In this game-theoretic set-up, regional strategic actions interrelate through GHG emissions, dependence on exhaustible natural resources, trade of oil and carbon permits, and technological R&D spillovers.

For this paper, two channels of endogenous technical change are accounted for in the model. Their characteristics are summarized and compared in Table 1. One type of formulation of technical change affects the investment costs of an alternative, carbon-free technology in the non-electric sector. This 'backstop' zero-emission fuel can be thought of as an advanced biofuel mitigation option whose costs are currently much higher (e.g. 10 times) than oil, due to lacking of sufficient knowledge for transforming cellulose into ethanol. With sufficient R&D and physical investments, the low carbon backstop can become a viable substitute to low carbon fossils. However, we also impose a global constraint on the resource base which can be used to produce the low carbon fuel, as a way to mimic the limitation of land use which can be devoted to growing the bio-feedstock. The global cap is fixed at 150 EJ/yr, in line with available estimates of bioenergy crop potential (see Calvin et. Al, this issue, for a detailed discussion of bioenergy). Thus, although at times we refer to this unnamed technology to as backstop in the paper, its implementation in the model provides a realistic representation of the technology as a bioenergy-based low carbon fuel. While the climate mitigation literature mentions also bioenergy-based systems capable of removing carbon from the atmosphere, by means of carbon capture devices, no negative emissions are envisaged through our backstop technology.

The externality nature of the backstop innovation process is modelled via international spillovers of *knowledge* and *experience* across countries and time. In each country, the productivity of this low carbon technology depend on the region's stock of energy R&D and on the global cumulative installed capacity, two proxies for knowledge and experience respectively. This is modelled via two factor learning curves. The regional R&D stock depends on domestic investments, previous domestic knowledge stock, and foreign knowledge stock through international spillovers. The spillover term for knowledge depends on the interaction between the countries' absorptive capacity, and the distance of each region from the technology frontier. On the other hand, there are complete spillovers of experience across countries.

The other main channel of technical change in WITCH is about energy savings. Following Popp (2006), energy efficiency is modelled through improvements in the productivity of the energy input in the production of the final good sector, via a constant elasticity of substitution (CES) production function. Differently from the previous case, innovation is now subject only to knowledge externalities through a single factor learning curve. The knowledge stock depends on domestic and foreign R&D investments in a similar way than the one used for the backstop, with the only difference that the new additions to the stock of knowledge depend also on the previous domestic stock of knowledge.

Further details for both innovation formulations can be found in (Bosetti et al., 2011) and at www.witchmodel.org. The most relevant equations are reported for convenience in the Appendix.

	Energy Efficiency	Carbon-free Advanced Biofuels (Backstop)
Technological implications of the innovation	Introducing new energy-saving equipment and devices in any of the energy end-use sectors (buildings, industry, and transport).	Introducing advanced carbon-free biofuels as a primary energy supply for non-electric energy end-use sectors (mainly transport).
Economic implications of the innovation	Increasing overall energy efficiency of output.	Reducing the costs of carbon-free non-electric energy supplies.
Integration in the model	As a substitute for energy supply in producing energy services.	As a substitute fuel for oil in meeting the non-electric energy demand.
Technical change drivers	1. Domestic & foreign investments in R&D.	1. Domestic & foreign investments in R&D. 2. Domestic & foreign experience (i.e. amount of advanced fuels already used).
Diffusion limitation	Implicit in the constant elasticity of substitution (CES) production function structure.	Explicit through expansion and total resource constraints.
Knowledge to actual technical change delay	None.	10 years lag.
References in the literature	Jones (1995) for the knowledge formulation, Popp (2002) for the empirical estimation of the parameters, and Popp (2004) for the integration as a CES.	Kouvaritakis et al. (2000) for the knowledge formulation, Bosetti et al. (2009) for further references on the empirical estimation and modeling, Calvin et al. (this issue) for cumulative deployment potential estimates.

Table 5: The two channels of innovation in WITCH.

When elaborating on regional results, we will be referring to the 13 native regions of WITCH, which are: USA, OLDEURO (Old Europe), NEWEURO (New Europe), CAJAZ (Canada, Japan, New Zealand), KOSAU (Korea, South Africa, Australia), CHINA (including Taiwan), INDIA, SASIA (South Asia), EASIA (South East Asia), LACA (Latin America, Mexico and Caribbean), MENA (Middle East and North Africa), SSA (Sub-Saharan Africa excl. South Africa) and TE (Transition Economies). For the sake of brevity, also the following aggregations will be used: EUROPE (OLDEURO + NEWEURO), OTHER-OECD (KOSAU+CAJAZ), OTHER-ASIA (SASIA+EASIA), and MEA (MENA+SSA).

A distinctive feature of WITCH is the ability to assess the optimal response to climate policies either in a competitive or in a cooperative setting. In the latter, a social planner chooses the optimal financial efforts to allocate in innovation and mitigation, in a way that welfare is maximized conjunctly with the achievement of a given climatic target. This type of optimization can be regarded as a useful benchmark for evaluating the consequences of internalizing the set of externalities which are taken into account in the WITCH model, namely: GHG emissions, dependence on exhaustible natural resources, and technological R&D spillovers. A particular advantage of this setting lies in the ability of estimating the economic benefits of a cooperative world, where classic climate policy instruments are replaced by sets of policy instruments that promote coordinated efforts in achieving the desired climatic targets.

As one could expect, full cooperation scenarios lead to lower consumption losses and higher accumulation of R&D backstop investments compared to the non-cooperative corresponding cases. The results obtained in the context of this paper with the cooperative settings are not reported here, as they are in line with previous studies with this same model (Bosetti et al., 2011), and with the aforementioned literature on R&D subsidies. For the sake of this paper, it is only worth mentioning that cooperation not only affects the global picture (with a general increase of investments), but also the regional contributions to innovation (with a more prominent role for developing countries).

3. Study design

To assess the role of energy innovation in decarbonizing the energy system, the 2° degrees target was translated into a set of significant scenarios implementable by the WITCH model. Most of the scenarios we consider here were defined in the context of LIMITS, whose purpose is to explore the implications on feasibility and costs of different policy assumptions, i.e. the probability of achieving the 2° degrees target, the timing and stringency of global and regional mitigation action, and the distribution of regional costs. Further details on the whole scenario framework adopted for this study, as well as on how the economy and the energy system of different IAMs respond to the different scenarios assumptions, can be found in the two overview papers by Kriegler et al. and Tavoni et al. in this issue.

