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Executive summary

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Introduction

In LIMITS a large number of scenarios have been developed that look into the required changes in the energy and land system for not exceeding the 2˚C objective. In most cases, the results are presented in terms of changes in the future energy portfolio, future investment patterns and costs. In order to get more in-depth insights into the feasibility and technology implications of such scenarios we analysed these scenarios in more detail.

This report has a ditochomous set-up, consisting of four separate studies divided in chapters 1 to 4. In the first part, chapter 1 and 2 look more into the implications of a deep mitigation scenario. chapter 1 discusses the the required changes and implications for the energy system and infrastructure, while chapter 2 provides a more systematic comparison of future trends against historical rates of change using several indicators. Next, chapters 3 and 4 focus on specific aspects of the 2˚C transitions. First, chapter 3 focusses more explicitely on demand side potential by looking into the implications of lifestyle change in stringent mitigation scenarios. Supplementary to this work, a model comparison exercise is included in chapter 4 that assesses sectoral mitigation potential of non-CO_2 emission sources (CH_4, N_2O and fluorinated gases) as opposed to the more common energy-related CO_2 emission reductions.

Chapter 1: A Cross-Model Comparison of Global Long-Term Technology Diffusion under a 2˚C Climate Change Control Target

In this chapter the long-term global energy technology diffusion patterns required to reach a stringent climate change target with a maximum average atmospheric temperature increase of 2˚C are analysed. If the anthropogenic temperature increase is to be limited to 2˚C, total CO_2 emissions have to be reduced massively, so as to reach substantial negative values during the second half of the century. Particularly power sector CO_2 emissions should become deeply negative from around 2050 onwards in order to compensate for greenhouse gas emissions in other sectors where abatement is more costly. The annual additional capacity deployment intensity (expressed in GW/yr) for solar and wind energy until 2030 needs to be around that recently observed for coal-based power plants, and will have to be several times higher in the period 2030-2050. Relatively high agreement exists in terms of the aggregated low-carbon energy system cost requirements on the supply side until 2050, which amount to about 50 trillion US$.

Chapter 2: The feasibility and implications of future technology trajectories in 2°C scenarios

This chapter assesses the feasibility of required rates of change as depicted under the 2°C objective by comparing future patterns of energy system changes with what has been observed in historical records. Several change indicators have been analysed varying in terms of aggregation (technology-specific or energy system wide), time scale (short or long-term), representation (relative or absolute) and speed (per year or over a lifetime) and extent (single year or over a period of time). We find that modeled rates of change for capacity expansion are within the range of those observed historically for the following decade but increase to unprecedented levels after 2030. In terms of technology diffusion we find that modeled technology diffusion is generally more conservative under the 2°C objective. Coal with CCS and biomass with CCS show the shortest diffusion lifecycle, whereas renewable energy technologies require nearly a century to fully materialize (ranging between 60-80 years for solar PV and 75-90 years for wind). On the more aggregate energy system level it is confirmed that transformations in the energy system under 2°C constraints are increasingly diverging from historical norms. However, although comparing to historic values may give confidence for future trends on the short term, they do not provide any further insight on the potential of exceeding current day rates of change.

Chapter 3: The implications of lifestyle change in 2°C scenarios

Most model studies involve an abundance of technical solutions in order to meet the 2˚C climate target, such as negative emissions and advance technologies of energy efficiency and supply. However, studies including non-optimal situations have found the 2˚C target to become unattainable. This addresses the need to look more into non-economic and non-technological drivers of energy system transformations that have generally not been included in long-term emission scenario studies. This study implements a set of lifestyle change measures for residential energy use, mobility and waste management in an integrative assessment context to analyze the implications of lifestyle changes under baseline and 2˚C climate mitigation scenarios. We find that lifestyle change measures mostly affect the end-use sectors in the absence of more stringent climate target, and alone are insufficient to meet the 2˚C climate objective. However, by preemptively reducing the energy demand and transitioning to a greater electrified system, opportunities are unlocked for greening the more resilient sectors (such as the transport sector with substantial additional emission reductions) or for more cost-efficient mitigation under 2°C ambitions without introducing additional major changes to the energy infrastructure. Integrated assessment models generally do not explicitly model behaviour (embedding behavioural heterogeneity in e.g. stylizing behavior change through proxy indicators, price elasticity or exogenous data), hence further research is recommended in how to internalize behavior into integrative assessment studies.

