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Report on the various mitigation requirements compatible with a global 2°C target

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1. Introduction and Overview

Climate change is a formidable policy change affecting all regions and sectors over centuries to come. Integrated scenarios of future socio-economic developments, greenhouse gas emissions, and the associated climate response have shown that humankind is bound to warm the planet by 3-4 degrees since preindustrial times, i.e. levels that have not been seen since the Pliocene 3 million years ago (Fisher et al., 2007). Related studies, based on integrated assessment models of the coupled energy-economy-climate system, have also shown that the goal to limit the warming to 2 degrees will require a massive transformation of the way we produce energy and use land (Clarke et al., 2009; Edenhofer et al., 2010).

This report will take a closer look into the transformation requirements of the 2°C target, and the implications for international climate policy negotiations. We ask how the achievability, and the economic requirements of reaching the 2°C target are affected by

• the interpretation of the stringency of the 2°C target. Those are captured in terms of different stabilization levels of greenhouse gases in the atmosphere (450 and 500 ppm CO2e) implying different probabilities of overshooting the 2°C target in the 21st century.

• the time a global target is adopted and an international climate policy regime ensuring global action is implemented. Two cases, the establishment of global carbon price after 2020 and after 2030 are investigated.

• The stringency of fragmented near-term action until 2020 or 2030. A weak and a stringent reference policy scenario are considered, based on the low (unconditional) and the high (conditional) end of the Copenhagen pledges.

The analysis is based on a comparison study of six integrated assessment and energyeconomy models that participate in the LIMITS project: the GCAM, IMAGE, MESSAGE, ReMIND, TIAM-ECN and WITCH models. The study used a scenario setup that was carefully designed to address the questions above. The study design also included an analysis of different burden sharing regimes. The results from that part of the study will be summarized in another report (LIMITS Deliverable D1.2).

The investigation of 2°C scenarios under different target interpretations and short term limitations is a core task of Work Package 1 of the LIMITS project. A major innovation compared to previous model comparison studies is the short term policy detail that was included to represent the current regional and international climate policy landscape. To this end, the scenarios aim to directly inform the ongoing negotiations under the Durban Platform for Enhanced Action. In addition, their focus on the vicinity of the 2°C target, including a 500 ppm CO2e target in the study design, is unique. These features make them highly policy relevant, and the most up to date study on the implications of the 2°C target for current international climate policy negotiations. The scenario results have been taken up by other work packages of the LIMITS project, and are being used for more detailed investigations of 2°C implications for the major economies concerning, e.g., clean energy investment needs and financing mechanisms



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(WP2), regional mitigation requirements (WP3), and trade-offs with energy security (WP4). Those results will be communicated in the respective deliverables of work packages 2-4.

The results on the transformation requirements of the 2°C target will be presented in three sections, starting with an overview of the study and its general results, followed by investigations of technological requirements of the energy and land use transformation. Those sections form self-contained papers that have been submitted to the academic journal Climate Change Economics, and that are currently under review. Thus, we present a preliminary version of the report that will be updated once the papers have passed the review process.

Can we still meet 2°C with global climate action? The LIMITS study on implications of Durban Action Platform scenarios: This paper provides an overview of the LIMITS model comparison study, and the transformation requirements of achieving the 2°C target. Results show that the probability of exceeding the 2°C limit increases with stabilization target from below one third for 450-470 ppm to 40-60% for 490-510 ppm in 2100. Global time-averaged economic costs of the Durban Action scenarios are limited across models, and are largely unaffected by the stringency of 2020 pledges. By contrast, the economic impact of delaying action beyond 2030 is much stronger on transitional costs. The main significance of short term action in the period 2010-2030 lies in preparing the ground for steep emissions reductions thereafter by inducing global emissions to peak and decline.

A Cross-model Comparison of Global Long-term Technology Diffusion under a 2°C Climate Change Control Target: The article investigates the long-term global energy technology diffusion patterns needed to reach the 2°C target. One of the main findings is that many different technology deployment pathways exist to reach such ambitious climate change control. If the anthropogenic atmospheric temperature increase is to be limited to at most 2°C, total CO2 emissions have to be reduced massively, so as to reach substantial negative values during the second half of the century. Particularly power sector CO2 emissions should become deeply negative from around 2050 onwards in order to compensate for GHG emissions in other sectors where abatement is more costly. In all energy transformation pathways, CCS constitutes a significant part of the climate mitigation technology mix, but applies, according to different models, to varying forms of primary energy (coal, gas and biomass) and types of energy carrier production (electricity, hydrogen and liquid fuels).

A multi-model analysis of the regional and sectoral roles of bioenergy in near-term and long-term carbon mitigation: The paper studies the near term and the longer term the contribution of bioenergy in different LIMITS scenarios. These scenarios have proven useful for exploring a range of outcomes for bioenergy use in response to both regionally diverse near term policies and the transition to a longer-term global mitigation policy and target. The results have highlighted the heterogeneity and versatility of bioenergy itself, with different types of resources and applications in several energy sectors. In large part due to this versatility, the contribution of bioenergy to climate mitigation is a robust response across all models, despite their differences.



Given the large dependence of 2°C transformation pathways on massive deployment of clean energy technologies and carbon capture and storage, it is an important question how the achievability and the transformation requirements are impacted if individual mitigation technologies are taken off the table, e.g. due to public opposition, sustainability constraints or difficulties to bring them to the market. While this question was not directly addressed in the LIMITS study, concurrent model comparison studies have investigated it in depth for the 450 and 550 ppm CO2e stabilization levels (Kriegler et al., in review). Those studies showed that versatile technologies such as CCS and bioenergy have largest value, due in part to their combined ability to produce negative emissions. The individual value of low-carbon power technologies, i.e. nuclear, solar and wind power, is more limited due to the many alternatives in the sector. Since the scale of the energy transformation is larger for the 450 ppm than for the 550 ppm CO2e target, the achievability and the costs of the 450 ppm target are more sensitive to variations in technology variability. In particular, most 2°C scenarios rely heavily on the use of negative emissions in the 2nd part of the century. If negative emissions technologies become unavailable, mitigation costs increase significantly in some models, and the two degree target moves out of reach in other models.

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2. Can we still meet 2°C with global climate action? The LIMITS study on implications of Durban Action Platform scenarios

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2.1 Introduction

Text Climate change is a major challenge faced by human society (IPCC 2007; Stern 2007; World Bank 2012a). While there is increasing recognition of this challenge around the world, there is also an increasing reluctance about enacting global climate policies in the near to medium term. This reflects the fact that international climate negotiations have faced only slow progress in recent years, and a global climate treaty mandating comprehensive greenhouse gas emissions reductions has remained illusive. Although a series of climate policy measures were adopted in several world regions (UNEP 2012; UNEP 2011), global emissions have been rising over the last decade with only a small downturn in 2008-9 in the wake of the financial crisis (EDGAR 2011). National and international policy agendas are currently overwhelmed with economic crisis and other significant world developments. This has led to climate policy slipping down the global policy agenda, casting further doubt on its near term prospect.

This paper provides an overview of 2°C scenarios that account for the fragmented nature of current mitigation efforts. They were tailored to represent a range of plausible outcomes of the on-going Durban Platform negotiations on a Post 2020 climate architecture. We use a set of six energy-economy and integrated assessment models to perform an original assessment of possible Durban Platform outcomes, which elucidate the relation between near term mitigation actions and the long term target of limiting warming to 2°C. The scenarios were produced in the context of the LIMITS project on the implementation of stringent stabilization pathways in major economies. Durban Action Platform scenarios have so far not been investigated in a model intercomparison study. The value of such model intercomparisons consists in a thorough assessment of the robustness in results across models.

While the LIMITS project is ongoing and will deepen its analysis of the socio-economic implications of stringent stabilization in a second phase, a number of insights can already be gleaned from the current study (see the articles in this special issue). This overview article focuses on a high level assessment of the global scale economic and climate outcomes of the Durban scenarios. Key questions are: What climate outcome can be achieved with stringent stabilization targets imposed from 2020 on? What are the implications for emissions reduction requirements in various sectors and global economic costs? What significance does the stringency of near term action until 2020 have for implementing the 2°C pathways? And what happens if the Durban Platform negotiations fail, in which case it may be unlikely that renewed attempts can establish a global treaty before 2030?





The paper is structured as follows. Section 0 reviews the current status of the climate negotiations, and its implications for the 2°C target. Section 0 introduces and motivates the scenario setup of the study and summarizes the participating models. Section 0 describes the emissions and climate outcomes of the Durban platform scenarios across models. Section 0 focuses on the economic impacts both in the shorter and longer term. Section 0 discusses the implications of our results and draws conclusions.

2.2 Climate negotiations, the 2°C target, and long term climate action studies

Text International climate policy negotiations have survived a major setback at the conferences of the parties (COPs) to the United Nations Framework Convention on Climate Change (UNFCCC) in Copenhagen in 2009. The failure of the Copenhagen conference to reach an international climate treaty sparked a backlash on multi-lateral climate action, but the ensuing COPs in Cancun, Durban and Doha have tried to drive put the process back on track. The proposal of limiting global warming to 2°C above preindustrial levels was recognized as a guiding principle for the long-term objective of the UNFCCC to "avoid dangerous interference with the climate system" (UNFCCC 1992). It was initially laid down in the Copenhagen Accord1 (Copenhagen Accord, 2009). However, while the Accord was agreed upon by 141 countries by the end of 2012 including all major emitters, it was never adopted as a legally binding agreement under the UNFCCC. Elements of the Accord were brought under the roof of the UNFCCC in Cancun in 2010 (Cancun Agreement, 2010). This included the recognition of the 2°C target2 as well as the Copenhagen pledges on 2020 emissions reduction targets made by 16 Annex I countries (UNFCCC Technical paper 2012). Several Non-Annex I countries also submitted

¹ "We agree that deep cuts in global emissions are required according to science, and as documented by the IPCC Fourth Assessment Report with a view to reduce global emissions so as to hold the increase in global temperature below 2°C, and take action to meet this objective consistent with science and on the basis of equity. We should cooperate in achieving the peaking of global and national emissions as soon as possible, recognizing that the time frame for peaking will be longer in developing countries and bearing in mind that social and economic development and poverty eradication are the first and overriding priorities of developing countries and that a low-emission development strategy is indispensable to sustainable development" (Article 2, Copenhagen Accord, 2009)

² Decision 1/CP.16 "*1.4 further recognizes* that deep cuts in global greenhouse gas emissions are required according to science, and as documented in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, with a view to reducing global greenhouse gas emissions so as to hold the increase in global average temperature below 2 °C above preindustrial levels, and that Parties should take urgent action to meet this long-term goal, consistent with science and on the basis of equity; *also recognizes* the need to consider, in the context of the first review, as referred to in paragraph 138 below, strengthening the long-term global goal on the basis of the best available scientific knowledge, including in relation to a global average temperature rise of 1.5 °C;" (Cancun Agreement, 2010).



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Copenhagen pledges which – under the name of nationally appropriate mitigation actions (NAMAs) – are of voluntary nature.3

The Durban conference in 2011 established the Durban Platform for Enhanced Action as a new track for negotiating an international climate treaty. The track aims to establish an international climate treaty to enter into force in 2020 (UNFCCC 2011). It was reinforced by the Doha climate conference in 2012, which established a second commitment period of the Kyoto protocol until 2020 to be superseded by such a global climate treaty after 2020. Doha also closed down the concurrent long-term action track based on the Bali Action Roadmap that was originally set up to deliver a climate treaty at the Copenhagen conference. These developments will allow international negotiators to focus their efforts on the Durban platform. Nevertheless, it is highly uncertain at this point if the Durban platform will fare better than the Bali roadmap. A few key parameters like the recognition of the 2°C target, the inclusion of emerging economies in the discussion of legally binding targets, and regional and national climate treaty in the near to medium term remains.

There is a perceived disconnect between the international recognition of the 2°C target, and the modest nature of existing emissions reduction pledges until 2020 and the uncertainty about global cooperative action thereafter. This has invigorated the debate about the viability of adopting the 2°C target as a long term goal for climate mitigation. Several studies have claimed that the 2°C target is close to becoming out of reach (IEA 2011; Stocker 2012). Other studies have pointed to the gap between current ambition levels for the year 2020 and mitigation pathways that are consistent with the 2°C targets (UNEP 2011; UNEP 2012). Such studies need to be put into context of their notion of achievability and their assumptions about the 2°C target. There is no direct translation of the 2°C target into an emissions pathway. First, temperature responds with a time lag to the cumulative amount of greenhouse gases in the atmosphere, implying that different emissions profiles with comparable cumulative amounts of emissions can reach similar temperatures in the long run. Second, the amount of cumulative greenhouse gas emissions consistent with the 2°C target depends on assumptions about carbon cycle and climate response (Meinshausen et al. 2009) and achievable emissions reductions rates in the long term which are, inter alia, a function of the availability of negative emissions technologies (Van Vuuren and Riahi 2011; Stocker 2012).