Besides the standard LIMITS scenarios, we have run three additional scenarios to address the specific questions under investigation. Specifically, we have assessed ‘second best’ policy scenarios in which no agreement is achieved on emission reduction policies, but in which countries decide to cooperate on R&D by investing at the optimal levels consistent with their stabilization objective, either 450 ppm-eq or 500 ppm-eq.

Table 2 reports a brief description for all of the scenarios used in this study. The last row shows the ones which are additional to the LIMITS study protocol.

Scenario	Description
Base	No climate policy, either global or regional, is in place.
RefPol	Regions are subject to 2020 targets that represent the lower end (or lower if more plausible) of their (or of their neighboring regional leaders) Copenhagen pledges. The stringency level of 2020 regional targets is extended until the end of the century by using average GHG emissions intensity improvements per year as a proxy.
StrPol	Like RefPol, but the more stringent end of their (or of their neighboring regional leaders) Copenhagen pledges are taken into account, and extended until the end of the century.
RefPol-450	Regions apply the RefPol policy package up to 2020, then a globally-harmonized carbon tax is adopted so that the concentration of GHGs reaches 450ppm-eq in 2100, with overshoot allowed. This corresponds to a likely to very likely (>70%) chance of reaching the 2 °C target.
RefPol-500	Like RefPol-450, but with an as likely as not (~50%) chance of reaching the 2 °C target, and with the concentration of GHGs reaching 500ppm-eq in 2100.
RefPol2030-500	Like RefPol-500, but with global commitment delayed till 2030.
RD-deal-450 RD-deal2030-500	These scenarios correspond to those with the same names where RD-deal is replaced with RefPol. In the near-term, carbon emission mitigation pledges are removed from the corresponding RefPol policy packages, while energy R&D is fixed at the optimal level. Afterwards, a globally-harmonized carbon tax is adopted so that the concentration of GHGs reaches the levels of the corresponding scenarios.

Table 6: List of scenarios used in this study, along with their description.

In the next sections, after describing the challenge for the economy and the energy systems to stabilize the climate to non-dangerous levels, the R&D investment gap is quantified for what can be considered as first-best settings, where mitigation action, even if fragmented, starts immediately, and global cooperation starts in 2020 or in 2030. Then, R&D figures are analyzed in a class of second-best scenarios, in order to see if other sub-optimal policies, where the regional emission reduction efforts of the Copenhagen pledges are replaced by high energy R&D investments and global cooperation is delayed up to 2030, could constitute viable cost-effective alternatives.

4. Challenges of stabilization to 2° degrees

A world without any climate policy is expected by WITCH to be a world with a temperature in 2100 of 4° degrees above the pre-industrial levels, which is likely to imply serious ecological, social and economic consequences. More than 60% of yearly global GHG emissions are related to CO2 emissions resulting from the burning of fossil fuels for energy related purposes, which are supposed to increase in the baseline on average by 1.3% per year. Population and global economy are also supposed to increase, at an average rate of 0.4% and 2.4% per year respectively, while global energy intensity levels are expected to decrease at an average rate of 1.4% per year. On one side, this implies an improvement of carbon intensity over the century, due to the expected diffusion of more efficient energy systems around the world. On the other side, countries are expected to show an increase in the average carbon emissions per capita, representing the worldwide claim for better living standards met by a fossil based energy system.

Looking at the regional emission contributions, the largest emitter is expected to be with wide margin China, with almost 30% of the total cumulated GHG emissions of the century. Following with 10.4%, 9.8% and 9.3% we find India, USA and LACA, respectively. Europe (6.7%) places itself in the middle of the list, after TE (8%) and MENA (7.6%). When considering emissions growth rates, India distinguishes itself with its average rate of 2.1%, followed by China and MENA, both at 1.5%, concurrent with double growth rate figures for GDP.

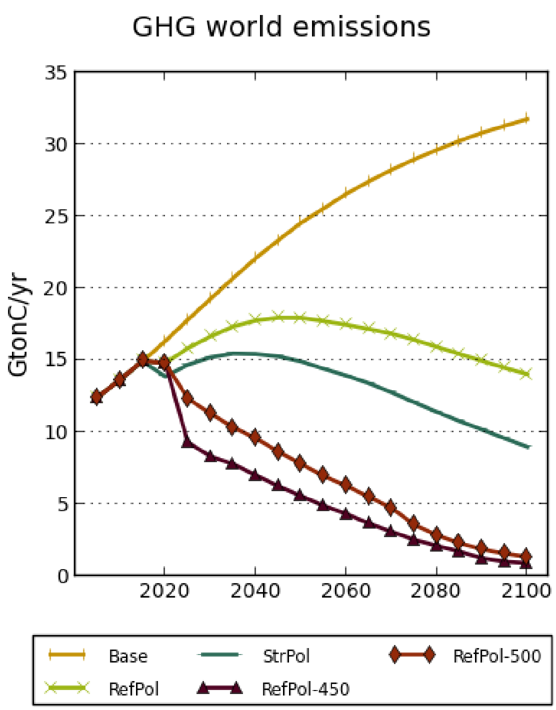

Figure 7: Emission profiles for a subset of LIMITS scenarios

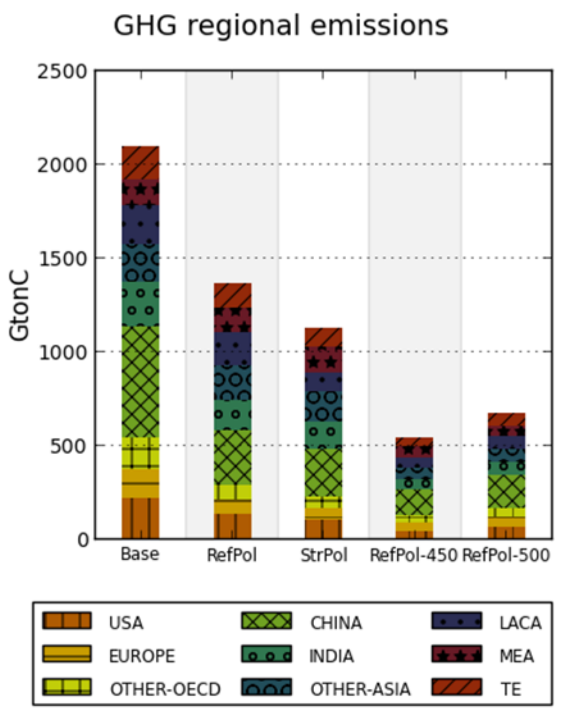

Figure 8: Cumulative emissions over the century decomposed by regions.