Chapter 4: Understanding the contribution of non carbon dioxide gases in deep mitigation scenarios.

The combined 2010 emissions of methane (CH_4), nitrous oxide (N_2O) and the fluorinated gasses (F-gas) account for about 20-30% of total emissions and about 30% of radiative forcing. At the moment, most studies looking at reaching ambitious climate targets project the emission of carbon dioxide (CO_2) to be reduced to zero (or less) by the end of the century. In order to support effective climate policy strategies we provide a more in-depth look at the role of non-CO_2 emission sources (CH_4, N_2O and F-gases) in achieving deep mitigation targets (radiative forcing

target of 2.8 W/m^2 in 2100). This annex zooms in at the sectorial mitigation potential and the remaining non-CO_2 emissions by using a set of different global energy-environment models. We find that by the end of the century in the current deep mitigation scenarios non-CO_2 emissions could form the largest part of remaining greenhouse gas emissions. Most of the remaining methane emissions in 2100 in the climate mitigation scenario come from the livestock sector. Strong reductions are seen in the energy supply sector across all models. For N_2O, less reduction potential is seen compared to methane and the sectoral differences are larger between the models. It is concluded that remaining non-CO_2 emissions are critical for the feasibility of reaching ambitious climate targets and the associated costs.

Conclusions

Together, the studies demonstrate that the 2°C objective requires greater changes to the energy infrastructure than currently embedded in the Copenhagen pledges. CO_2 emissions have to be reduced much more substantially than so far professed – with the majority of emission reductions postponed till the later half of the century posing dependencies, and simultaneously uncertainties, on the development and utilization of several key technologies (i.e. bioenergy, carbon capture and storage). Although the projected rates on emission reductions and capacity expansion rates may be consistent with historical achievements on the short term, they start to deviate more significantly over time, exceeding values known to date for some indicators already by 2030. Lifestyle change could contribute in terms of easening the mitigation effort that needs to be induced by technology changes through energy demand reduction. Finally, non-CO_2 emissions are shown to become more critical over time in the attaining of the 2°C target with significant impact if reductions can be utilized.

1 A Cross-Model Comparison of Global Long-Term Technology Diffusion under a 2˚C Climate Change Control Target

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1.1 Introduction

Implementing strategies in order to keep temperature increase to less than 2°C will require substantial changes in the energy infrastructure and land use patterns in major economies. The question whether these changes are feasible is a major subject of debate. The analyses within the LIMITS project (see Kriegler et al., forthcoming) have shown that a large number of models conclude that the required changes are feasible in the context of models, but it should be noted that these models only account for technical and economic factors. There are many other factors that influence the feasibility of low greenhouse gas concentration targets in the 'real world' such as the outcomes of political processes and expected inertia in policy making (Van Vuuren and Stehfest, 2013; Staub-Kaminski et al, forthcoming). In fact, others have indicated serious concern that within the current policy setting the target is not feasible (Anderson and Bows, 2008).

One way to get some insight into the difficulties of the transition trajectories suggested by the model studies is to express results in terms of time trends for variables which can be compared to historical rates. This allows some assessment of feasibility. Some key studies include those of Van der Zwaan et al. (forthcoming), Wilson et al. (2013), Riahi et al. (2013) and Van Vuuren and Stehfest (2013). These studies have looked into the changes in terms of absolute capacity additions, relative changes in capacity (as percentage of the total system), annual changes in emissions and the annual greenhouse gas intensity improvement rates. Clearly, by using different variables these studies show quite different insights on the feasibility of transition pathways. For instance, Riahi et al. (2013) show that the rate of emission changes of the scenarios is unprecedented in history, except for brief periods such as during the collapse of the Former Soviet Union. Also Van Vuuren and Stehfest (2013) conclude that the annual rate at which such changes need to be implemented (6-8%) deviates considerable compared to historically proven achievable carbon intensity improvement rates (1-2%). Still, Asian regions managed to reach high decarbonization rates of 3–5 % per year during the late 1980s /early 1990s (Van Vuuren and Stehfest, 2013) - stimulated by high investment rates and structural change processes. Finally, Wilson et al. (2013) looked at the penetration of technologies in specific markets in relative terms. They find that future technology trajectories are not unlike the rather dramatic changes that occurred historically, such as the penetration of coal and oil into the existing energy systems.