Global coupled energy-economy-land use-climate models, so called integrated assessment models (Weyant et al. 1996), are used to assess the feasibility and socio-economic implications of 2°C pathways. Such models have been deployed extensively in intercomparison projects to explore climate targets in the range of 450 to 550 ppm CO2 equivalent (CO2e) concentration of GHGs in the atmosphere (Clarke et al. 2009; Edenhofer et al. 2010; Luderer et al. 2012; Calvin et al. 2012; Kriegler et al. 2013). Since a stabilization target of 450 ppm CO2e, or equivalenty a radiative forcing level of 2.6 W/m², is found to be consistent with a likely (probability > 70%) achievement of the 2°C target (Meinshausen et al. 2011; Rogelj et al. 2013), those studies are relevant for assessing the implications of adopting the 2°C target. They show that under highly idealized assumptions about climate policy, including immediate and full cooperation of all regions and sectors in reducing emissions, full technology availability including negative emissions technologies, and no significant global market distortions pushing up the cost of

³ Many pledges by Annex I and Non-Annex I countries are conditional on reciprocal action of others. See <u>http://unfccc.int/meetings/copenhagen_dec_2009/items/5262.php</u> for details.



climate policy implementation, mitigation pathways consistent with 2°C can still be pursued at moderate economic costs.

While such idealized implementation scenarios are very useful as an analytical benchmark, they obviously will not materialize in their pure form. There is a gap between projected emissions reductions from existing pledges in 2020, and emissions reductions in idealized 450 ppm implementation scenarios (UNEP, 2011, 2012). Thus, the question about the feasibility of 2°C does not only relate to the existence techno-economic pathways consistent with this target, but also to the institutional feasibility of stringent and cooperative mitigation action in the coming decade . Recent IAM comparison studies have explored the impact of delayed action (compared to idealized implementation) on 450 ppm mitigation pathways (Luderer et al. 2013; Rogelj et al. 2013; Rogelj et al. 2012; Jakob et al. 2012; Riahi et al. 2013). They found that such a stabilization level can still be reached by the end of 2100, albeit at the expense of greater forcing overshoot, greater dependence on the availability of negative emissions, and greater institutional challenges after adopting the long term target. These findings highlight the need for an in-depth investigation of the implementability of 2°C mitigation pathways taking into account the existing policy situation.

2.3 Methods

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2.3.1 Scenario design

The LIMITS study focused on plausible outcomes of the Durban Action Platform (DAP) negotiations that can be broadly consistent with the objective of keeping global mean warming below 2°C since preindustrial levels. To exploit the potential range of 2°C emissions pathways, it explores two ambitious mitigation targets that a global climate treaty established in the Durban negotiations might aim for, i.e. reaching atmospheric greenhouse gas (GHG) concentrations at roughly 450 and 500 ppm CO2e in 2100. Overshoot of these stabilization targets before 2100 is allowed. The choice of climate target should be understood as a proxy for the stringency of the global cap on future emissions that is implied by a potential climate treaty. It is not implied that those targets have to be adopted literally in a Durban Platform agreement. A comparison of the 450 and 500 ppm concentration targets in terms of their mitigation requirement has not yet been undertaken with a multi-model ensemble.

Since the Durban Agreement calls for the implementation of the international climate treaty by 2020, the DAP scenarios assumed that a globally uniform carbon price is fully established in the first model year following 2020. For the period until 2020, it was assumed that individual regions follow domestic climate and technology policies that include emissions reduction targets for the year 2020 as laid down in the Copenhagen pledges with inclusion of some plausibility considerations of the pledges. Two variants of the fragmented action until 2020 were considered and implemented as fragmented climate mitigation scenarios, a more lenient reference policy (RefPol until 2020) reflecting the unconditional Copenhagen Pledges and a more stringent version (StrPol until 2020) based on conditional Copenhagen Pledges. Not all regions are assumed to take early action before 2020.

The four DAP scenarios (RefPol-450, StrPol-450, RefPol-500, StrPol-500) then constituted the combinations of the lenient and stringent fragmented action scenarios until 2020 with the long



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term targets of 450 or 500 ppm CO2e implemented thereafter. To incorporate the possibility of a further delay of international climate negotiations, a scenario with lenient fragmented action until 2030, followed by the adoption of the 500 ppm climate target (RefPol2030-500) was included. The study also considered extrapolations of the fragmented action scenarios over the entire 21st century at the level of ambition reflected in the 2020 targets, scenarios RefPol and StrPol. Finally, the study included a baseline run without climate policy as a common reference case for all climate policy scenarios and the benchmarking cases of immediate global cooperation to reach the 450 and 500 ppm climate targets for analytical purposes

Scenario class		Scenario Name	Scenario Type	Near-term Target / Fragmented Action	Fragmented Action until	Long-term Target
No policy baseline		Base	Baseline None		N/A	None
Fragmontod	action	RefPol	Reference	Lenient	2100	None
Fragmented action		StrPol	Reference Stringent 2		2100	None
Immediate action		450	Benchmark	None	N/A	450 ppm
		500	Benchmark	None	N/A	500 ppm
		RefPol-450	Climate Policy	Lenient	2020	450 ppm
	DAP	StrPol-450	Climate Policy	Stringent	2020	450 ppm
Delayed action	scenarios	RefPol-500	Climate Policy	Lenient	2020	500 ppm
		StrPol-500	Climate Policy	Stringent	2020	500 ppm
		RefPol2030-500	Climate Policy	Lenient	2030	500 ppm

Table 1: Overview of scenarios considered in this article. Additional scenarios of different burden sharing regimes were investigated by the companion study of Tavoni et al. (this volume).

2.3.2 Implementation of the long term climate target

An aggregate atmospheric greenhouse gas concentration is specified in terms of the CO2 equivalent concentration that would lead to the same radiative forcing as the full collection of greenhouse gases. Thus, CO2 equivalent concentration and radiative forcing are equivalent metrics. In LIMITS, the 450 and 500 ppm CO2e targets were imposed on the combined radiative forcing from all anthropogenic radiative agents with the exception of three agents whose forcing is more speculative and often treated exogenously in the models: nitrate aerosols, mineral dust aerosols, and land use albedo changes (which has been called AN3A forcing; Kriegler et al., 2013) It needs be distinguished from Kyoto gas forcing that only refers to the long-lived GHGs (CO2, CH4, N2O, HFCs, PFCs und SF6) controlled under the Kyoto protocol. The AN3A forcing target levels were set to 2.8 W/m² in 2100 for the nominal 450 ppm target, and to 3.2 W/m² in 2100 for the nominal 500 ppm target. Both targets allow overshoot before 2100. The more stringent target has a similar level of stringency as the RCP2.6 (Representative Concentration Pathway; (Representative Concentration Pathway; Van Vuuren et al. 2011).

The adoption of a climate target induces a price on the emissions controlled under the target. Full where (region) and what (sector) flexibility of emissions reduction was assumed ensuring the selection of the cheapest globally available mitigation option at the margin. In the LIMITS study, models only priced Kyoto emissions under the target, while the non-Kyoto forcers remained uncontrolled. However, those models that include them endogenously by source, can account for





the effect of mitigation strategies on non-Kyoto emissions. The models used their endogenous atmospheric chemistry and forcing representation to establish consistency with the AN3A forcing target.

2.3.3 Probabilistic climate projections

The climate outcome of the emissions scenarios from the LIMITS models were calculated with the carbon-cycle/climate model MAGICC in probabilistic mode (Meinshausen et al. 2009). This approach differs from previous model comparisons which used the endogenous climate information from the integrated assessment models where available. The LIMITS approach has the advantage of providing a unified treatment of carbon cycle and climate system uncertainty and offers the possibility to generate climate information for model scenarios that do not provide it endogenously. It was chosen to relate the climate outcome of the Durban Action scenarios to the probability of limiting global warming to 2°C.

For each IAM emission scenario, MAGICC was run 600 times, each time with different set of carbon-cycle, atmospheric-chemistry, forcing and climate-system parameters. Carbon-cycle parameters were drawn from 9 sets of parameters that enable the model to emulate the responses of nine different carbon-cycle models. These sets were randomly combined with the 600 sets of other model parameters, selected from a much larger set by constraints that let the model reproduce several climate variables as observed over the past century (with uncertainty ranges) and produces an overall (posterior) distribution of climate sensitivity consistent with IPCC AR4's meta-analysis: median sensitivity of 3°C global-men temperature increase for a doubling of CO2 and 74% likelihood of sensitivity between 2 and 4.5°C (Rogelj et al 2012). The overall distribution of outcomes provides a "best-estimate" (median) of climate projections and a broad carbon-cycle/climate-system uncertainty range.

Initial emissions in 2010 were harmonized for the MAGICC6 runs. Emissions from TIAM-ECN and WITCH were supplemented with Non-Kyoto emissions derived from projections of the other models. In general, the endogenous forcing and temperature outcomes of the models will differ somewhat from MAGICC6 results due to the probabilistic approach and differences in representations of the carbon cycle and climate system. In this paper, we will only show the consistent forcing outcomes as derived with MAGICC6. This implies that emissions scenarios can lead to a larger spread in anthropogenic forcing than implied by the nominal targets.

2.3.4 Participating models

A total of seven energy-economy and integrated assessment models participated in the LIMITS study: AIM-Enduse, GCAM, IMAGE, MESSAGE, REMIND, TIAM-ECN, WITCH. The models represent the global energy system with various levels of sectoral and regional detail. All models covered the time period until 2100 with the exception of AIM-Enduse (to 2050) Since this paper will focus on the long term implications of 2°C emissions pathways, it will restrict the analysis to the results of the models covering the entire 21st century.

The participating models also differ regarding their methodological approaches: the partial equilibrium (PE) models GCAM, IMAGE and TIAM-ECN calculate cost-minimal energy supply given a final energy or energy service demand. The inter-temporal general equilibrium (IGE) models MESSAGE, REMIND and WITCH embed the energy sector into the larger context of the



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economy. Moreover, the models differ in their representation of GHG emissions and their sources, energy demand and supply sectors, population and GDP baselines, and assumptions about techno-economic parameters (cf. Table 1). These are key factors influencing the results analysed in this study. The differences reflect different choices of modellers on how to best approach the analysis of mitigation pathways, and the structural uncertainties regarding the underlying mechanisms. This diversity in model structure and assumptions allows to explore the associated range of uncertainties.

Model name	Model	Anticipation/	Land use	GHG and air	Negative
	category	Foresight	change	pollutant	emissions
		C	and	emissions	technologies
			forestry		C
GCAM	Partial Equilibrium	Recursive dynamic	Endogenous	full basket of greenhouse gases	BECCS(for electricity, biofuel, biogas, hydrogen production), Afforestation
IMAGE/TIMER	Partial Equilibrium	Recursive dynamic	Endogenous	full basket of greenhouse gases	BECCS (for electricity, biofuels and hydrogen production)
MESSAGE-MACRO	General equilibrium	Perfect foresight	Endogenous	full basket of greenhouse gases	BECCS(for electricity, biofuel, biogas, hydrogen production), Afforestation
REMIND	General equilibrium	Perfect foresight	Endogenous	CO2, CH4, N2O, F- gases, Montreal gases, CO, NOX, VOC, and aerosols. Emissions of fluorinated gases are exogenous.	BECCS (for electricity, biofuels and hydrogen production)
TIAM-ECN	Partial Equilibrium	Perfect foresight	Endogenous	CO ₂ , CH ₄ , N ₂ O from energy, non-energy and land use. No F- Gases represented	BECCS (for electricity, biofuel, biogas, hydrogen production)
WITCH	General equilibrium	Perfect foresight	exogenous land use change emissions, endogenous avoided deforestation	CO2, CH4, N2O, flourinated gases and SO2 aerosols	BECCS (for electricity production)

Table 2: Key characteristics of models participating in the LIMITS model-comparison study





2.4 Emissions and climate outcomes of Durban Action Platform Scenarios

Stabilizing atmospheric greenhouse gas concentrations in the range of 450 to 550 ppm CO2 equivalent (CO2e) requires a massive reduction of GHG emissions until 2100 (Clarke et al. 2009; Edenhofer et al. 2010). The LIMITS study elaborates on this by comparing emissions trajectories achieving nominal 450 and 500 ppm CO2e targets after a period of fragmented action (cf. Figure Emissions increase until 2020 in both fragmented action scenarios with lenient (RefPol: 52-57 GtCO2e) and stringent interpretation of Copenhagen pledges (StrPol: 49-54 GtCO2e). This constitutes a small reduction compared to a baseline without climate policy (56-61 GtCO2e), and somewhat higher emissions compared to the corresponding immediate action scenarios 450 and 500 (not shown in Figure 1; 43-51 GtCO2e for 450 ppm and 48-53 GtCO2e for 500 ppm in models without massive afforestation until 2020). The gap between projected 2020 emissions levels in the lenient reference policy and the 450 ppm immediate action scenario is in the range of 4-11 GtCO2e, slightly lower than estimated in (UNEP 2012). It is further reduced by the more stringent fragmented policy. One important reason for the lower estimate is that UNEP (2012) mostly relied on mitigation scenarios that assumed 2010 as a start year for emission reductions, while our idealistic immediate action scenarios fixed 2010 emissions to the baseline development. Another reason lies in the fact that the LIMITS fragmented action scenarios show slightly lower 2020 emissions levels for the stringent policy case than the UNEP study as result of a number of implemented low carbon technology targets in various world regions.