If regional economies were able to respect a weak fragmented commitment to climate mitigation, as foresighted in the RefPol scenario, cumulated GHG emissions over the century could be reduced by about one third. A further 10% could be abated with a more stringent fragmented commitment (as in StrPol). The rate of carbon intensity reduction varies across regions, according to explicit targets set after 2020. Focusing on the RefPol case, for some regions like MEA, OTHER-ASIA and LACA, the baseline carbon intensity profile already meets the assumed pledge. For other regions, this target involves a binding constraint on emissions, pushing the transformation towards a less carbon intensive energy system. This transition is further elicited by explicit targets on the amount of renewable energy over the total final or electrical energy production after 2020, and of wind and nuclear capacity installed by 2020. Again, China happens to be one of the most significant players, with huge reductions in emissions and a significant slowdown of GDP. Of the 780 GTonC reduced from baseline in the RefPol, 322 (~41%) are to be attributed to China, more than what OECD countries together are supposed to mitigate (269 GTonC). This impacts its GDP with a yearly 2.9% loss with respect to the baseline, on average over the century, a rate which is above the average of 1% that is globally experienced. The countries with the highest losses are CAJAZ, TE and KOSAU, with yearly average GDP losses of 3.3%, 3.2% and 2.2% respectively. The carbon intensity rate improvements these regions are asked to provide on average are between 1 to 3 times those of the Base scenario.

A substantial decarbonisation of the economy is required if more ambitious emissions targets are to be imposed, namely those where GHG concentrations reach 450ppm-eq and 500ppm-eq in 2100. This implies deep changes both in the electric and in the non-electric energy production sectors. Concerning the former, the reduction of carbon emissions is achieved in four ways: i) decreasing the power demand through efficiency improvements and economy contraction; ii) limiting the use of fossil fuels, partially switching to expensive technologies of carbon capture and storage (CCS); iii) increasing the diffusion of renewable energy sources; iv) enforcing the role of nuclear power, as a consequence of the reduction in the use of the base-load fossil technologies, and the limitations in the share of wind and solar power supply due to their intermittency issues[17].

Fossils cover around two thirds of the present world electric demand. In the Base scenario, this quota slightly increases over the century mostly at the expense of renewables, decreasing from 20% to 12%, while nuclear slightly decline from 14% to 12%. In the moderate Copenhagen scenarios, instead, fossil fuels are progressively substituted, especially in the second part of the century, mainly by nuclear and renewables: in 2100, nuclear settles around 20%, renewables take 25% of the power share, while fossils decrease accordingly. It is interesting to note that the role of CCS technologies grows considerably with the stringency of the climatic policy. Even if they only appear in the last decades of the century in the RefPol and StrPol cases, their share amounts to 13% and 22% in 2100. In the more stringent stabilization scenarios, finally, a complete decarbonisation of the power sector takes place over the century: fossil fuel power supplies constantly decline, and need to be fully combined with CCS technologies. The diffusion of renewables is extensive: biomass plants reach 20% of the share, almost all of them with CCS, while wind and solar plants rise to 20%, capped by the aforementioned intermittency-related system integration constraints. In absolute terms, 2100 electricity consumption decreases by

[17]The penetration of intermittent renewables in the electric system is limited by 1) penalty costs dependent on the share of intermittent renewables in the power mix 2) equations ensuring the presence of flexible generation options, like coal and gas plants, to adequately compensate for the intermittency of wind and solar supplies.

23%, 32%, 49% and 50% in the considered scenarios (RefPol, StrPol, RefPol-500 and RefPol-450) with respect to the corresponding Base value. These reductions complement the transition to a less carbon intensive power system in meeting the emissions targets.

A strong decarbonisation is recognizable also when looking at the overall energy sector. Again, energy efficiency improvements allow for equal levels of GDP given smaller final energy amounts. Jointly with a shrink of the economy forecasted by the model to meet the various targets, these effects determine a considerable decline in the absolute demand: in 2100, it is 12 ÷ 25% lower than the Base case in the Copenhagen scenarios, while it is more than halved in the stabilization. Besides demand reduction, significant impacts of the policies under study can be seen in the share of fossil fuels and renewables in global primary energy supply, demonstrating a progressive transfer of production quotas from the former to the latter. Nonetheless, one of the most important factor in assisting the regional mitigation actions remains the diffusion of the carbon-free backstop in the non-electric sector. While this technology doesn't enter in the baseline, it turns out to be very reactive to the stringency of the climatic policy when one is imposed. At the end of the century, the 25%-32% of the non-electric demand is satisfied by the backstop in the fragmented cases, whereas the share rises to 72% in the stabilization ones. In the latter scenarios, a complete switch from oil to advanced carbon-free biofuels is envisioned by the model by 2090.

The diffusion of the backstop, along with the energy efficiency improvements, is an essential part of the optimal model response to the ambitious targets under investigation. The huge reductions in energy demand would not be economically reasonable without adequate investments in energy efficiency improvements. Furthermore, if the transportation energy demand and the decarbonization requirements are to be jointly met, replacing oil with carbon-free alternatives becomes essential for the levels of stringency under consideration. The deployment of these two mitigation strategies would not be possible without specific investments in R&D, which will be explored in detail in the following sections.

5. The R&D gap for 2°C

In this section we quantify the R&D investments which are optimal for the set of 2°C compatible scenarios outlined in the previous sections. As described above, the WITCH model features two types of R&D investments that can improve the economic efficiency of the energy system. The first aims at compensating the need for final energy by increasing the energy efficiency of the whole energy sector. A second type involves the deployment of a non-electric carbon-free technology.