In this deliverable we present the insights provided by the analysis of Van der Zwaan et al. (forthcoming). This method looks at absolute additions of capacity per technology. The advantage of this method is that it provides a rather detailed picture that can be directly compared to historical rates of change. It should be noted, however, that the method does not really account for the fact that the global energy system is growing – and that therefore, even without a transition towards a low carbon system, future capacity additions are likely to be higher than historical rates. In this deliverable, that has been published earlier as a research article, we inspect how much technological innovation is required if the international community follows weak or more stringent versions of the national policy 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. We examine which energy options should be phased out, as well as how fast, which others need to be expanded, and at what scale. In section 2 of this report 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 CO_2 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 CO_2 capture and storage (CCS), (5) the low-carbon technology costs required to achieve an ambitious climate change 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 public and private sectors.

1.2 Methodology

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. CO_2 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*., 2013; Rösler *et al*., 2013) and WITCH (Bosetti *et al*., 2006, 2009). In the figures reported in this article these models will often be referred to, for reasons of brevity, by their first two letters (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 an emissions-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 three main 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/m^2 in 2100 corresponds to a GHG concentration of approximately 450 ppmv in that year.

Base:	Baseline 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.
RefPol-450:	Reference regional climate policies (Copenhagen pledges) until 2020 and global coordinated action to 2.8 W/m^2 from 2020.

While we introduce several more scenarios later in this article, we focus mostly 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 (conditional plus unconditional) political pledges delivered in association with the UNFCCC Copenhagen Accord (2009) and apply to the entire 21st century. We find that 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 (unconditional) 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 RefPol-450, overshoot in terms of radiative forcing is allowed: in this scenario during several decades values of over 3.0 W/m^2 pertain before stabilization occurs at 2.8 W/m^2.

1.3 Results

1.3.1 CO_2 emissions

From the left plot in Figure 1 we see that a scenario with stringent regional climate policies (StrPol) leads to similar global CO_2 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 CO_2 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 (a few %) below their level today.

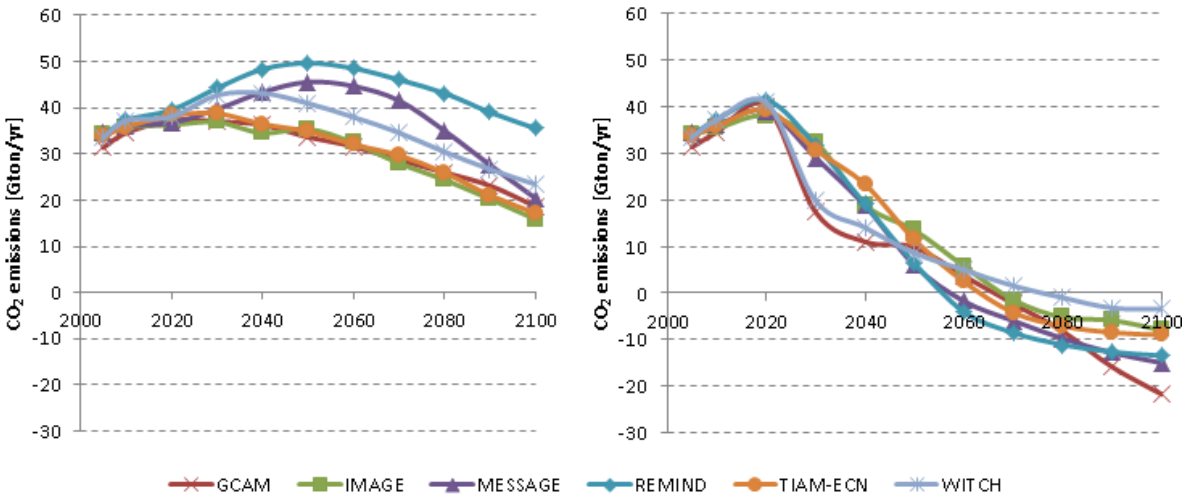


Figure 1. Global CO_2 emissions in scenarios StrPol (left) and RefPol-450 (right).

The variety in modelling outcomes is less large in the right plot of Figure 1 depicting CO_2 emission profiles matching a long-term global anthropogenic radiative forcing maximum of 2.8 W/m^2. CO_2 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/m^2 forcing target. For all models CO_2 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).