An important observation is the fact that differences in emissions between strict and lenient pledges are small and within the range of uncertainties that are projected until 2020. The bulk of emissions reductions happen after 2020. Figure 1a highlights the increasingly large emissions gap between the DAP scenarios, and an extrapolation of fragmented action at the level of ambition suggested by current pledges. The fragmented action scenarios lead to a peaking of global emissions during 2040-70 and a return to slightly above (RefPol) or below (StrPol) 2005 emissions levels by the end of the century. This implies an increase of anthropogenic climate forcing to 4.4-6.2 W/m² in 2100 (Figure 1b; corresponding to 640-890 ppm CO2e) which is clearly inconsistent with greenhouse gas stabilization below 550 ppm CO2e. Our results confirm the findings of other studies that a continuation of the current level of ambition as suggested by existing emissions reduction commitments is insufficient to achieve ambitious climate mitigation targets (Luderer et al. 2013a; Blanford et al. 2013).

The DAP scenarios peak in 2020 and lead to a complete or near-complete phase out of global emissions by 2100 (-2.4 to 4.4 GtCO2e for RefPol-450 and 0 to 7.4 GtCO2e for RefPol-500). The GCAM model shows large negative emissions in both scenarios that are significantly below these ranges due to a massive deployment of bioenergy with CCS (BECCS) by the end of the century. The 2100 emissions levels in the DAP scenarios are somewhat lower compared to immediate action (by 0–2.2 GtCO2e for 450 ppm) or stringent fragmented action until 2020 (by - 0.2–0.7 GtCO2e for 450 ppm) to compensate for larger emissions in the delay period. A noticeable difference between lenient (RefPol) and more stringent (StrPol) action consists in the immediate impact of adopting the stabilization target in 2020 (Figure 1c and d). The trend break in emissions is more abrupt in RefPol-450 compared to StrPol-450. Post-2020 emissions reductions rates are increased faster under the 450 ppm target compared to the 500 ppm target.



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The study also included a scenario in which the adoption of a global agreement is further delayed, and the fragmented reference policy is followed until 2030 (RefPol2030-500). This scenario has a larger impact on the emissions gap and the trend break of emissions at the time of adoption than the variation of the DAP scenarios (Figure 1c). Reference policy emissions increase to 57-65 GtCO2e by 2030, amounting to a significant gap of 5-20 GtCO2e (500 ppm) and 12-26 GtCO2e (450 ppm) to the immediate action scenarios. However, all models participating in the study could still implement the 500 ppm CO2e target in such a setting. The case of reaching the 450 ppm target with a delay until 2030 was not taken up in the LIMITS study design, but one model included it as a sensitivity case (Aboumahboub et al., this volume). An indepth analysis of the implications of delayed action until 2030 for the achievability of long-term mitigation targets is provided in a concurrent study (Riahi et al. 2013).



Figure 1: CO2 equivalent Kyoto gas emissions over the period 2010-2100 (Panel a), and the period 2005 -2050 (Panels c & d) for different selections of LIMITS scenarios. The resulting median radiative forcing as calculated with MAGICC is shown in Panel b. The GCAM model was not included in the funnels because of the qualitatively different behavior due to a strong afforestation response to the adoption of the long term target.



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The MAGICC6 simulation of the LIMITS emissions scenarios show that the radiative forcing outcomes of the 450 and 500 ppm emissions scenarios deviate slightly from the nominal AN3A and Kyoto forcing targets they aimed for (Figure 1b). Models also differ among each other. Van Vuuren et al. (2011) have shown that structural uncertainty between climate modules in integrated assessment models can be significant. There is evidence that particularly the representation of the carbon cycle drives differences in forcing results (Blanford et al., 2013). In this study, models fall into two groups with high forcing emissions scenarios (MESSAGE, TIAM-ECN, WITCH) and medium forcing emissions scenarios (GCAM, IMAGE, REMIND) relative to the nominal stabilization target. As a consequence, emissions scenarios broadly cover the forcing range between 2.6-3.7 W/m² (450-550 ppm) in three clusters: 450-470 ppm (Ref/Strpol-450 for medium emissions models), 490-510 ppm (Ref/StrPol-500 for medium, and Ref/StrPol-450 for high emissions models) and 530-550 ppm (Ref/StrPol-500 for high emissions models).

Figure 2 shows the median estimate for global mean warming (left panel) and the probability of exceeding 2°C (right panel) for the DAP and 2030 Delay scenarios. All emissions trajectories overshoot the 2100 forcing target, and as a result lead to somewhat higher peak temperatures (left bar) than attained in 2100 (right bar). It can be seen that the emissions scenarios in the 450-470 ppm range (Ref/StrPol-450 for GCAM, IMAGE, REMIND, WITCH) lead to a median peak warming well below 2°C°C and a likely chance (> 66%) of not exceeding the 2°C target until 2100. Scenarios in the 490-510 ppm range (Ref/StrPol-450 for MESSAGE and TIAM-ECN, 500 for the others) have a median peak warming around 2°C (+/ 0.1°C), and are roughly as likely as not to exceed the 2°C target (40-60%). Finally, the least ambitious scenarios (Ref/StrPol-500 for MESSAGE and TIAM-ECN) are likely to exceed the 2°C target in the 21st century. However, since all scenarios show a declining temperature trend at the end of the century, they will reach or maintain 2°C beyond 2100 if mitigation efforts are maintained. Their distinguishing feature is their probability of overshooting 2°C until 2100 ranging from unlikely (<34%) for 450-470 ppm to as likely as not (40-60%) for 490-510 ppm to likely (70%) for 530-550 ppm.



Figure 2: Median global mean warming (panel a) and probability of exceeding 2°C for the Durban Action Scenarios (panel b). The left (higher) bars show the maximum warming / exceedance probability in the 21st century; the right (lower) bars shows the warming / exceedance probability in 2100.



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The results show that the choice of acceptable probability of overshooting 2°C in the 21st century is a key determinant of 2°C emissions pathways. We note that this probability will never be zero even under most stringent emissions pathways. On the other hand, the probability quickly saturates at values above 90% for concentration levels that exceed 550 ppm CO2e in 2100. Thus, flexibility in the overshoot probability does not imply that the choice of concentration and emissions reductions targets becomes arbitrary. This study finds that if the probability is bounded to be below 70%, the median estimate of the overshoot is below 0.3°C. The DAP scenarios in this study have 84-99% probability of exceeding 1.5°C warming, and therefore would be largely inconsistent with a temperature target of 1.5°C.

The anthropogenic forcing of the climate system is a function of the accumulated stock of greenhouse gas emissions in the atmosphere, and therefore closely correlated with cumulative greenhouse gas emissions (Meinshausen et al. 2009; Matthews et al. 2009). This relationship is evident in the LIMITS emissions scenarios. Figure 3 shows the cumulative Kyoto gas emissions during 2010-2100 for the RefPol-450 and 500 scenarios. We observe that the available 21st century emissions budget is very sensitive to the forcing level in 2100. Furthermore, the direct (Kyoto) forcing from the long-lived greenhouse gases controlled under the Kyoto protocol does not directly translate into full anthropogenic forcing. Non-Kyoto forcing substances such as aerosols and tropospheric ozone add a net variation of -0.3 to 0.1 W/m² in the LIMITS scenarios, which is large enough to affect scenario stringency in terms of temperature outcome (cf. Figure 2). Thus, non-Kyoto forcing constitutes an important consideration for 2°C mitigation pathways (Hansen and Sato 2001; Rose et al. 2013) although the bulk of anthropogenic forcing will come from Kyoto gas emissions.



Figure 3: Cumulative Kyoto gas emissions over the period 2010-2100 (black diamond) and breakdown onto individual sector in absolute terms (panel a) and as share of total emissions (panel b). The emissions budget for fossil fuel combustion and industry (FF&I) is net of negative emissions from the combination of bioenergy production with CCS.



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Figure 3 provides a breakdown of cumulative greenhouse gas emissions into CO2 emissions from fossil fuel combustion and industry (FF&I), CO2 emissions from agriculture, forestry and land use (AFOLU), and non-CO2 emissions from a variety of sectors, the bulk of which N2O and CH4 emissions from agriculture and waste. The LIMITS scenarios assume uniform emissions pricing of Kyoto gases to allocate emissions reductions between the different sectors. This implies that models exploit the cheapest abatement option at the margin across sectors. Differences in the sectoral breakdown of GHG emissions reflect differences in model assumptions about the abatement potential of individual sectors. However, a number of robust results can be identified. Although the share of CO2 FF&I emissions has increased steadily in the past to two thirds of global GHG emissions in 2010 (EDGAR v.4), its remaining cumulative emissions have a smaller share, which is further decreasing with the stringency of the stabilization target. Thus, fossil fuel-based energy use is the main venue for mitigation, including the option to produce negative emissions from the combination of bioenergy production with CCS. Cumulative Non-CO2 emissions are less responsive to the stabilization target (Blanford et al. 2013). This reflects the fact that abatement options in this sector can lower the emissions intensity of an activity or reduce its level, but cannot fully eliminate or compensate its residual emissions. It is also important to note that while energy related emissions are closely correlated with economic activity, non-CO2 emissions from agriculture and waste are more directly impacted by population. All models in the study assume a medium population growth scenario reaching a world population of 9-10 billion in 2100, and therefore do not cover the full range of non-CO2 emissions that may emerge under lower and higher population scenarios. Finally, the largest model differences can be seen for CO2 emissions from land use. GCAM and MESSAGE include the option to absorb atmospheric CO2 by afforestation. Particularly GCAM uses this option extensively, starting as early as 2020 in the DAP scenarios. Afforestation in GCAM amounts to a cumulated amount of 500 Gt CO2 absorbed from the atmosphere. This is on the order of magnitude of the carbon dioxide that was put into the atmosphere by deforestation over the past 200 years (CDIAC). At such a scale, afforestation can compensate for a guarter or more of the residual emissions in the other sectors in stringent mitigation scenarios. The resulting flexibility is exploited by the energy sector. As a comparison with REMIND reveals, GCAM's CO2 FF&I emissions budget is significantly higher despite comparable levels of Kyoto gas emissions, and is less affected by the strengthening of the stabilization target from 500 to 450 ppm. Thus, the value of afforestation grows with target stringency. It can be a major option for implementing 2°C emissions pathways, but uncertainty about the scope and the institutional implications of land use based mitigation remains large (Calvin K. et al. this issue; Popp et al. 2013).



w

1000

900

800

700



StrPol-500

RefPol-500

StrPol

RefPol

Base

G

G

500

RefPol-450

StrPol-450

G

150

While the remaining 21st century GHG emissions budget is very sensitive to the stabilization target, it is largely unaffected by the type of the delay in achieving the target. Excess emissions in an early period have to be compensated in the subsequent period until 2100. Figure 4 investigates the impact of delay on near term emissions budgets until 2030. We observe that cumulative emissions until 2030 vary by around 10% or less with the choice of lenient vs. more stringent fragmented action until 2020, as well as the choice of 450 or 500 ppm long term target. Differences of up to 200 GtCO2e (approx. 20%) exist to the case of unabated GHG emissions (Base), lenient fragmented action until 2030 (RefPol), and immediate action to reach the 450 ppm target (450). This implies that near term emissions reductions cannot be expected to contribute much in absolute terms to long term mitigation. Rather, their significance lies in providing a basis for large-scale and cost-efficient emissions reductions in the period thereafter.



Figure 5: Radiative forcing overshoot (of Year 2100) forcing vs. cumulative negative emissions from BECCS.

In the DAP scenarios, close to 50% of the remaining 21st century emissions occur until 2030, and 70-90% until 2050. Models buffer the phase in of massive emissions reductions by exploiting the potential for negative emissions from bioenergy use in combination with CCS (BECCS) in the 2nd half of the century. The resulting emissions trajectories lead to an overshoot, i.e. forcing levels that temporarily exceed the prescribed 2100 stabilization target. Figure 5 reveals a close relationship between cumulative carbon dioxide absorption from the atmosphere via BECCS and the amount of forcing overshoot for all models but TIAM-ECN. Models differ in the extent of BECCS deployment, but most increase the deployment in line with an increasing stringency of the target and with descending near-term abatement. BECCS deployment can vary by up to 200 GtCO2 across the set of LIMITS scenarios. Thus, BECCS, or more broadly the capability to produce negative emissions, is a main determinant of the allocation of emissions reductions over time in 2°C emissions pathways (van Vuuren and Riahi, 2011). It is used to shift some of the required emissions reductions into the future, and to attenuate additional mitigation requirements due to excess emissions in an early period or a more stringent stabilization target. Thus, the deployment of negative emissions technologies is a key contributor to the 2-degree emissions pathways. The LIMITS study did not explore scenarios where BECCS was excluded from the technology portfolio, but other studies have shown that the unavailability of negative emissions severely impact the achievability and costs of the stringent mitigation targets (Riahi et al. 2013; Krey et al.; Rogelj et al. 2013; Azar et al. 2010).