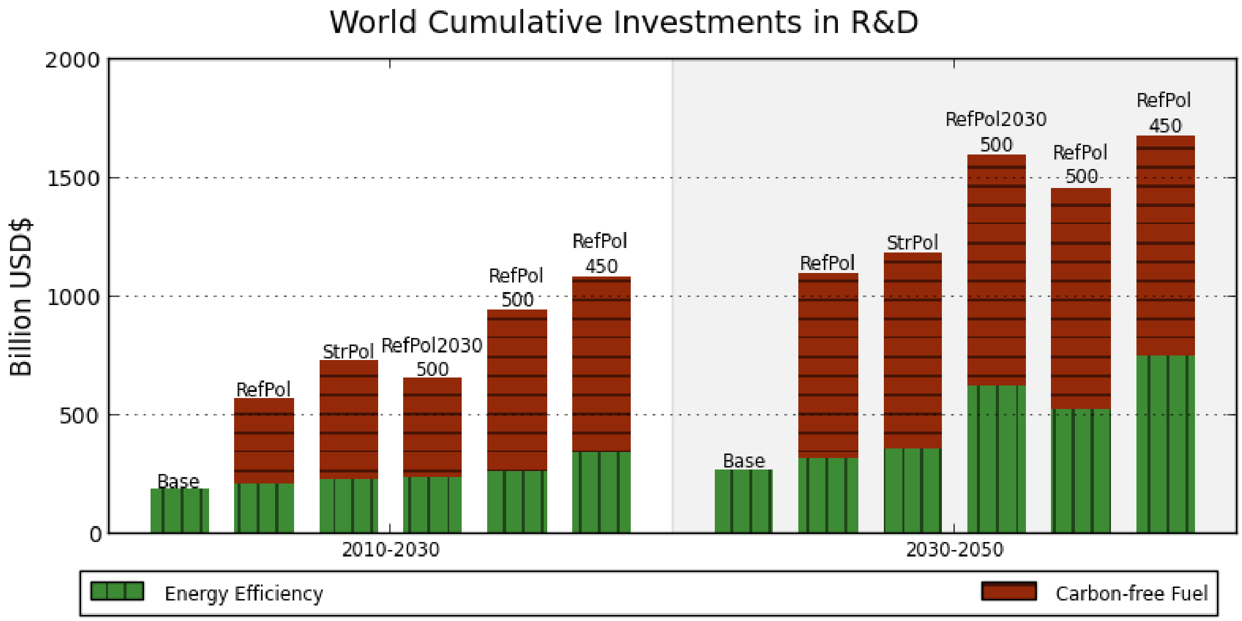

Figure 9: Optimal innovation investments in response to different climate policy scenarios

It is interesting to note that the model promotes a certain level of innovation effort already in the baseline case, where no particular climate policy is in place. This is related to the economic benefit of reducing the cost of the energy production by saving energy, but does not involve investing in carbon-free fuels given that no price is attached to CO2, and that fossil fuels are assumed to be relatively available throughout the century. Regarding the impact of climate policies on R&D, as shown by Figure 3, investment cumulative levels increase both over time and in the stringency of the climate policy. RefPol2030-500 shows a lower effort in the near term, similar to RefPol[18]. In the medium term, the avoided initial investments are fully recovered, bringing the overall cumulative amount to a level comparable with the RefPol-500 scenario.

The increase in investments due to the stringency of the climatic policy is not equal in the two sectors, as the non-electric carbon free R&D appears to be much more sensitive to the climate policy stringency. This is due to the fact that energy efficiency R&D is carried out already in significant quantity in the Base case, because of the rising cost of the energy production factor. Further investments provide smaller benefits, due to the assumption of decreasing returns. On the other hand, carbon-free R&D is particularly valuable in the presence of the climate policies, since it provides a carbon free alternative in a sector which is notoriously difficult to decarbonizes, namely the transportation sector.

Overall, Figure 3 indicates that the global R&D investment needs for attaining 2°C is approximately 1 USD Trillion in the period 2010-2030, and 1.6 USD Trillions in the period 2030-2050, if we consider RefPol-450 and RefPol-500 as our benchmark scenarios. Depending on the desired climatic target and on the near-term stringency of commitment, we can also quantify the

[18] Even if one would expect that the 2010-2030 cumulative investments of RefPol2030-500 should be exactly the same of the RefPol, in period 2030 investments of the delayed scenario are let free to deviate from the RefPol, otherwise also the next period would be mostly fixed. This also applies to scenarios with a delay up to 2020, in which case investments are let free from period 2020.

gap between the optimal corresponding R&D investments efforts and the business-as-usual case. As no advancement is done in clean non-electric technologies, the global R&D gap to the no-policy baseline on average ranges from 30 (RefPol) to 58 (RefPol-450) USD Billions per year, up to 2050. These figures roughly double when considering the second half of the century in the same setting. The estimates reported above are consistent with previous studies with the same model (Bosetti et al., 2009), and more recent studies conducted by IEA (IEA, 2010), which establish the current annual public RD&D spending shortfall between 40 to 90 USD Billions. This projected additional effort asked to clean energy investors is 3 to 6 times the total annual amount of RD&D, averaged in the period 2005-2010, spent by IEA member states, which account for almost all of the OECD, and most of the global, R&D spending in that period (IEA, 2011). Cumulatively, between 1990 and 2010, the same countries invested about 220 USD Billions, less than half of the amount WITCH suggests to be optimally invested by OECD countries for the next 2 decades consistently with the 2°C target.

In relative terms, even if today R&D investments represent a small percentage of the world GDP (around 0.02%), it is clear from our results that most stringent scenarios will definitely benefit from increasing this share, and especially from doing so in the early near-term. This is what has been consistently found in the considered framework, where investments relative to GDP peak at around 2020 at 0.1%, and then gently decline to 0.05% towards the end of the century, as the return on investments decrease. For comparison, the level of investments in capital of wind and solar electric plants in 2020 is about 0.17%, and peaks before 2020 to 0.23% (RefPol) - 0.35% (StrPol) when imposing the constraints following from the Copenhagen pledges, and declines to 0.1% at the end of the century. Further characterization of the R&D dynamics can be gained by inspecting the regional distribution of the R&D investments. This is illustrated first for the efficiency case in Figure 4. The chart highlights a rather constant allocation of regional contributions across time and scenarios. While China among non-OECD regions is the one that increases its share the most over time, the coverage of efficiency R&D investments by OECD countries remains dominant, fluctuating around 80%. The reason for this dynamics depends on the fact that the current energy intensity is considerably lower in industrialized countries, which use more efficient technologies and have a less energy intensive economic production[19]. As a result, further improvement in energy saving technologies must be fostered by inventive activities (in this model dependent on R&D investments), whereas - in emerging economies - there are more opportunities for reducing energy intensity by adopting more efficient technologies and shifting the production structure towards a more capital intensive one.

More diversity in terms of regional R&D schedules is evident when focusing on the regional shares of backstop investments (Figure 5). The chart shows that the more stringent the climate target, the higher the share of investments in non-OECD countries. This is due to the fact that, for climate stabilization policies, the majority of the mitigation effort happens in the developing countries (see Tavoni et al., this issue). For the policy more compatible with 2°C (the 450ppm-eq case), R&D investments in low carbon fuels in the next 20 years are shown to be evenly balanced between industrialized and developing economies. This equal regional split consolidates in the medium term (2030 to 2050) for all scenarios.