1.3.2 Primary energy

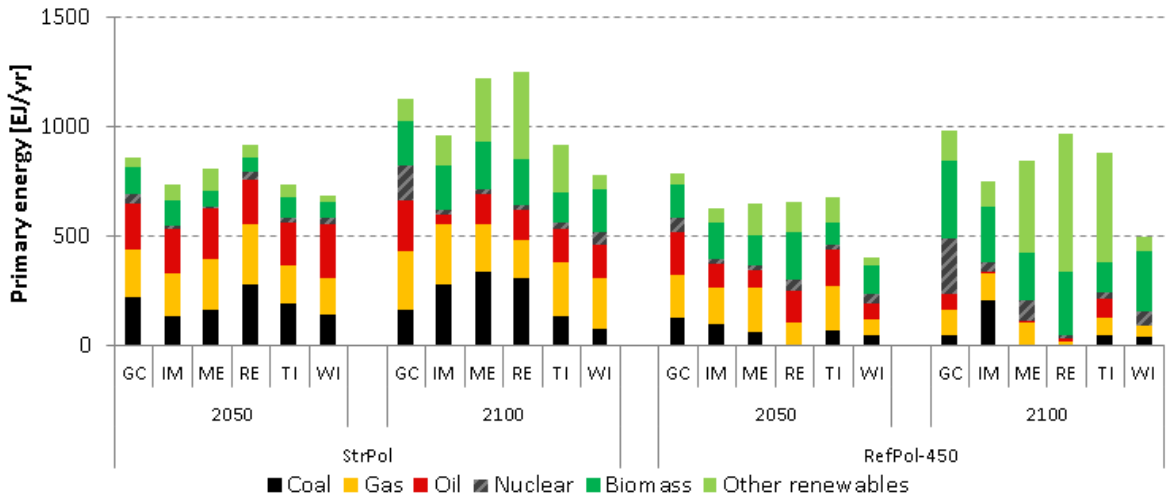


Figure 2. Global primary energy use in 2050 and 2100 in scenarios StrPol and RefPol-450.

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 CO_2 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/m^2 is targeted (right half of Figure 2), the differences between models in terms of global primary energy use are large in both 2050 and 2100. Coal is entirely phased out in REMIND and eventually also in MESSAGE, while it continues to play a role in the other models during the whole century (as we will see below though, it will essentially only do so if complemented with CCS technology). All models except REMIND (that projects an energy system in the long run almost entirely relying on biomass and other renewables) expect fossil fuels plus nuclear energy to account for at least ¼ up to ½ 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/m^2 climate control target can be achieved by using different GHG mitigation measures. From the right half of Figure 2 we can see that already in 2050 well over half of all primary energy for essentially all model simulations derives from low-carbon sources (when accounting for the fact that most of the coal and much of the natural gas use is complemented with CCS, and that biomass is all non-traditional). This is compatible with the target of the UN's Sustainable Energy for All initiative (UN, 2012), which encourages a doubling of renewable final energy shares by 2030.