2.5 Economic implications of Durban Action Platform scenarios

An important consideration for international climate negotiations will be the economic impact of a climate treaty. This includes overall economic costs but also the immediate impact of adopting a long term stabilization target that caps the amount of future GHG emissions to be released into the atmosphere. It can be expected that the adoption of such a target after a period of fragmented action would lead to a rapid adjustment of expectations and quickly be reflected in carbon and energy price increases. Such price jumps may lead to higher transitory economic costs than over the long run.

Figure 6 shows global average mitigation costs over the period 2010-2100. Costs are measured in terms of consumption losses from general equilibrium models (MESSAGE, REMIND, WITCH) and total abatement costs (= area under marginal abatement cost curve) from partial equilibrium models (GCAM, IMAGE, TIAM-ECN). They are both expressed as fraction of net present value economic output in the counterfactual baseline case w/o climate policy using a 5% discount rate. It can be seen that average 21st century costs for the DAP scenarios range between 0.4 -1.6% for the 500 ppm target and 0.6-2.2% for the 450 ppm target (Figure 6a). The large variation of costs between models is due to structural model differences, the different cost metrics (Consumption losses include economy wide effects), and the different stringency of emissions budgets under the climate targets (see Figure 3). Regional mitigation costs can differ substantially from the global average, and are not only a function of global emissions reduction requirements, but also regional mitigation potentials and international burden sharing regimes. These factors and their impact on the distribution of regional mitigation costs are analyzed in a companion model comparison paper (Tavoni et al. this issue) and individual model studies (Aboumahboub et al. this volume).



Figure 6: Global net present value mitigation costs for the period 2010-2100 (discounted at 5%) as a fraction of net present value GDP in the baseline (left panel) and relative to the RefPol-500 scenario. Cost metric is consumption losses for REMIND, MESSAGE, WITCH and area under marginal abatement cost curve for GCAM, IMAGE and TIAM-ECN.





Figure 7: Annual average reduction of consumption growth rate for the period 2010-2100 (lower right bars) and for the decade with highest reduction (following the adoption of the long term target; higher left bar).

Global average costs are mainly affected by the choice of the long-term target. Adopting a 450 ppm instead of a 500 ppm target raises global costs by 30-70% independently of the level of stringency of near term fragmented action (Figure 6b). Only small variations are seen with the level of near term ambition. Delaying the adoption of global cooperative action until 2030 –while keeping the regional emission commitments to the Reference Policy- raises average costs by 0-30%, while the adoption of more stringent near-term action for 500 ppm leads to a negligible impact on costs for most models. Similar results hold for a comparison with the hypothetical immediate action scenarios. Cost increases from delayed action until 2020 are around or below 10% in most models.

The small increase of average 21st century mitigation costs due to delayed action has also been noted in a concurrent study (Luderer et al., 2013a). The costs of delay are, however, lower than those found in other studies (Clarke et al. 2009; Jakob et al. 2012). This is due to a series of factors. As shown before, models rely heavily on negative emissions technologies to achieve deep emissions cuts in the second half of the century (and for some models even before then). This abatement strategy allows considerable extra flexibility in the early periods, limiting the penalty of the delayed effort. Secondly, all scenarios –even the delayed ones- assume interim policies which limit emissions. The earlier studies also assumed mitigation action to start already in 2010, which resulted in a greater differential between the immediate and delayed action scenarios, but is counter-factual from today's point of view. Clarke et al. (2009) considered a scenario where the climate regime remains fragmented until 2050.

Moreover, as pointed out in Luderer et al. (2013), the effect of delay will be most visible in transitory costs between fragmented action and the adoption of a stabilization target. To explore



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transitory costs in greater detail, Figure 7 compares the annual average reduction of consumption growth over the 21st century (lower right bars) to the maximum growth reduction over a decade (higher left bars) for the general equilibrium models (MESSAGE, REMIND and WITCH), which represent macro-economic effects of climate policy. The maximum reduction occurs in the decade after adoption of the long term target (2020-2030 in the DAP scenarios and 2030-2040 in RefPol2030-500), and it is significantly higher (by 50-400%) than the average reduction. A clearer signal of the type of delay can now be identified. Maximum growth reductions are largest for a delay until 2030 even though the long term target of 500 ppm is less stringent than the 450 ppm target. This reflects the strong trend break in emissions that a delay until 2030 would require (see Figure 1). The stringency of the long term target still has a significant impact on consumption growth reductions, particularly in the decade following the adoption of the target (Ref/StrPol-450 vs Ref/StrPol-500). In contrast, the stringency of the fragmented action until 2020 does not influence consumption growth reductions significantly (RefPol-450/500 vs StrPol-450/500).

It needs to be noted, though, that despite the inclusion of a period of fragmented action until 2020/30, other modeling assumptions are optimistic. This includes the efficient implementation of the climate regime after the adoption of the target, globally efficient markets and the full availability of mitigation options. If some of these assumptions are not met, global economic costs can be significantly higher both in immediate and DAP scenarios. It is therefore important to include additional indicators for the economic challenge of transitioning to a climate stabilization regime into the analysis. Prices of energy and carbon are important indicators in this regard. Figure 8 shows the carbon (equivalent) price in the years 2020, 2030 and 2040, and Figure 9 the annual and global average electricity price increases for the periods 2010-2020, 2020-2030 and 2030-2040 in the DAP scenarios and the 2030 delay case. In the period until 2020, global average carbon prices are around \$10/tCO2 in the lenient reference policy case, and substantially higher (\$20-\$80/tCO2) in the more stringent fragmented action case. Carbon prices jump to \$25-\$55/tCO2 and \$40-\$100/tCO2 in 2030 after the adoption of the 500 ppm and 450 ppm climate policy regime, respectively. This amounts to a significant carbon price shock in the case of transitioning from lenient reference action to the stringent 450 ppm target, while the price increase is more gradual in the other cases. The strongest price shock occurs for a delay until 2030 where carbon prices remain around \$10/tCO2 until 2030 and then jump to \$45-175 in 2040. Carbon prices increase more steadily in the case of adopting the global regime in 2020.



Figure 8: Global average carbon prices in 2020 (left bars), 2030 (middle bars) and 2040 (right bars).



Figure 9: Annual average increase in electricity prices over 2010-20 (left bars), 2020-30 (middle bars) and 2030-40 (right bars).

Electricity prices increase throughout 2010-40. The strongest increases occur during the fragmented period 2010-2020 with an annual average of up to 5% (RefPol) and 7% (StrPol), but there is large uncertainty between models. Price increases decline during subsequent decades



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with the exception of the two cases with strongest trend breaks and largest carbon price shocks, i.e. a delay until 2030 and a transition from lenient reference action to the stringent 450 ppm target in 2020. The fact that electricity price increases tend to saturate until 2040 is testimony to the rapid decarbonization of the electricity sector in the Durban Action scenarios (Van der Zwaan et al. this issue). Price impacts on non-electric energy that is slower to decarbonize can be larger. In addition, regional price effects may differ substantially from the global average. A detailed analysis of the regional implications of the Durban Action scenarios for the major economies is provided in (Van Sluisveld et al. this issue).

Another important indicator for the near to medium term challenges of adopting a stringent climate treaty in 2020 are the resulting requirements on the speed of decarbonizing economic output. Figure 9 shows that the global carbon intensity improvement rates in the Durban action scenarios increase consistently over the next three decades to levels that are well beyond historically observed rates. Rates are particularly affected by the choice of long term climate target reaching 2-5% and 3-8% in the 500 and 450 ppm case, respectively, for the period 2030-2040. As before, a jump in decarbonization rates after the adoption of the long term target is particularly visible for the two cases with the largest trend breaks, the RefPol2030-500 and RefPol-450. Delay until 2020 leads to a maximum of 0.3-1.7% higher decarbonization rates compared to the immediate action scenarios. The high decarbonization rates highlight the challenge of implementing 2°C emissions pathways. These challenges vary with the associated choice of long term stabilization target, but remain significant in any case.



Figure 10: Annual average carbon intensity improvement rate (of CO2 emissions from fossil fuel combustion and industry per unit of GDP) for the periods 2010-20 (left bars), 2020-30 (middle bars) and 2030-40 (right bars).



2.6 Conclusions

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The LIMITS study on Durban Action Platform scenarios investigated a set of different outcomes of the Durban Platform negotiations on reduction targets for 2020, and long-term climate targets. The study also investigated "Durban failure" scenarios where the adoption of a global treaty is delayed until 2030, and where fragmented action in the absence of a global treaty is projected over the entire 21st century. The scenarios were run by an ensemble of six integrated assessment and energy-economy models allowing an evaluation of the robustness of results against structural model uncertainty. The climate outcome of the various climate policy scenarios was derived with the climate model MAGICC which provides a probabilistic representation of uncertainty about the climate response.

Seven key findings can be identified. First, if fragmented action at the level of ambition of current emissions reduction pledges continue over the 21st century, global greenhouse gas emissions return to 60-140% of today's level by 2100. This leads to atmospheric greenhouse gas concentration in excess of 640 ppm in 2100 and rising, which is inconsistent with ambitious climate policy objectives. Stringent climate targets below 550 ppm scenarios require a near phase out of global emissions by 2100. These results confirm findings by other studies (e.g., Kriegler et al. 2013; Luderer et al. 2013).

Second, negative emissions technologies are a key element of implementing the emissions pathways in the Durban Action scenarios. As shown in previous studies, negative emissions allow a phase out of net global emissions in the long run by compensating for residual emissions in sectors with limited abatement potential. They also offer the flexibility to shift some emissions reductions into the future accommodating for the delay in implementing a global climate treaty and smoothening the transition into a global climate regime (van Vuuren and Riahi, 2011; Tavoni and Socolov, 2013). We find that the more stringent the long term stabilization target and the larger the excess emissions in an early period, the larger the deployment of negative emissions technologies in the long run.

Third, further flexibility in implementing stringent mitigation pathways results from the allocation of emissions reductions onto sectors (cf. Blanford et al, 2013). Fossil fuel combustion is the main venue for mitigation, while a socket of hard to mitigate non-CO2 emissions is retained even under tight emissions controls. Land use based mitigation can potentially play a large role by compensating fossil fuel emissions via afforestation, but uncertainties are large (Popp et al. 2013).

Fourth, due to the overshoot nature of the Durban Action emissions pathways, global mean warming peaks during the 21st century and is characterized by declining temperatures in the year 2100. This means that the Durban Action scenarios studied here will eventually return to 2°C in the 22nd century if emissions reduction efforts are maintained. The probability of exceeding the 2°C limit during the 21st century is a key parameter for judging the consistency of Durban Action scenarios with the 2°C target. It is also a key parameter for determining the stringency of the end of century stabilization target and the overall shape of 2°C emissions pathways. The choice of exceedance probability is akin to setting a risk threshold. The exceedance probability will be larger than zero even for the most stringent emissions pathways.

Fifth, emissions reductions until 2030 do not contribute much in absolute terms to the overall 21st century emissions reduction requirement independently of the stringency of near term fragmented action. Thus, we do not find the emissions gap until 2020 to be an indicative



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parameter for the cumulative post-2020 mitigation requirement in accordance with other studies (Meinshausen et al. 2009).

Sixth, average costs of the Durban Action scenarios are limited across models, and are largely unaffected by the stringency of near term action. The economic impact of delay is stronger on transitional costs and price responses that relate to the institutional challenges of implementing a global climate treaty.

Seventh, increasing transitional impacts such as a jump in carbon prices and decarbonization rates can be seen with increasing trend breaks in emissions trajectories across the DAP scenarios. This reflects the fact that the emissions reduction effort is compressed into a shorter time frame with much higher yearly emission reduction rates required to meet the target. A further delay of a global climate treaty until 2030 greatly increases the transitional challenge, raising doubts about the possibility of maintaining the 2°C target in such circumstances (Rogelj et al. 2013; Luderer et al. 2013).

The findings need to be put into the context of the scope of the LIMITS study. While a set of plausible outcomes of Durban Platform negotiations were covered, other scenarios are conceivable. In particular, models have made idealized assumptions about the implementation of a global treaty after 2020. Those include a globally uniform carbon price exploiting the cheapest mitigation option in the sector and region at the margin, and the assumption of well-functioning markets. Economic impacts of the Durban Action scenarios will be higher under less favorable conditions. In addition, all models included the availability of producing negative emissions, albeit to different degrees. An exclusion of negative emissions technologies can greatly reduce the achievability of 2°C emissions pathways (Riahi et al., 2013; Krey et al., 2013). Our analysis could only touch upon the institutional challenges that the implementation of 2°C pathways and the transition to a global climate regime could entail. It does not discuss the incentives of the major economies to join such an effort. More research will be needed on the regional implications of 2°C pathways. It should be noted that our economic assessment of the Durban Action scenarios focused exclusively on the direct impacts of mitigation, and did not include the benefits from avoided climate change impacts (World Bank 2012a) and the co-benefits from climate action to other policy objectives (Riahi et al., 2012) both of which can be substantial.