[19] In WITCH, GDP is measured in MER. Using the PPP metrics, instead, might weaken this effect, by reducing the energy intensity gap between industrialized and developing economies.

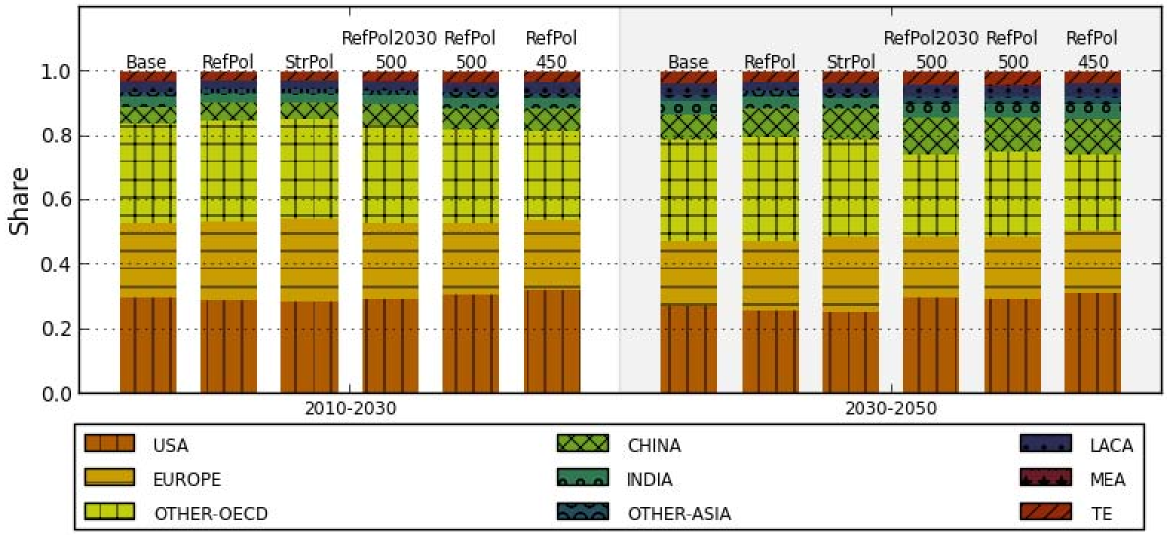

Figure 10: Regional shares of cumulative R&D investments in energy efficiency for the near and medium terms.

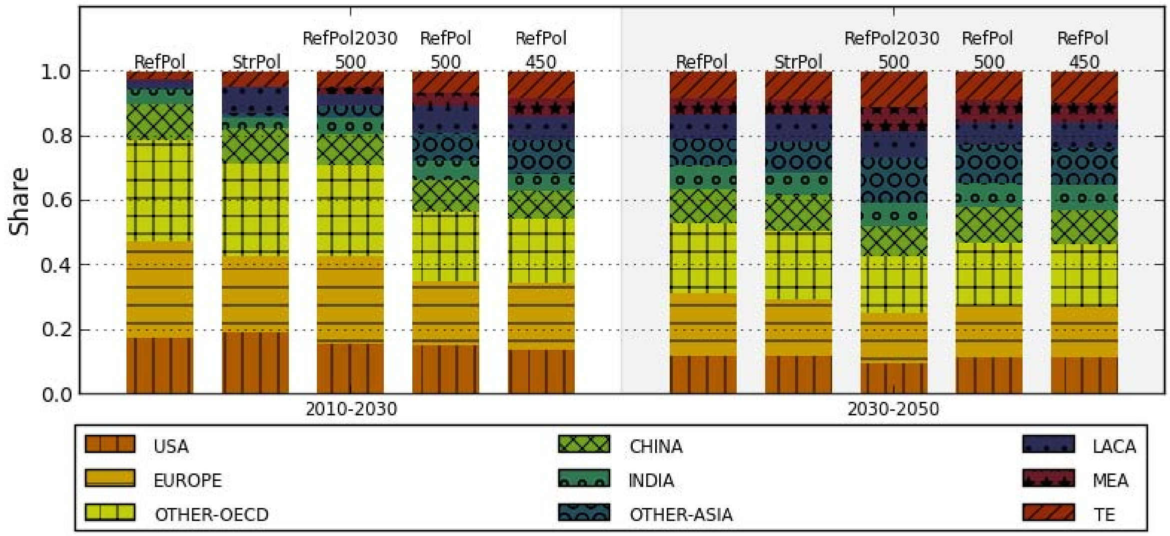

Figure 11: Regional shares of cumulative R&D investments in carbon free fuel for the near and medium terms.

Still focusing on the non-electric sector, it is useful to assess the consequences of the R&D investments by comparing the resulting backstop price with the price of oil, which is its main market competitor. In 2010, the carbon-free fuel is assumed to enter the energy scene with a price 13 times the price of oil. Thanks to the R&D efforts, its unit cost decreases at an average rate of 4-6%/yr to 2050, depending on the scenario and on the region. Simultaneously, oil price increases with its increasing cumulative extraction, in such a way that the two prices meet between 2025 and 2035, depending on the scenario. After that point, the backstop provides an alternative cheaper than oil for the rest of the century to the non-electric (mainly transport) energy needs.

6. Assessing the chances of an R&D deal to get us to 2° degrees

In the previous section, the optimal energy R&D response as proposed by the WITCH model was studied in the context of a set of idealized scenarios. These scenarios assume a policy commitment by all the regions, albeit fragmented and not particularly ambitious till 2025. However, the current state of international negotiations is dominated by huge uncertainties, and it is possible that a global consensus might not emerge under the Durban action platform negotiation round. The aim of this section is to analyze alternative policy designs which target innovation rather than emission reductions in the short term.