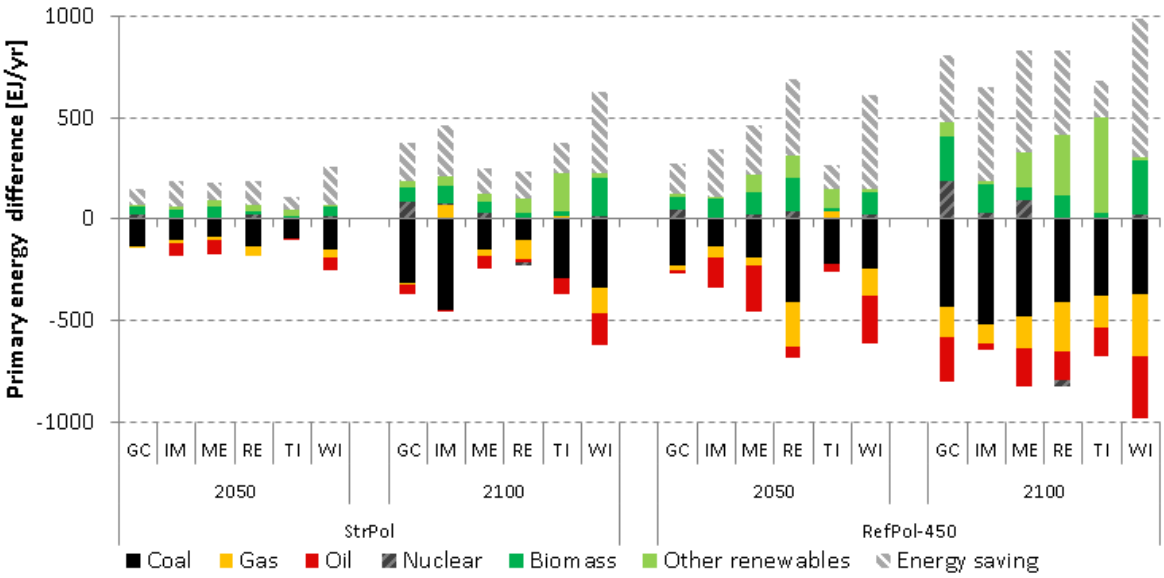
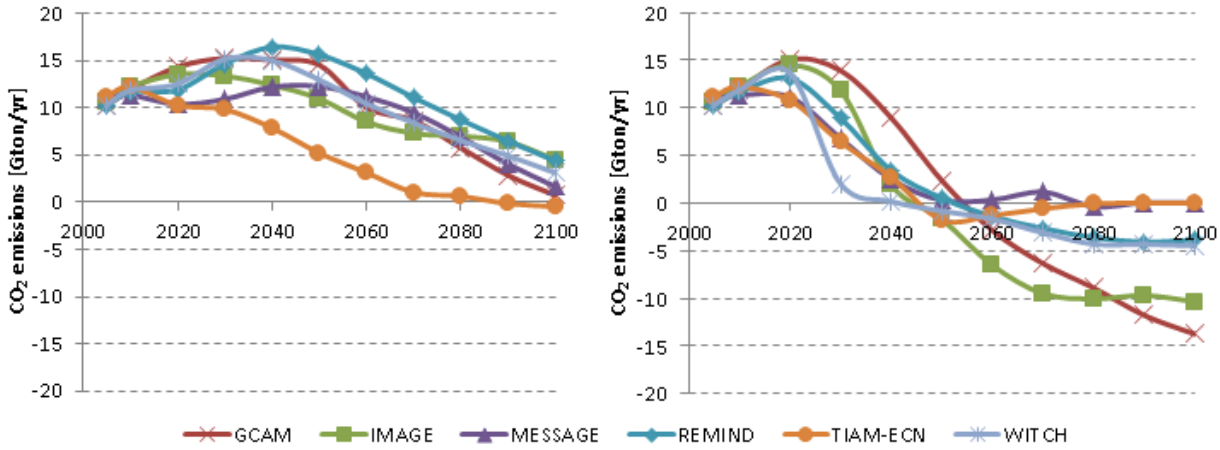


Figure 3. Global primary energy change from Base to scenarios StrPol and RefPol-450.

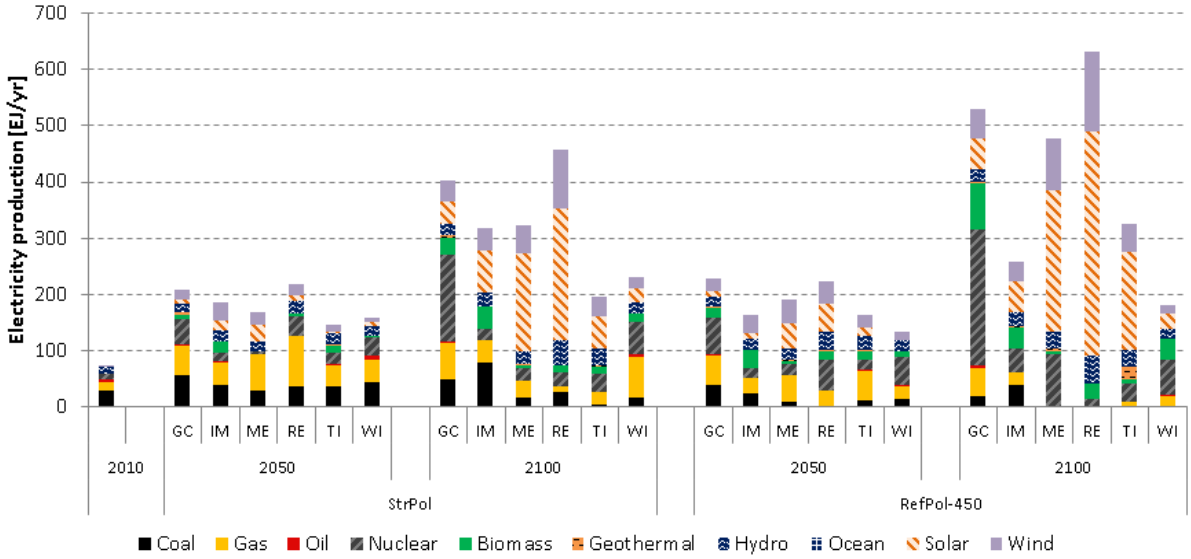
Besides differences, the models show some similar developments as well: for all models both the stringent climate policy and the 2.8 W/m^2 forcing target scenarios lead to a large reduction in the use of fossil fuels with respect to the baseline scenario, as can be seen in Figure 3. There is also clear 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 deployment (that is, with respect to the baseline) of (biomass plus non-biomass) renewable energy. These results match the increasing attention given to 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).