We conclude that the main significance of short term action in the period 2010-2030 lies in preparing the ground for steep emissions reductions thereafter. This includes in particular the peaking of global emissions during this period while buffering the economic impact of the trend break. It is in this way that the emissions gap to immediate action scenarios may be indicative, although other indicators may relate more directly to the question of which climate options are still open at a given point in time. The Durban Platform negotiations can still deliver an outcome that would be broadly consistent with a 2°C target, and therefore - if successful in implementing global climate action by 2020 - can play an important role in keeping this option open.

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3. A Cross-model Comparison of Global Long-term Technology Diffusion under a 2°C Climate Change Control Target

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3.1 Introduction

In this paper we investigate the energy technology requirements for reaching a 2°C global climate change target. The international research teams contributing to the LIMITS project analysed, amongst others, the needs to reach this ambitious aim for climate control from a global technology diffusion perspective. Their main tools, integrated assessment energy system models that serve studying the energy-economic implications of environmental protection, allow for researching the extent, direction and cost of technological change necessary to significantly abate emissions of greenhouse gases (GHGs). We inspect in this article how much technological innovation can be expected if the international community follows weak or more stringent versions of the pledges adopted during the UNFCCC Conference in Copenhagen in 2009, and how much more effort is needed from a technological point of view if from 2020 a global climate treaty will come into force. In particular, we examine which energy options should be phased out, as well as how fast, and which others need to be expanded, and at what scale. We also assess what the costs are of this technological transformation, and to what extent and how we need to invoke alternatives involving 'negative GHG emissions'. We hereby connect to a growing body of literature on this subject matter (GEA, 2012; IPCC, 2011).

Of course, none of these questions can be answered with certainty, but integrated assessment models can take away some of the uncertainties, and the ensemble of their diverse outcomes is indicative for the nature of the technological change our societies need to initiate. In section 2 of this paper we briefly introduce the methodology used for this study, and list the models on which our research results are based. Section 3 reports our main findings in several subsections dedicated, respectively, to (1) global CO2 emission pathways, (2) primary energy supply (including fossil, nuclear and renewable resources), (3) electricity production (with coal and natural gas fuelled power plants, or with technology based on renewables such as biomass, solar and wind energy), (4) the multiple applications of CO2 capture and storage (CCS), (5) low-carbon technology costs required to achieve an ambitious climate control target, and (6) the possible transformation pathways available in the transport sector. In section 4 we discuss our results, draw some conclusions and formulate several recommendations for stakeholders in the private and public sectors.



3.2 Methodology

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The features of the integrated assessment models used in this technology diffusion comparison analysis vary widely: some are of a purely bottom-up type, while others involve a mix of top-down and bottom-up characteristics; they include different degrees of simulation respectively optimisation routines; they vary in terms of the representation of technological detail, diversity and inclusiveness in the energy system, as well as concerning technical, (macro-)economic and climatic parameter assumptions; they are distinct with regards to the way in which they represent technological change, including or not phenomena like R&D or the accumulation of experience; they differ regarding assumptions on land-use emissions and greenhouse gas species; they are diverse vis-à-vis assumed natural resource availabilities and prices, such as of fossil fuels (but also e.g. CO2 storage options); et cetera. For model descriptions we refer to publications by their respective modelling teams: GCAM (Calvin et al., 2011); IMAGE (MNP, 2006; van Vuuren, 2007); MESSAGE (Riahi et al., 2007); REMIND (Bauer et al., 2012a&b; Leimbach et al., 2010; Luderer et al., 2012), TIAM-ECN (Keppo and van der Zwaan, 2012; van der Zwaan et al., 2012; Rösler et al., 2012) and WITCH (Bosetti et al., 2006, 2009).4 In the figures reported in this article these models will often be referred to, for reasons of brevity, by their first two letters only (hence, respectively, GC, IM, ME, RE, TI, WI).

A cross-model comparison study of global long-term technology diffusion under a 2°C climate change target can involve analyses of many types and aspects of technological change. Our focus is first of all on the options available for the primary energy mix, in order to comprehend the dynamics behind the main energy resources required if one adopts stringent climate change control action. We also investigate two particular sectors, electricity production and transportation. The reason for choosing these two is that they do not only represent two large GHG emitting sectors, but are also adaptable towards complete decarbonisation (and in principle even further than that, yielding negative emissions). We inspect the behaviour under stringent climate policy of a broad range of different energy technologies, including high-carbon coal, oil and natural gas based, as well as low-carbon nuclear, solar, wind and biomass based, used through multiple energy carriers such as electricity, hydrogen and liquid synthetic fuels. We thus try to answer how, how fast and with what costs the transition materializes from fossil to non-fossil options. We also assess the use of CCS, because it could prolong the use of fossil fuels in a climate-constrained world and is expected to play a role in reaching ambitious climate change control, either or not as bridging technology.

We perform our analysis around eight different scenarios, shortly described below. For more detailed descriptions of these scenarios and their underlying Copenhagen pledges schemes (as well as reinforcements and extensions thereof) we refer to Kriegler et al. (2013). A climate stabilisation plan with a radiative forcing target of 2.8 W/m² in 2100 corresponds to a GHG concentration of approximately 450 ppmv in that year, and a of 3.2 W/m² target to a concentration of about 500 ppmv.

⁴ For one figure in this paper we also use results from the AIM-Enduse model (see Hibino *et al.*, 2012).



Base:	Baseline (BAU) involving no climate policies and a large-scale continuation of fossil fuel usage for all main energy services.
StrPol:	Stringent regional climate and energy policies with enhanced
	Copenhagen Accord ('plus') pledges during the 21st century.
450:	Global coordinated action from today to reach climate
	stabilisation with radiative forcing target of 2.8 W/m ² .
500:	Global coordinated action from today to reach climate
	stabilisation with radiative forcing target of 3.2 W/m ² .
RefPol-450:	Reference regional climate policies (Copenhagen pledges) until
	2020 and global coordinated action to 2.8 W/m ² from 2020.
StrPol-450:	Stringent regional climate policies (Copenhagen pledges 'plus')
	until 2020 and global coordinated action to 2.8 W/m ² from 2020.
RefPol-500:	Reference regional climate policies (Copenhagen pledges) until
	2020 and global coordinated action to 3.2 W/m ² from 2020.
StrPol-500:	Stringent regional climate policies (Copenhagen pledges 'plus')
	until 2020 and global coordinated action to 3.2 W/m ² from 2020.

We focus most on scenarios StrPol and RefPol-450 and the deployment of low-carbon energy in their GHG mitigation pathways. StrPol involves a set of stringent regional climate and energy policies that represent enforcements and extensions of the political pledges delivered in association with the UNFCCC Copenhagen Accord (2009) and apply to the entire 21st century. This scenario implies GHG emission reductions that are far from ambitious enough to reach a 2°C maximum global atmospheric temperature increase: it generates a rise of around 3°C with median probability by the end of the century (and more thereafter). RefPol-450 simulates until 2020 a set of relatively weak climate policies corresponding to the Copenhagen pledges, and from 2020 implies global GHG emission reductions deep enough so as to reach, with a 70% probability, a stabilised climate with a temperature increase of at most 2°C. In all scenarios listed above, overshoot in terms of radiative forcing is allowed. In RefPol-450, for instance, during several decades values of over 3.0 W/m² pertain before stabilization occurs at 2.8 W/m².

3.3 Results

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3.3.1 CO2 emissions

From the left plot in Figure 1 we see that the stringent global climate policy scenario (StrPol) leads to similar global CO2 emission paths for three of the six models (GCAM, IMAGE and TIAM-ECN): the current increasing trend continues until emissions reach a maximum around 2020-2030, after which they decrease to amount in 2100 to a level about half of that today. The other three models (MESSAGE, REMIND and WITCH) foresee significantly higher emissions under the same stringent global climate policy, at least part of which can be explained by the relatively optimistic GDP growth assumptions in these models (some of the reductions targets included in the set of stringent climate policies are not absolute but expressed in terms of economic growth). We observe that for MESSAGE and REMIND CO2 emissions start to decrease only after 2050 and that REMIND is the only model that by the end of the century yields emissions only slightly below their level today.



Figure 1. Global CO2 emissions in scenarios StrPol (left) and RefPol-450 (right).

The variety in modelling outcomes is equally large in the right plot of Figure 1 depicting CO2 emission profiles matching a long-term global anthropogenic radiative forcing maximum of 2.8 W/m². CO2 emissions in 2020 are higher than in the stringent climate policy case (left plot of Figure 1), since until this year only weak climate policies apply. All models need to rapidly decrease emissions from 2020: these reductions have to be much deeper than in the stringent climate policy scenario in order to reach the 2.8 W/m² forcing target. For all models CO2 emissions need to become negative during the second half of the century. This can be reached, for example, by using biomass as feedstock for the production of electricity, hydrogen or other synthetic fuels, and complementing these processes with CCS. The extent to which such options need to be employed varies significantly from one model to another (see section 3.4).



3.3.2 Primary energy

Figure 2. Global primary energy use in 2050 and 2100 in scenarios StrPol and RefPol-450.



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Figure 2 (left half) shows that for the stringent climate policy case the global primary energy consumption mix is fairly consistent across models in 2050. In 2100 the variability between models increases, not only in terms of the total level of energy use but also regarding its breakdown: most striking are the differences between models vis-à-vis the use of oil, nuclear energy and non-biomass renewables (such as solar and wind power). This heterogeneity in the primary energy mix also holds for the three models that show similar developments of CO2 emissions in Figure 1 (left). Hence, the same emission reductions can be achieved through mitigation pathways involving quite different technological options. If an ambitious maximum global radiative forcing of 2.8 W/m² is targeted (right half of Figure 2), the differences between models in terms of global primary energy use are large in 2050, and get more pronounced in 2100. Coal is entirely phased out in REMIND, while it continues to play a role in the other models during most of the century (as we will see below though, it will essentially only do so if complemented with CCS technology). All models except REMIND (that generates an energy system eventually almost entirely relying on biomass and other renewables) expect fossil fuels plus nuclear energy to account for at least $\frac{1}{4}$ up to $\frac{1}{2}$ of all primary energy supply in 2100. While oil is essentially phased out in some models, and maintained in others, all models agree that at least half of all primary energy sources derive from biomass or other renewables. The large variety in primary energy breakdown across models demonstrates that the ambitious 2.8 W/m² climate target can be achieved by using different GHG mitigation measures.





Besides differences, the models show some similar developments as well. For all of them both the stringent climate policy and the 2.8 W/m² forcing target scenarios lead to a large reduction in the use of fossil fuels with respect to the baseline scenario, as can be seen in Figure 3. There is also clear consensus between models that, in order to achieve global climate change objectives, energy savings have an important role to play. In fact, for almost all models, scenarios and timeframes, energy savings are larger in magnitude than incremental (biomass plus non-biomass) renewable energy deployment. These results match the increasing attention given to



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this topic by the international policy making scene (see, for example, IEA-WEO (2012), in which similar findings are reported). Energy savings result in all models from both reductions in energy services and the application of more efficient energy production and end-use technologies. Some of the differences between models in this respect can be explained by their top-down versus bottom-up nature (see e.g. Sue Wing, 2006; van Vuuren et al., 2009).

3.3.3 Electricity production

For power production, technology deployment under a stringent climate policy regime is particularly pertinent, not only since it is among the largest CO2 emitting sectors, but also because it represents a part of the energy system in which emission reductions can be realized at costs lower than incurred in several other sectors such as road transportation or aviation (see also IEA-ETP, 2012). Figure 4 shows the development of CO2 emissions in the power sector (a) and the overall electricity production level as well as the mix in contributions thereto (b) for our six models under two different climate control scenarios.



Figure 4. CO2 emissions in the power sector (a) and electricity production mix in 2050 and 2100 (b) for scenarios StrPol (left) and RefPol-450 (right).

Figures 4(a) and 4(b) show that, under stringent climate policy, power sector CO2 emissions by 2050 are about 0.7-1.4 times their current level, while the amount of generated electricity is more than 2 to 3 times that of today. Hence, the power sector becomes substantially less carbon intensive in the time frame of several decades. During the second half of the century this decarbonisation process proceeds: CO2 emissions decline in all models, to reach in 2100 at most half their level today, whereas electricity production continues to increase, in some models by as much as a factor of two with respect to the level reached in 2050. In the 2.8 W/m² forcing target scenario the carbon intensity improvements develop faster: power production related CO2 emissions drop to zero or negative levels around 2050 and decrease to substantial negative



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values around 2100 in all models except MESSAGE (in this model essentially all biomass is directed toward industry and transportation), while electricity production increases 3- to 9-fold between 2010 and 2100.