We thus consider two additional scenarios, based on an R&D based policy which might provide a trade-off between the inertia of regional political systems to seriously commit to climate change policies and the willingness to limit the GDP loss in view of a long-term acceptable climatic target. In these scenarios, called RD-Deal-450 and RD-deal2030-500, countries replace the fragmented commitment to reduce emissions till 2025 or 2035, respectively, with an agreement to cooperate on energy R&D. Specifically, investments in both energy efficiency and low carbon technologies R&D are set to the optimal levels. Optimal levels are computed from first best runs in which full cooperation starts already in 2015. Thus, these R&D policies are assumed to enter into force already in 2015. After this initial period, where no mitigation action happens and only accumulation of energy R&D knowledge is enforced[20], a globally harmonized carbon tax ensures that a carbon budget compatible with 450 or 500 ppm-eq respectively is met. The RD-deal-450 thus mimics a policy case in which, at the UNFCCC conference of parties in 2015 in Paris, countries decide to immediately adopt R&D investment objectives - maybe because of difficulties in agreeing upon short term emission reduction targets - for a transition period of 10 years, after which they decide to cooperate on the objective of achieving 2°C with high probability. The RD-deal2030-500 case mimics a case of prolonged difficulties in setting emission reduction objectives, and in which countries decide instead to focus on R&D cooperation for 20 years (e.g. from 2015 to 2035), and to cooperate afterwards. These two cases are direct counterparts of the RefPol-450 and RefPol-2030-500, against which they will be compared in what follows.

We also tried to run scenarios with a procrastinated agreement on R&D, but found that the 2°C could not be met[21]. Specifically, we have found that R&D deals to 2030 and 2040 are

[20] As detailed in Kriegler et al., this issue, beyond carbon emission constraints, the reference policy has explicit regional targets on the amount of renewable energy over the total final or electrical energy production after 2020, and of wind and nuclear capacity installed by 2020. These targets are retained in the RD deal scenarios, allowing for a more direct comparison with the corresponding RefPol ones. We also run the RD deal cases without these technology pledges, and we found negligible impacts on the results. Thus, in this framework it is appropriate to solely focus on the distinction between early mitigation and early innovation commitments.
[21] The model could not find a feasible solution to these programmes.

incompatible with attaining 2°C with likely (e.g. 450ppm-eq) and as likely as not (e.g. 500ppm-eq) probabilities respectively. This is an important result by itself, which shows a fundamental trade-off between investing for better future technologies and locking in currently dirty ones. The R&D agreement sets the right incentives for the first issue, but not for the second; as a result, carbon intensive capital is continued to be built while climate R&D investments are carried out. Due to the long term nature of energy investments, the RD deal - if carried out for too long - jeopardizes the chances of meeting the stringent carbon budget consistent with 2°C, even if it provides a more favorable technological future[22].

We begin our investigation of the R&D policy deals on the levels of investments in R&D. These are shown in Figure 6 for the two R&D deal scenario, and their respective Durban Action platform LIMITS scenarios. For energy efficiency (left panel), the chart shows that R&D investments are below the optimal levels (at which the RD deal scenario are set by design) till the time of inception of full cooperation on climate mitigation (2020 or 2030). For R&D aimed at making carbon free fuel competitive, investments are lower than optimal before full cooperation, but higher afterwards, in an effort to compensate the missed opportunity of starting to abate earlier. Investments eventually align between the RD deal and the Durban Action scenarios, as expected since in the long term the objective to collectively reduce emissions dominates the climate action strategy. The timing of investments is different between energy efficiency and decarbonization; for the former, investments continue to increase over time, since they represent continuous and gradual improvements in energy efficiency enhancing technologies. For the latter, investments peak and then revert to a common optimal level of investments. The initial peak, which would be even more notable if measured in share of GDP, is needed to bring down the cost of the breakthrough technology, so as to make it competitive with fossil alternatives. Once this happens, investments are somewhat reduced, though only to a limited extent, since the stock of knowledge needs to be maintained to keep the low carbon alternative in the market.

[22] It should be remarked that in this version of the model we don't feature R&D processes for innovative CO2 absorbing technologies such as Direct Air Capture (DAC). Allowing for such an option could potentially provide additional leverage to the R&D deal, as more negative emissions can be done later in the century, though it would also increase the chances of exceeding the temperature target. For a discussion about the impact of DAC for climate stabilization in the WITCH model, see Chen and Tavoni (2013).

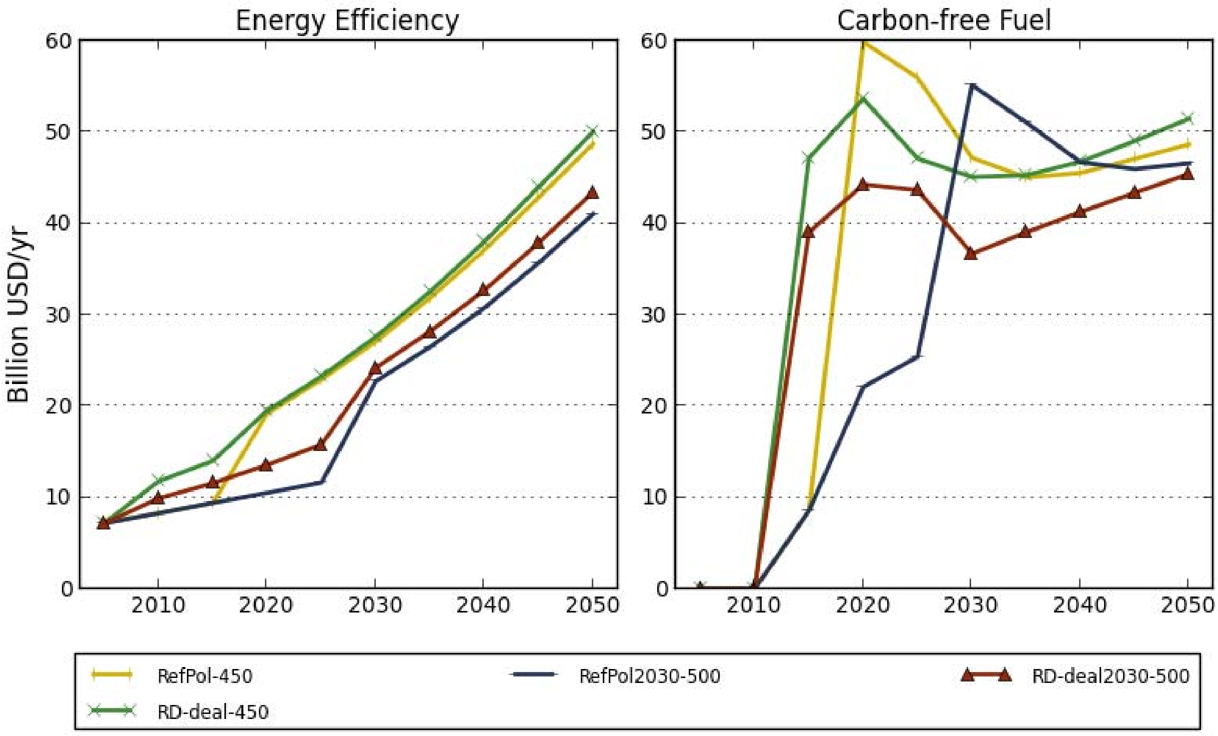

Figure 12: Time profile of the annual global investments in energy R&D in second-best scenarios.