1.3.3 Electricity production

For power production, innovative technology deployment under a stringent climate policy regime is particularly pertinent, not only since it is among the largest CO_2 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 (a) the development of CO_2 emissions in the power sector, and (b) the overall electricity production level as well as the mix in contributions thereto, for our six models under two different climate control scenarios.



(a)



(b)

Figure 4. CO_2 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 CO_2 emissions by 2050 are about 0.4-1.4 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: CO_2 emissions decline in all models, to reach in 2100 at least less than 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/m^2 forcing target scenario the carbon intensity improvements develop faster: power production related CO_2 emissions drop to zero or negative levels around 2050 and decrease to substantial negative values around 2100 in all models except MESSAGE and TIAM-ECN. In the latter two

models essentially all biomass is directed toward industry and transportation, so that the use of biomass cannot be exploited to generate negative emissions in the power sector (in conjunction with CCS). Electricity production increases 3- to 9-fold between 2010 and 2100.

As we will also further see below, the reduction of CO_2 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 CO_2 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/m^2 forcing target scenario represent more than 50% of total power production. Nuclear energy possesses the largest share in the global electricity mix for GCAM, MESSAGE and WITCH, while for IMAGE most of the main mitigation options are rather equally distributed, with roles also reserved for fossil and biomass-based power plants equipped with CCS.