As we will also further see below, the reduction of CO2 emissions per kWh of produced electricity is achieved by an increase in the use of essentially three categories of low-carbon technologies: (1) renewable energy, (2) nuclear power and (3) CCS. CCS may be applied to fossil fuel based power stations or alternatively electricity plants with biomass as prime combustion fuel (through which negative CO2 emissions can be reached); the extent to which these two different options are utilised diverges significantly between models. As can be seen from Figure 4(b), the differences in the simulated power mix become large by 2100. MESSAGE, REMIND and TIAM-ECN report high solar electricity contributions, which in 2100 in the 2.8 W/m² forcing target scenario represent a share of more than 50% of total power production. Nuclear energy possesses by far the largest share in the global electricity mix for GCAM and WITCH, while for IMAGE most of the main mitigation options are rather equally distributed, with clear roles also reserved for fossil and biomass based power plants equipped with CCS.



Figure 5. Electricity production from solar and wind energy in 2050 and 2100 in scenarios Base, StrPol and RefPol-450.

A closer inspection of individual technologies demonstrates more clearly the large deployment and electricity generation differences reported by the six models. Figure 5 depicts simulated solar and wind power production levels in 2050 and 2100 for the baseline and two climate change action scenarios. Solar power production grows from an amount currently below 0.1 EJ/yr to values in 2050 that range from 0.1 to 15 EJ/yr for the baseline scenario, from 7 to 30 EJ/yr for the stringent climate policy scenario and from 10 to 49 EJ/yr for the 2.8 W/m² forcing



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target scenario. In absolute (but not in relative) terms these increases become even larger during the second half of the century. In the most optimistic case (simulated by REMIND) we observe a three orders of magnitude expansion of solar power during the 21st century. Uncertain future developments regarding technology costs and performance imply large differences across models in assumptions regarding these variables, which are reflected in the large error margins depicted in Figure 5.

MESSAGE and REMIND report solar electricity generation that by 2100 exceeds twice the total current power production level even in the baseline scenario (hence without climate change intervention), while other models show only little increase in solar electricity generation when no climate action is implemented. All models agree that the amount of solar power produced when climate policy is introduced is higher than in the business-as-usual scenario, but in WITCH this increase is only limited, which is partly explained by the fact that WITCH only simulates concentrated solar power (CSP) and not photovoltaics (PV). For electricity production from wind energy we observe similar results, except for the fact that, especially in the long run and for most models, wind power does not reach the pervasiveness of solar power. For three models (MESSAGE, REMIND and TIAM-ECN) wind energy generates about 3 times less power than solar energy in 2100. The uncertainty range for wind power amounts to more than 100 EJ/yr in 2100 in the 2.8 W/m² forcing target scenario. WITCH is the only model that expects more wind than solar power across all scenarios, mainly because of the partial representation of solar energy with just CSP.

Figure 6 shows annual capacity additions, both for the recent past (2000-2010, except nuclear energy: 1980-1990) and short to medium term future (2010-2030 resp. 2030-2050) for various conventional and low-carbon energy technologies in the RefPol-450 scenario. The annual new capacity deployment intensity (expressed in GW/yr) needed for solar and wind energy until 2030 needs to be around the same of that recently observed for coal based power plants, and will need to be several times higher during the period 2030-2050. The manufacturing and installation industry will need to prepare for this massive growth. In the medium term, gas turbines (in the future equipped with CCS technology) and nuclear power plants will need to be deployed at about twice the rate they have experienced during the hay days of their popularity. Biomass power plants, complemented with CCS, will in the medium term need to be built at about the rate that gas fuelled plants have been constructed in the recent past. In addition to industrial challenges, such expansion rates imply infrastructural, financial, socio-political and institutional requirements not yet experienced at this scale. Wilson et al. (2012) investigate whether scenarios for future capacity growth of energy technologies are consistent with historical evidence and find that future low-carbon technological growth in the power sector appears to be conservative relative to what has been evidenced historically. Differently from them, and probably because they use a different analysis framework (expressing their findings in terms of speed-based technology diffusion variables), we find that average annual capacity additions for a couple of low-carbon energy technologies (solar and wind power) are the opposite of conservative in historic terms, that is, they are several times higher than the maximum average annual capacity additions rate observed in the recent past (i.e. for coal based power plants, at a little over 50 GW/yr).





N.B. Historical data correspond to 2000-2010, except for nuclear energy (1980-1990) and are assembled from various sources: EPIA, GWEC, IAEA/PRIS, IEA and Platt's. Two REMIND data points fall outside the scale of the figure: 400 and 300 GW/yr for solar resp. wind.



Figure 7. Electricity production from coal and gas plants in 2050 and 2100 in scenarios Base, StrPol and RefPol-450.

In comparison to renewable energy, the opposite trend can be observed for coal and gas based power plants: electricity generation with these two fossil fuels decreases in most models under the stringent climate policy and the 2.8 W/m² forcing scenario, with respect to the baseline (see Figure 7). As we already saw, coal and gas are not phased out entirely in all models by the end of the century, given the presumed availability of CCS. Because of CCS, some models (such as TIAM-ECN) may actually see an increase in the use of natural gas when climate policy is implemented. Given that nuclear power is a low-carbon power production option (van der Zwaan, 2013), nuclear energy benefits from climate change action in most models (but not in REMIND, because of limited availability of uranium resources; see Figure 8). The extent of its expansion varies strongly across models: GCAM has by far the highest electricity production from nuclear power plants in all scenarios, while MESSAGE and WITCH also show significant increases under climate change control scenarios. It is to be seen whether such large expansion is realistic, given concerns over e.g. radioactive waste, reactor accidents and nuclear proliferation (see, for instance, Glaser, 2011).



Figure 8. Nuclear power production in 2050 and 2100 in scenarios Base, StrPol and RefPol-450.

3.3.4 CCS technology

It is broadly recognised that CCS is an important candidate technology in the set of mitigation options needed to control global climate change (IPCC, 2005; IEA-ETP, 2012). Our model runs confirm this view, and imply that CCS may become an indispensable option to reach deep CO2 emissions reductions, as demonstrated in Figure 9. Most environmentalists would argue that CCS should mainly function as transition technology, on the road towards sustainability in which ultimately only renewable resources deliver energy services (see e.g. ENGO, 2012). Figure 9 shows that during the 21st century CCS plays a role larger than merely as transition option: in either of the depicted climate control scenarios CCS is associated with hundreds EJ/yr of primary energy production, especially during the second half of the century. Great variety exists between models in terms of the primary energy carrier to which CCS technology is applied: coal, gas or biomass. In the long run, and especially when a 2.8 W/m² forcing target is aimed for, CCS is particularly used in combination with biomass options. The reason is that CCS (that possesses an imperfect capture rate) applied to fossil fuel technologies emits levels of CO2 too high for reaching an ambitious climate control target, whereas CCS associated with biomass as combustion fuel can generate negative emissions.



Figure 9. Primary energy use in combination with CCS in scenarios StrPol and RefPol-450.

Figure 10, depicting the production of three main secondary energy carriers (electricity, hydrogen and synfuels) in combination with CCS technology, shows in a complementary fashion that the usage of CCS differs strongly among models, especially in the long term. MESSAGE and REMIND rely in 2100 (not in 2050) relatively little on CCS as climate mitigation option for fossilbased power production, probably because these models find large roles for renewables in this sector. Consequently, as also demonstrated in Figure 10, these two models can reserve global geological CO2 storage capacity for other applications, such as CCS in combination with hydrogen and (liquid fossil) synfuel production. A difference between the two climate action cases is that in the medium term (2050) CCS for all fossil options (notably coal and gas) increases significantly when tightening CO2 emission abatement efforts (compare Figure 10a with b), while in the long term (2100) the reverse holds for coal (but not necessarily for all models for natural gas). CCS in combination with oil for power production is essentially negligible: climate mitigation and the availability of CCS technology are not sufficient drivers for oil to re-emerge in the power sector (to which it contributed substantially in the 1970s), the reason for which is that limited oil resources remain largely reserved for usage in transportation. Electricity generation from biomass with CCS increases, for all models, both in time and when taking more stringent climate control action. In 2100, under the 2.8 W/m² forcing target scenario, GCAM and IMAGE generate the highest usage of CCS aggregated over all applications.



Figure 10. Production of electricity, hydrogen and synfuels in combination with CCS in scenarios StrPol (a) and RefPol-450 (b).

3.3.5 Technology costs of reaching 2°C

Figure 11 presents two cross-model comparison scatter-plots depicting cumulative total energy technology costs (including upfront investment, fuel and O&M costs) versus cumulative



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capacity until 2050 for four low-carbon power supply options (CCS, nuclear, solar and wind energy) for two cases: scenarios implying a 50% probability of reaching the 2°C climate control target (left) and scenarios implying a 70% probability of reaching that target (right). Data points shift to the upper right corner when going from the left to the right plot, the reason for which is that tighter climate control plans imply more low-carbon power production and thus higher deployment costs for the corresponding low-carbon technologies. From the sets of three points (triplets) depicted per model per energy option it can be observed that there is significant impact on technology diffusion from whether a global climate treaty (in a cost-minimising framework from a modelling perspective) towards 2.8 or 3.2 W/m² climate stabilisation is adhered to from today or if this is done after only a decade (hence from 2020 onwards) while the intermediate period is covered through (weak or stringent) Copenhagen type of policy pledges. The latter approach usually incurs additional technology deployment costs.

Figure 11 also shows that apart from technology diversity across models, there is also sizeable variability in terms of the technology cost assumptions between them. For example, WITCH finds about the same capacity as TIAM-ECN for accumulated wind power capacity, but reports cumulative costs that differ by about a factor of two. The inverse also sometimes holds: MESSAGE and REMIND find roughly the same cumulative costs for CCS deployment, but simulate cumulative installed capacity that diverges by about a factor of two. For nuclear and solar energy, on the other hand, all data points lie pretty much on a linear diagonal through the origin of the plots, implying that the models adopt similar cost assumption for these technologies. The aggregated costs resulting from the deployment of CCS, nuclear power, plus solar and wind energy capacity amount over the time frame until 2050 to about 50 trillion US\$(2005) for each of the models, which is well over a trillion US\$(2005)/yr for the next four decades. TIAM-ECN reports triplets of data points that are often more broadly spread than for other models. This is a recognition of the fact that, in the absence of learning-by-doing effects, within a cluster of technologies larger capacity requirements usually imply a switch to different (more expensive) options within the cluster, such as from onshore to offshore wind, from CSP to PV, or from CCS applied to fossil fuels to biomass based power plants.



Figure 11. Cumulative cost versus capacity until 2050 for four low-carbon power supply options in scenarios 500, RefPol-500 and StrPol-500, respectively, scenarios 450, RefPol-450 and StrPol-450.



3.3.6 Transport sector

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The types of models employed for this study typically tend to simulate late decarbonisation for transportation, given the relatively high costs associated with new climate-friendly vehicle options (see e.g. van der Zwaan et al., 2012). These models differ thereby fundamentally from models dedicated only to the transport sector, in which new automotive options spread more quickly. This article does not investigate the divergence in results between these different methodological frameworks, but rather concentrates on the types of technologies that may, sooner or later, dominate in transportation. As with many of the results reported above, models show large differences in cost-optimal low-carbon solutions for the transport sector. Even in the absence of global climate policy, transportation is likely to experience fundamental change over the decades to come, mostly as a result of the gradual depletion of many of the currently known oil reserves and thus higher prices for oil. This change is demonstrated in Figure 12. Whereas some models expect a very diverse future energy carrier mix for the non-oil based part of transportation in 2100 (like GCAM and TIAM-ECN), others expect only one or at most a few options to dominate, such as hydrogen (in IMAGE) or a combination of fossil- and biomass-derived synthetic liquid fuels plus electricity (in MESSAGE and REMIND).



Figure 12. Fuel use in the transport sector in the Base scenario in 2050 and 2100.

In Figure 13 the difference in transportation fuel use between the baseline and two climate control scenarios is shown. A major consistent finding across models is that the use of oil is significantly downplayed as a result of climate policy, and even more so in later periods in time (especially by the end of the century). The reason for this replacement of oil adds to the one originating from the depletion of oil fields and associated rise in oil prices, as observed in the baseline scenario. Another stable outcome, mirroring real-life developments, is the role efficiency improvements and energy savings can play in reducing fuel consumption and GHG emissions in transportation. Energy savings may still play out after the transition towards alternatives to traditional automotive fuels has been completed (as shown in the results for IMAGE in 2100 under the 2.8 W/m² forcing target scenario). Whether natural gas, biofuels, electricity or hydrogen

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will ultimately dominate in the transport sector, or some balanced combination between them, is a question not answerable today, as visualized through the diversity in results reported in Figure 13.