Policy-efficiency considerations can be formulated by looking at Figure 7, which allows comparing the costs of the policies under discussion, assuming as a measure of cost the GDP loss with respect to the base case. The chart shows that till 2050 (left panel), policy costs are essentially identical for the 450 scenarios. This is reasonable since the two policies differ only in the strategies to 2020. For the 500 cases in which we assumed that full cooperation is enforced only after 2030 (precisely in 2035), the difference between the two scenarios is more clear. The R&D deal cases is as expected cheaper in the short term, since R&D investments are cheaper than actual mitigation measures, albeit at a reference policy levels[23]. The higher initial costs in the RefPol2030-500 are due to the partial cooperation on the Copenhagen commitments, which are assumed to be achieved independently for all regions with no opportunity to trade emission reductions. This leads to a diversity of regional carbon prices, with an associated efficiency loss. Over time, though, the RD-deal2030-500 policy turns out to be more expensive, due to the higher abatement needed to comply with the given concentration target (500ppm-eq) and the lower abatement carried out before 2030. Looking beyond 2050 (right panel), the cost difference persists in the 500 cases, whereas it remains negligible –or even changes sign- for the 450 scenarios. If policy costs are looked in terms of net present values over the whole century, the RD-deal policy marginally underperforms the Copenhagen commitments for discount rates up to 8%.

[23] If measured in Consumption losses rather than GDP losses, policy costs for the R&D deal scenario would be higher in 2020 and 2035, due to the crowding out of consumption. On the other hand, in 2030 the opposite would hold, since by then R&D investments in the RefPol2030 case is higher than the ones in the RD-deal scenario, as shown in Figure 6.

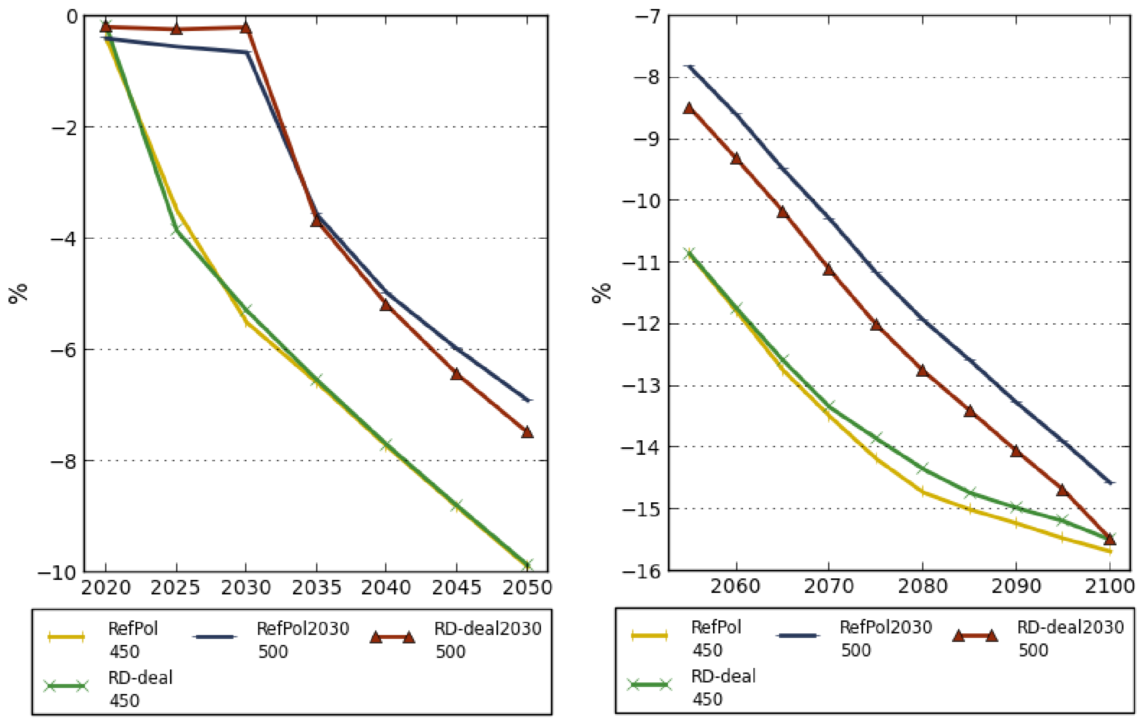

Figure 13: Time profile of the world GDP loss in second-best scenarios expressed as a percentage with respect to the GDP of the Base case. The two panel show costs for the periods 2020-2050 and 2050-2100 respectively.

While excessive emissions due to delayed mitigation makes the RD-Deal worse off, such a policy may still be beneficial on the long term with respect to a potential carbon lock-in of the energy system. By investing more in R&D, more advanced technologies are available, and the energy system is capable of faster and deeper rates of decarbonization than what would be possible in a less innovative future. This is confirmed both in terms of emissions per unit of GDP and emissions per unit of final energy. These indicators decrease in the second part of the century by at least 5% and 2% respectively in the RD-deal2030-500 scenario with respect to the RefPol2030-500 case. Also final energy per unit of GDP benefits from the RD-deal, with a relative decrease between 1% and 3% in the second half of the century with respect to its counterpart.

Thus, two main points emerge from our results. If there is willingness to commit to a stringent global climate policy rather quickly (e.g. after 2020), then the actions undertaken before than - be them either some mild fragmented mitigation or a collaborative international R&D programme - do not have a major economic impact once full cooperation is enacted. In the very long term (after 2060), the R&D deal strategy might be actually preferable, since it would allow for more deployment of advanced technologies. If on the other hand the international community opts for deferring global action to post 2030, then a strategy focusing on R&D would be preferable (in economic terms) till 2035, and worse after then. The ultimate choice between an agreement on innovation as opposed to a fragmented mitigation action would thus depend on the time preferences of the legislators, as well as on their aversion to a potential lock-in to a set of economically and environmentally suboptimal technologies. In both cases, however, delaying cooperation increases policy costs.