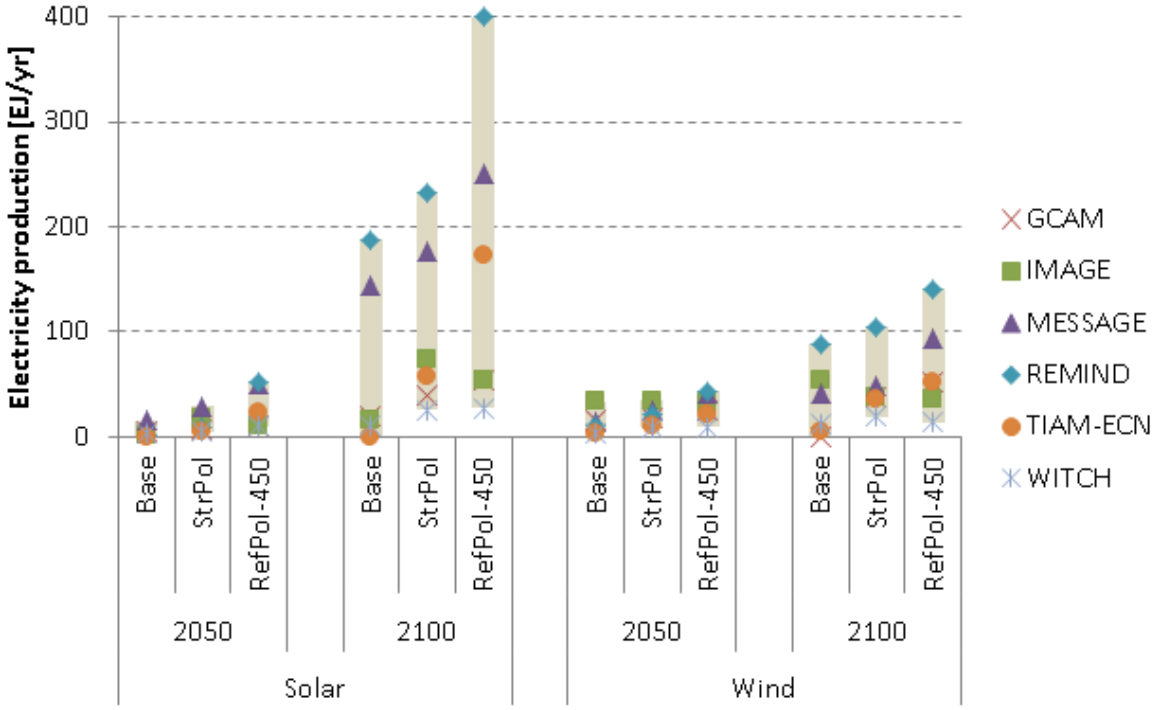


Figure 5. Electricity production from solar and wind energy in 2050 and 2100 in scenarios Base, StrPol and RefPol-450.

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/m^2 forcing 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. The high levels of solar and wind energy in especially models like REMIND and MESSAGE eventually require addressing issues of intermittency and could also have pervasive land-use implications (IPCC, 2011). Uncertain future developments regarding technology costs and performance imply large differences across models in assumptions regarding these variables, which are reflected in the large ranges depicted in Figure 5 for both solar and wind energy.

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 baseline (business-as-usual) scenario, but in WITCH this increase remains relatively limited with an electricity production level of about 27 EJ/yr. 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) in the 2.8 W/m^2 forcing target scenario wind energy technology generates about 3 times less power than solar energy technology in 2100. The uncertainty range for wind power amounts to more than 100 EJ/yr in 2100 in the 2.8 W/m^2 forcing target scenario, with the boundaries formed by REMIND and WITCH, like in the case of solar power.

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) required for 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. For solar energy a similar exponential expansion needs to materialize, but slightly delayed in comparison to that for wind energy, so as to receive its full momentum after 2030. The manufacturing and installation industry will need to prepare for the massive growth of both these renewable energy options. In the medium term, gas turbines (in the future equipped with CCS technology) and nuclear power plants will need to be deployed at about three respectively two times 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 more than 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 (GEA, 2012; IEA-ETP, 2012; IPCC, 2011). 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).