3.4 Conclusions and policy & strategy implications

Our first main finding is that the CO2 emission reductions needed to reach a high probability to stay below a maximum 2°C global temperature increase, are much deeper than those that correspond to even a significantly enhanced and extended version of the so-called Copenhagen pledges. Indeed, if we are to stabilize the average anthropogenic temperature increase at 2°C, CO2 emissions have to be reduced much more substantially than so far professed, because deep negative CO2 emission values have to be reached during the second half of the century. In order words, not only do national and regional policy makers need to ascertain that the fragmented promises made during the UNFCCC summit in Copenhagen in 2009 are matched with concrete and effective local climate change control measures to meet these promises, the international policy making community must imminently act in order to go well beyond the pledged goals, so as to guarantee the conclusion of a negotiated global climate treaty over the next couple of years that enables achieving much farther reaching emission abatement targets.

Through our modelling exercises we found that, while the role of most fossil-based primary energy resources needs to be substantially reduced from today onwards, and of all of them during the second half of the century, they do not need to be phased out if a large-sale implementation of CCS materializes. In order to reach a broad diffusion of CCS technology in the longer run, today the important step must be undertaken to move from the accomplished phase of CCS technology having been proven on relatively small (test) scales to the stage at which it is put to practice in real-life large-size CO2 point sources in industry and power production. On a global level the power sector should start generating negative CO2 emissions from around 2050 in order to compensate for GHG emissions in other sectors where abatement is more costly. Such



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negative emissions can be achieved through the application of CCS technology to power plants that use biomass as primary fuel (Calvin et al., 2013, this special issue). As long as the large-scale use of biomass remains uncertain, however, other options to generate negative CO2 emissions must also be investigated, including direct air capture devices such as researched by Keith et al. (2009) and Lackner et al. (2012).

We point out in this paper that, for large-scale low- or negative-carbon electricity generation, renewables like biomass, solar and wind energy dominate our present view of future global energy systems (for biomass, see especially Calvin et al., 2013). We recognize, however, that other currently known options could also play a moderate to even significant role, among which e.g. hydropower, tidal/wave and geothermal energy; particularly also nuclear energy cannot be ruled out, even while it remains troubled by concerns over radioactive waste, reactor accidents and atomic weapons proliferation. Dedicated policy instruments can incentivize and support the emerging technology markets for renewables, e.g. through subsidies, R&D, carbon pricing, feedin tariffs, and loan guarantees. As we show in this study, different experts foresee substantially varying scales for the global contraction of high-carbon energy resources, respectively the diffusion of low-carbon energy technologies (even while all models agree that the changes involve shifts of hundreds of EJ/yr), which is an expression of the multitude of pathways available to establish a climate-neutral energy system. While our model results tend to strongly diverge in the various scenarios we developed, as we highlighted in this paper, the ensuing uncertainty in the global energy system transformation process yields important implications for the public sector: the policy making scene ought not to try to pick winners, since we do not (yet) know what the best, optimal, or most cost-effective way is of reducing GHG emissions. Certain, however, is that massive-scale mitigation must take place if society wants to achieve the 2°C target. Hence we need to design policies so as to generically stimulate the deployment of low-carbon energy options, while not selecting any supposed victors upfront.

Our study bears also important strategic lessons for the private sector, since the annual capacity deployment intensity (in GW/yr) needed for e.g. solar and wind energy until 2030 needs to be similar to that recently observed for coal based power plants, and will have to be several times higher between 2030 and 2050. Industry needs to prepare for this. The promising technology of CCS, according to all modelling teams, constitutes a large part of the climate mitigation technology mix involving hundreds of EJ/yr of primary energy, but it applies to different forms of primary resources (coal, gas and biomass) and types of energy carrier production (electricity, hydrogen and liquid fuels). Hence industry must undertake the necessary R&D to steer its decision process regarding where to invest its commercial activity most optimally. Not only does uncertainty abound with regards to the technology type and diffusion extent of lowcarbon energy alternatives that need to be deployed until 2050, but also concerning the respective cumulative costs involved. Clear is though, from our cross-model comparison exercise, that high agreement exists in terms of the aggregated total required technology costs on the supply side, amounting to about 50 trillion US\$ until the middle of the century, that is, on average over 1 trillion US\$/yr until then (and, as it proves, at least as much after that; see, for instance, McCollum et al., 2013; Kober et al., 2013, in this special issue). As for transportation, many options exist to decarbonize this sector, but unclear today is which of the currently competing options should optimally or will ultimately dominate it, and/or whether a mix of options will serve the transformation of this sector best. Here too, private sector R&D can help determining the optimal pathway.





3.5 References

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4. A multi-model analysis of the regional and sectoral roles of bioenergy in near-term and long-term carbon mitigation

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4.1 Introduction

Biomass energy, or bioenergy, is a heterogeneous set of renewable resources with a wide array of potential uses in different energy sectors. Traditional forms of biomass such as fuel wood and animal wastes have been used worldwide for millennia. In more recent times, crops high in sugar and starches are readily converted to ethanol, and oil crops such as soy and jatropha are sources of biodiesel. Lignocellulosic resources, which come from a variety of resources including agriculture and forest residues, as well as cultivating dedicated energy crops such as switchgrasses and short-rotation woody crops, have potential uses in several energy applications including electric power, gasification, liquid fuels, and direct use as biosolids. (See Chum et al 2011 for a comprehensive overview.)

Bioenergy has enormous technical potential for mitigating CO_2 emissions from the energy system. Bioenergy can be used as a substitute for fossil fuels for a wide variety of energy applications such as generating electricity or creating liquid fuels, as well as direct use as final energy. The combination of bioenergy with CO_2 capture and storage (CCS) has been shown to hold significant potential for achieving deep emissions reductions (Luckow et al. 2010). However, there are sustainability and mitigation effectiveness questions associated with large-scale reliance on bioenergy. Among the most important of these is the issue of indirect land use CO_2 emissions from bioenergy, which has been identified and studied by several authors, including Fargione et al (2008), Searchinger et al (2008), Wise, et al. (2009), Melillo et al (2009), and Popp, et al (2012).

In this paper, we study the near term and longer-term energy system contribution of bioenergy to carbon mitigation in different LIMITS scenarios as modeled by the participating models in the LIMITS project. First, we briefly summarize the scenarios and the approaches used to model bioenergy in each of the participating models. Second, we discuss the overall contribution of bioenergy to climate mitigation policies across all models. Third, we take advantage of the regional heterogeneity of these scenarios in the near term, as well as the heterogeneity of modeling approaches and assumptions, to explore a range of outcomes for biomass use in different energy sectors in different regions. Fourth, we look for common outcomes as well as key differences in the results for the long term, when all regions are assumed to converge to a common mitigation outcome. Finally, we finish with a discussion of results.



4.2 Models and Scenarios

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This paper analyzes the use of bioenergy in the seven global integrated assessment models participating in the LIMITS project. These models vary in their representation of bioenergy (Table 1), as well as their representation of other aspects of the economy and energy-system. In the interest of brevity, we refer the reader to other papers for more complete descriptions of the models: IMAGE (van Vuuren 2007), MESSAGE (Riahi et al. 2007), ReMIND (Luderer et al. 2012), TIAM-ECN (Keppo and Zwaan 2012), WITCH (Bosetti et al. 2009), and GCAM (Calvin 2011).

	Bioenergy Technologies]		
	Elec	tricity	Liquid	l fuel	Hydro	ogen				
Model	w/o CCS	w/ CCS	w/o CCS	w/ CCS	w/o CCS	w/ CCS	Biogas	Biomass heat	Land-Use Model	Limited Bioenergy Supply
AIM-Enduse	x	x	x		x	Х	х	x		
GCAM	x	x	x	х	x	Х	х		x	
IMAGE	x	x	x		x	Х			x	
MESSAGE	x	x	x	х	x	Х	х	x		x
ReMIND	x	x	x	х	x	Х	х	x	x	x
TIAM-ECN	x	x	x	х						x
WITCH	x	x	x							

Table 1: Representation of bioenergy in the models analyzed

We focus on six of the twelve LIMITS scenarios (Table 2) for this bioenergy analysis. We use the first three scenarios (Base, 450, and 500) to explore the effect of climate policy, in the form of a globally harmonized carbon price), on bioenergy production and consumption (Section 3). The remaining three scenarios (RefPol-500, StrPol-500, RefPol2030-500) include regional emissions and renewable energy policies in the near-term (see LIMITS Protocol), and transition to globally harmonized carbon price scenarios in the long-term. In each of these three scenarios, the long-term climate target is the same as the 500 scenario. Thus, we use these scenarios to explore the effect of near-term policy on bioenergy consumption in the near- (Section 4) and long-term (Section 5).



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	Cli			
	2020	2100 Climate Target		
Base	None	None	None	N/A
450	Global Carbon Price	Global Carbon Price	Global Carbon Price	450 ppm CO ₂ -e
500	Global Carbon Price	Global Carbon Price	Global Carbon Price	500 ppm CO ₂ -e
RefPol-500	Emissions constraints, Emissions intensity targets, Renewable energy targets, Technology-specific capacity targets	Global Carbon Price	Global Carbon Price	500 ppm CO ₂ -e
StrPol-500 (Stricter Policies)	Emissions constraints, Emissions intensity targets, Renewable energy targets, Technology-specific capacity targets	Global Carbon Price	Global Carbon Price	500 ppm CO ₂ -e
RefPol2030-500	Emissions constraints, Emissions intensity targets, Renewable energy targets, Technology-specific capacity targets	Emissions constraints, Emissions intensity targets, Renewable energy targets, Technology-specific capacity targets	Global Carbon Price	500 ppm CO ₂ -e

Table 2: Scenarios

4.3 The Effect of Carbon Prices on Bioenergy

In the Base scenarios, in the absence of the climate and other policies specified here, bioenergy plays an important, but not transformational role in the energy sector. Total consumption of bioenergy ranges from 35 to 65 EJ per year in 2020 (6-10% of total primary energy) and from 100 to 180 EJ per year in 2100 (10-15% of total primary energy), depending on the model (Figure 1A). Common across many of the models is a decline in total bioenergy consumption over the first few decades followed by a steady increase in the latter half of the century. From Figure 1D, most of the decline can be attributed to a decreased use of biosolids in direct end-uses, much of it in the form of traditional bioenergy forms, as access to more modern, convenient forms of energy is expanded. The later growth in the Base scenarios is due mainly to increased production of bioliquids, as well as more modest growth in bioenergy for electricity (Figures 1B and 1C).

The imposition of a climate policy results in increased bioenergy consumption in all models, particularly in the second half of the century. Some models, however, reach total constraints on bioenergy, and thus, have no increases in bioenergy use between the 500 and 450 scenario. Those models do show earlier deployment of bioenergy under the 450. Other models have increased bioenergy with target stringency. That bioenergy would increase under tighter mitigation targets in these models indicates that there is a net positive mitigation between bioenergy and land use change in the deployment of bioenergy as computed in these models. Total consumption of bioenergy in the 500 scenario ranges from 135 to 335 EJ/yr in 2100 (14-40% of total primary energy), with the highest value of over 350 EJ/yr in the GCAM 450 scenario.

The range of values is not simply due to different assumptions about the bioenergy production possibilities and transformation technologies. The bioenergy results are also driven by



IMITS

the heterogeneity of assumptions across the models about energy technologies, mitigation technologies, agricultural productivity, socioeconomic growth, and many other factors. In fact, all of the results are well within the estimated technical potential of 500 EJ/yr by 2050 as estimated by Dornburg et al (2010), where technical potential is the production possibility given assumptions about land priority for food, fiber, and timber. And they are much less than the theoretical potential of over 1,500 EJ/yr derived by Smeets et al (2007).

The scenario results show a higher dependence on bioenergy in liquids production, than they do in electricity generation (Figure 1B,C). That is, bioenergy has a higher share of liquid fuels production than it does of electricity production.⁵ Without climate policy, all models have more bioliquids production in absolute terms, than they do bioelectricity after 2030. Under a climate policy, this is true for five of the seven models, with the exceptions being GCAM in the second half of the century and TIAM in all years. These differences are a result of different economics of mitigation alternatives in the liquids and electricity production sectors of the models, and they highlight different plausible pathways for mitigation using bioenergy. However, the common result is that most of the models show significant amounts of bioenergy in both of these sectors, regardless of which uses more.

Direct bioenergy consumption varies quite a bit across models than across scenarios (Figure 1D). In AIM-Enduse, REMIND, and WITCH, consumption declines steadily through time, indicating a trend toward phasing out of traditional bioenergy. Interestingly, IMAGE model results show high growth of biosolids use in all scenarios, highlighting the feasibility of a scenario of a network of modern biosolids production and use for residential and industrial energy. Consumption is slightly increasing in the GCAM Base scenarios and all TIAM-ECN scenarios, while it shows a peak and decline pattern in the GCAM policy scenarios and all MESSAGE scenarios. In some scenarios (e.g., all IMAGE scenarios, all TIAM-ECN scenarios, GCAM Base), direct consumption is significant, i.e., of a similar magnitude to bioelectricity and bioliquids. In GCAM and TIAM-ECN, the imposition of the climate policy drives down biosolid consumption in the second half of he century as it becomes more valuable for mitigation in the electric and liquids sectors.