7. Conclusions

This paper has tried to provide some answers to two key questions related to the interplay between climate change mitigation and clean energy innovation policies. 1. What are the clean energy R&D investment needs to get to 2°C? 2. In the short term, is an international agreement on R&D better suited at preparing the ground for climate stabilization than continuing with fragmented and moderate emission reduction measures? Both questions are of high policy relevance for the Durban negotiation process which is assessed in the LIMITS special issue, to which this paper contributes. To our knowledge, both questions have not been yet addressed with the tools of integrated assessment modeling.

We have tackled these policy relevant questions by means of the WITCH integrated assessment model, which features endogenous technical change and multiple externalities. We have run a set of Durban Action Platform scenarios, integrating them with two additional ones based on a clean energy R&D climate deal, meant to replace early emission reduction Copenhagen commitments with early high R&D investments efforts. A series of key findings emerge.

i. We find that in order to attain 2°C with sufficiently high probability, a strong decarbonisation of the energy system is required, and mitigation actions call for an increased financing in climate R&D. We quantify the global climate mitigation R&D investment needs for attaining 2°C is approximately 1 USD Trillion cumulatively over the period 2010-2030, and 1.6 USD Trillions in the period 2030-2050.
ii. The investments would be initially concentrated in the industrialized countries, but would balance off with those of developing economies after 2030. The largest share of investments would be concentrated for the development of low carbon alternative fuels, though energy efficiency investments would also play an important (and growing) role.
iii. We find that focusing on an international clean energy R&D effort slightly underperforms a continuation of the fragmented mitigation effort outlined by the Copenhagen pledges for the sake of climate stabilization. Nonetheless, the actual ranking between fragmented mitigation or R&D investments in the short term depends on the time preference of the legislators, and on their aversion to a potential carbon lock-in.
iv. An exclusive focus on R&D at the expenses of mitigation is however incompatible with climate stabilization if maintained for too long. Specifically, R&D deals to 2030 and 2040 do not attain 2°C with likely (e.g. 450ppm-eq) and as likely as not (e.g. 500ppm-eq) probabilities respectively.

These considerations lead to some direct policy implications. If the chances of getting to a global climate agreement before 2030 remain slim (as they appear to be today), then one could consider shifting the focus of short term policy from emission reduction targets towards an R&D investment objective, if the latter has better chances of being legislated. This policy shift would not significantly affect the ultimate objective of climate stabilization, which in any case requires full cooperation on emission reductions no later than 2030. An agreement on R&D and innovation might have more political capital given the current debate on competitiveness, and has been proposed in the past as way out of the backlog of climate negotiations (De Coninck et al., 2008b; Newell, 2008b). Actual experiences in the field of climate, such as the 'Asia-Pacific Partnership on Clean Development and Climate (APP)', have not yielded significant results, but the same can be claimed for some emissions reductions programs. A refocus towards innovation could generate a risk of 'policy lock-in', which for the case of R&D we showed would eventually jeopardize the chances of meeting climate stabilization. However, the study has clearly highlighted the importance of dedicating significant investments - either by means of specific R&D policies or indirectly by the incentives induced by carbon pricing - to innovating for energy efficiency and decarbonization. These investments - of the order of 50 USD Billions per year - are an essential pre-requisite for meeting the huge transformation of energy and land use required by climate stabilization. The effectiveness of these investments remains conditional to the need of achieving a comprehensive agreement on GHGs mitigation by 2030, if the 2°C target is to be met.

This analysis is limited by the assumptions embedded in the specific model which we have used. The multi model ensembles carried out by the modeling community over the past few years, of which LIMITS represents an important contribution, has invariably shown that models differ widely in terms of results, for many key variables. Thus, single model assessments should be taken with care. Moreover, the difficulty of understanding and representing the process of technical change poses considerable challenges for the modelers involved in the type of analysis presented in this paper. More work, both on empirical and modeling sides, is needed to improve our grasp of climate innovation, and our ability to represent it as a result. Hopefully, more modeling papers and more multi model ensembles will address the fundamental issue of innovation and climate in the future.

8. Appendix

$$ES_{n,t} = \left[\alpha_{HE} HE^{\rho}_{n,t} + \alpha_{EN} EN^{\rho}_{n,t}\right]^{1/\rho} \quad (1)$$

$$Z_{n,t} = a_n IRD^{b}_{n,t} HE^{c}_{n,t} SPILL^{d}_{n,t} \quad (2)$$

$$HE_{n,t+1} = HE_{n,t}(1-\delta) + Z_{n,t} \quad (3)$$

ES energy services (input to gross domestic production)

EN energy supply (input to energy services production)

HE stock of energy efficiency knowledge (input to energy services production)

IRD investments in energy efficiency knowledge

Z flow of new ideas that adds to the previously cumulated stock

$\alpha_{HE}, \alpha_{EN}, \rho$ parameters of the energy services CES

a, b, c, δ parameters of the energy efficiency knowledge stock update equations

n region

t time period

$$SPILL_{n,t} = \frac{HE_{n,t}}{\sum_{n' \in nHI} HE_{n',t}} \left(\sum_{n' \in nHI} HE_{n',t} - HE_{n,t} \right) \quad (4)$$

where nHI is the set of OECD countries, representing the technology frontier.

$$\frac{P_{n,t}}{P_{n,0}} = \left(\frac{KRD_{n,t-2}}{KRD_{w,0}}\right)^{-r} \left(\frac{\sum_{t' \in [0,t)} K_{w,t'}}{K_{w,0}}\right)^{-s} \quad (5)$$

$$Z_{n,t} = a_n IRD^{b}_{n,t} SPILL^{d}_{n,t} \quad (6)$$

$$KRD_{n,t+1} = KRD_{n,t}(1-\delta) + Z_{n,t} \quad (7)$$

P average cost of backstop

KRD stock of backstop knowledge

IRD investments in backstop knowledge

K stock of backstop used

Z flow of new ideas

r learning-by-researching index

s learning-by-doing index

w world

0 first time period

	Energy Efficiency	Carbon-free Advanced Biofuels (Backstop)
r (Learning-by-researching index)	0.20	0.20
s (Learning-by-doing index)	n.a.	0.15
a	(average) 0.04	1.00
b	0.18	0.85
c	(average) 0.39	n.a.
d	0.15	0.15
δ (Depreciation of knowledge capital)	5%	5%
Regional initial stock of knowledge (OECD) [USD Billions]	(average) 20	0.5
Regional initial stock of knowledge (Non-OECD) [USD Billions]	(average) 1	0.5
World initial stock of experience [TWh]	n.a.	278

Table 7: Parameter values for the R&D equations

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