⁵ Note that this does not mean that more bioenergy is consumed by the liquids sector than the electricity sector. These two conversion processes have different efficiencies and thus there is not a one-to-one correspondence between production and consumption.



••••WITCH 450

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Panel C: Bioliquids production

EJlyr

2020

2005

2035

2050

Panel D: Bioenergy solid consumption 180 AIM-Enduse Base 120 AIM-Enduse Base - - AIM-Enduse 500 - AIM-Enduse 500 ••••AIM-Enduse 450 160 AIM-Enduse 450 GCAM Base GCAM Base 100 - GCAM 500 - GCAM 500 140 ••••GCAM 450 ••••GCAM 450 -IMAGE Base -IMAGE Base 120 80 - - IMAGE 500 - - IMAGE 500 ••••IMAGE 450 ••••IMAGE 450 100 MESSAGE Base MESSAGE Base ۰۵ آپر 10 آپر - - MESSAGE 500 - MESSAGE 500 80 ••••MESSAGE 450 ••••MESSAGE 450 REMIND Base REMIND Base - - REMIND 500 60 - - REMIND 500 ••••REMIND 450 ••••REMIND 450 TIAM-ECN Base 40 TIAM-FCN Base TIAM-ECN 500 20 TIAM-ECN 500 ••••TIAM-ECN 450 •TIAM-ECN 450 20 WITCH Base WITCH Base -- WITCH 500 -- WITCH 500

0

2005 2020 2035

2050

2065

2080

2095

EJ/yr

Figure 1: Global bioenergy production and consumption

2065

2080

2095

4.4 The Effect of Near-Term Policy on Bioenergy in 2020

••••WITCH 450

Three of the scenarios analyzed in this paper (RefPol-500, StrPol-500, and RefPol2030-500) include region-specific near-term policies that can affect the production and use of bioenergy. The policies considered include: (1) emissions constraints, which incentivize bioenergy and other low-carbon fuel sources, (2) emissions intensity targets, which behave similarly to emissions constraints, (3) renewable electricity standards, which incentivize bioelectricity and other renewable electricity technologies, (4) renewable energy standards, which incentivize bioelectricity, bioliquids, direct consumption of bioenergy, and other renewable energy technologies, and (5) technology-specific capacity targets, which require a specific amount of installed capacity for particular technologies. The first four policies will tend to increase the use of

Panel B: Bioelectricity production







bioenergy.⁶ However, the degree of increase and the sectors targeted depend on the policy type and the policy stringency. For example, renewable electricity standards will not have a direct effect on bioliquids production. Because each region has a different combination of policies, we discuss the effects of these policies in the near-term by region, focusing on Europe, North America, China+, and India+.

To assist in explaining the results, Figure 2 compares the year 2020 global carbon price in the 500 scenario to the regional carbon prices for the other scenarios for each of the models. From the figure, there is variation by model and region as to whether the regional-specific 2020 policies are more or less stringent than the mitigation taken under the global carbon policy taken in the 500 scenario. The different carbon prices reflect differences in assumptions of key factors such as socioeconomic growth and technology development.



Figure 2: 2020 Regional CO2 Prices by Scenario and Model in Context with Global 500 Scenario

⁶ Theoretically, the fifth type of policy could also increase bioenergy production. However, the capacity targets included in the LIMITS scenarios are limited to wind, solar, and nuclear.



4.4.1 Europe

IMITS

In 2020, Europe has a GHG emissions constraint (15% reduction from 2005 in the RefPol cases, and 25% reduction from 2005 in the StrPol cases), and a renewable energy policy (20% of final energy from renewables).⁷ The European carbon price with near-term policies (RefPol-500, RefPol2030-500, and StrPol-500) is higher than the global 500 scenario in some models and lower in others. However, emissions are lower in 2020 in Europe with near-term policies than they are in the 500 scenario and bioenergy consumption is higher (Figure 3B) in all models. Both effects are influenced by the renewable energy policy. All models use bioenergy to meet the renewable targets, however, the degree to which this is true varies (Figure 3A). MESSAGE uses more non-biomass renewables than bioenergy. GCAM relies heavily on biosolids. WITCH relies heavily on bioliquids. Bioelectricity increases with the near-term policies (Figure 3C), but is a small contributor to the renewable target in all models, with the highest contribution in TIAM at ~2.5% of final energy. The increased use of bioliquids in response to the near-term policy is pronounced in GCAM, IMAGE, and WITCH (Figure 3D).

⁷ The policies listed here are for EU27. Other portions of Europe may have slightly different policies (e.g., Turkey has a 20GW wind capacity target).







Figure 3: The effect of near-term policy on renewables, primary energy, electricity, and liquids in Europe in 2020

4.4.2 North America

In 2020, North America has a GHG emissions constraint (5% reduction from 2005 in the RefPol cases, and 17% reduction from 2005 in the StrPol cases), and a renewable energy policy (13% of electricity in the RefPol cases and 25% of electricity in the StrPol Cases). The North American carbon price with near-term policies (RefPol-500, RefPol2030-500, and StrPol-500) is lower than the 500 scenario in most models (GCAM, TIAM, and IMAGE StrPol-500 are exceptions). Emissions are higher in 2020 in North America with near-term policies than they are



in the 500 scenario in most scenarios (StrPoI-500 in GCAM, MESSAGE, and WITCH are exceptions). The change in bioenergy consumption is strongly correlated with the carbon price in North America (Figure 4B). Increases in bioenergy consumption (and significant declines in coal use) are seen in models where the carbon price is higher than in the 500 scenario (GCAM, TIAM-ECN, IMAGE StrPoI-500). Declines in bioenergy (and increases in coal use) are seen in MESSAGE. Unlike in Europe, the renewable target is for electricity alone, and thus, bioliquids (Figure 4D) and bio solids cannot contribute. All models rely on non-biomass renewable electricity to meet their target, with bioelectricity contributing a relatively small amount (Figure 4A). Bioelectricity production is increased relative to the 500 scenario, but the magnitude of the change is small (Figure 4C).



IMITS



Panel C: Change in Electricity Production from 500











Figure 4: The effect of near-term policy on renewables, primary energy, electricity, and liquids in North America in 2020



4.4.3 China+

IMITS

In 2020, China+ has an emissions intensity target (40% reduction from 2005 in the RefPol case, and 45% reduction from 2005 in the StrPol cases), a renewable energy policy (25% of electricity), and technology capacity targets (200 GW of wind, 50 GW of PV, and 41 GW of nuclear in the RefPol-500; 300 GW of wind, 80 GW of PV, and 80 GW of nuclear in the StrPol-500). The China+ carbon price with near-term policies (RefPol-500, RefPol2030-500, and StrPol-500) is lower than the 500 scenario in almost all scenarios (TIAM-ECN StrPol-500 is the sole exception). Therefore, the largest changes in energy consumption are not bioenergy related (Figure 5B). For example, there are large increases in coal use compared to the 500 scenario in many models due to the lower carbon price. And, there are increases in non-biomass renewable electricity generation due to technology targets and the renewable electricity standards (Figure 5C).





Panel C: Change in Electricity Production from 500

12





Figure 5: The effect of near-term policy on renewables, primary energy, electricity, and liquids in China+ in 2020



4.4.4 India+

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In 2020, India+ has an emissions intensity target (20% reduction from 2005 in the RefPol cases, and 25% reduction from 2005 in the StrPol cases) and technology capacity targets (20 GW of wind, 10 GW of solar, and 10 GW of nuclear in the RefPol-500; 40 GW of wind, 20 GW of solar, and 20 GW of nuclear in the StrPol-500). The India+ carbon price with near-term policies (RefPol-500, RefPol2030-500, and StrPol-500) is lower than the 500 scenario in all models and scenarios. Therefore, like China+, the largest changes in energy consumption are not bioenergy related (Figure 6B). Again, we observe large increases in coal use compared to the 500 scenario due to the lower carbon price and increases in non-biomass renewable electricity generation and nuclear power in some models due to technology targets (Figure 6C).



Panel C: Change in Electricity Production from 500









Figure 6: The effect of near-term policy on renewables, primary energy, electricity, and liquids in India+ in 2020







4.5 The Effect of the Near-Term LIMITS Policy on Bioenergy in 2100

After 2020 (2030 in the RefPol2030-500), the only policy remaining is a globally harmonized carbon price, just as in the 500 scenario. Bioenergy consumption will vary across scenarios in the long-term due to differences in carbon prices and differences in existing long-lived capital as a result of investments made to meet the 2020 policy targets.⁸

The effect of near-term policy on long-term carbon prices varies across models (Figure 7). GCAM and IMAGE show little difference in 2100 carbon prices across the scenarios analyzed. For REMIND, WITCH, MESSAGE, near-term policy increases long-term carbon prices. The increase is most pronounced in RefPol2030-500. This increase implies that the imposition of these specific near term policies may have an impact on long-term economic efficiency of the global climate mitigation policy, though there may be other important justifications for these near-term policies. For TIAM-ECN, near-term policy decreases long-term carbon price. In TIAM-ECN scenarios, the regional carbon price in the near term policies are much higher than the global 500 scenario for North America and somewhat higher elsewhere, as seen in Figure 2. This higher level of near-term carbon pricing offsets the carbon price and mitigation amounts required in the rest of the century to meet the target.

⁸ Constraints on bioenergy consumption in some models may prohibit responses to carbon prices.





Figure 7: Global carbon price in 2100

MITS

Looking at global bioenergy results across the scenarios in the year 2100 (Figure 8), we only observe differences in 2100 bioenergy consumption in IMAGE and WITCH. WITCH has very modest increases in all near-term policy cases with respect to the 500 scenario, corresponding to the higher carbon prices. IMAGE has slightly less bioenergy in the RefPol-500 and slightly more bioenergy in the StrPol-500 scenario, but the differences in these levels, as well as the carbon prices levels, is not significant. For GCAM, bioenergy consumption is consistent across scenarios because the carbon price is nearly invariant. For REMIND, MESSAGE, and TIAM, bioenergy is constrained to an upper bound, preventing further deployment despite the different carbon prices.⁹ This figure also shows the amount of bioenergy is used with CCS. The models generally include CCS options in electricity and liquid fuel production, but CCS is assumed to be impractical or costlier in direct end use consumption of biosolids. In REMIND, all direct consumption of biosolids is driven out in the climate policy scenario by 2100, and all of the bioenergy deployed uses CCS. A similar effect is seen in GCAM and MESSAGE, though not to the same degree.

⁹ Prior to 2100, bioenergy consumption does vary across scenarios in REMIND, with higher bioenergy consumption in the scenarios with near-term policy.





Figure 8: Global Bioenergy Consumption in 2100

MITS

Finally, bioenergy must be considered and understood not alone but in the context of the entire energy system. By 2100, bioenergy is an important but not dominant source of energy in each of the scenarios for each of the models (Figure 9). From Figure 9A, although bioenergy with CCS is a major component of emissions mitigation in several of the models, it still only accounts for about 20-30% of total primary energy in the GCAM ad REMIND results, the models with the highest use of bio CCS. In all scenarios in all models, most of the rest of the energy system is decarbonized with CCS on coal and gas, other renewables, and increased use of nuclear power in some models. An examination of the differences in the sectoral energy composition sheds more light on the differences in bioenergy and the primary energy mix among the models (Figure 9B, 9C, and 9D). For electricity production, GCAM shows a mix of sources among fossil fuel and bioenergy with CCS, as well as a substantial amount of nuclear and renewables. IMAGE and WITCH have a similar mix to GCAM, but much lower amounts of final electricity demand. MESSAGE is the only other model that assumes a large role for nuclear power. In both MESSAGE and REMIND electricity generation is dominated by renewables, with little to no bioenergy, which is instead used extensively with CCS for liquid fuels. GCAM is the only one of the models to use bioenergy with CCS extensively for both electricity and liquid fuels. Though





neither WITCH nor IMAGE model technologies for bioenergy with CCS for liquid fuels, their responses to the policy are quite different from each other. WITCH uses the highest amount of bioliquids, while IMAGE shows a decreased reliance on liquid fuels. Instead, final energy in IMAGE is comprised of biosolids and hydrogen, in addition to electricity. TIAM-ECN illustrates a similar mitigation pathway by relying less on liquid fuels and more on gas (methane) and hydrogen for final energy, in addition to electricity.







4.6 Discussion

IMITS

The LIMITS scenarios have proven useful for exploring a range of outcomes for bioenergy use in response to both regionally diverse near term policies and the transition to a longer-term global mitigation policy and target. The use of several models has provided a source of heterogeneity in terms of incorporating uncertain assumptions about future socioeconomics and technology, as well as different paradigms for how the world may respond to policies. The results have also highlighted the heterogeneity and versatility of bioenergy itself, with different types of resources and applications in several energy sectors. In large part due to this versatility, the contribution of bioenergy to climate mitigation is a robust response across all models, despite their differences.

4.7 References

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