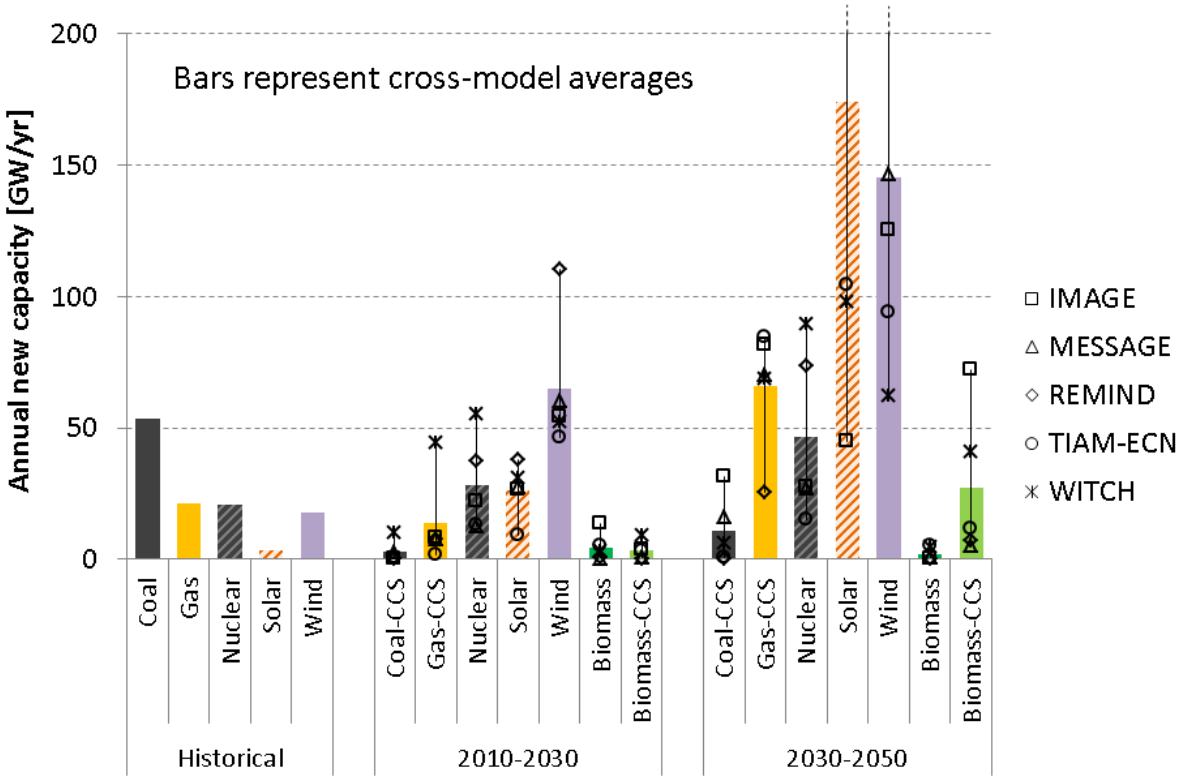


Figure 6. Average annual capacity additions (history and short to medium term future) for various fossil-based and low-carbon energy technologies in the RefPol-450 scenario.

N.B. Historical data correspond to 2000-2010, except for nuclear energy (1980-1990) and are assembled from: EPIA (2012), GWEC (2013), IEA-CCS (2012) and Platt's (2013). Two REMIND data points fall outside the scale of the figure: 400 and 300 GW/yr for solar resp. wind.

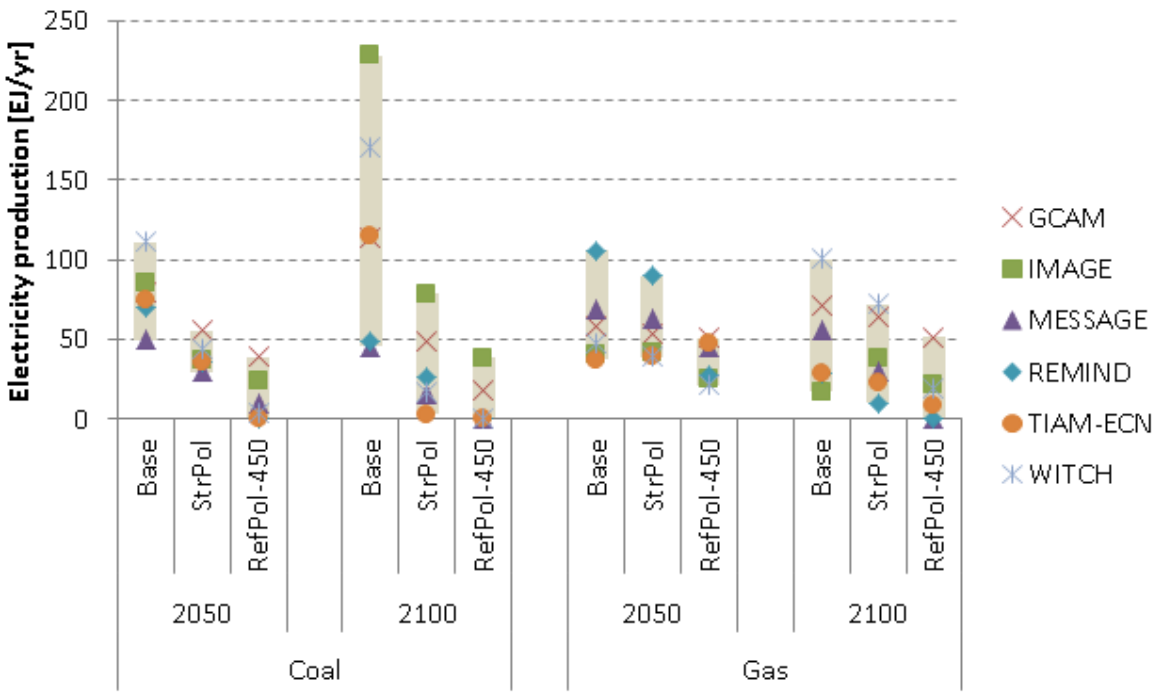


Figure 7. Electricity production from coal and gas plants in 2050 and 2100 in scenarios Base, StrPol and RefPol-450.

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/m^2 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 (since fossil-fuelled power plants and especially natural gas-based plants may be needed to provide flexibility or back-up capacity for operating the electricity system when intermittent renewable energy technologies are used broadly). Because of CCS, some models (such as IMAGE) 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 presumed 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 cases, while in 2100 in the 2.8 W/m^2 forcing target scenario MESSAGE also shows a large increase and IMAGE, TIAM-ECN and WITCH display middle-range nuclear expansions. 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).

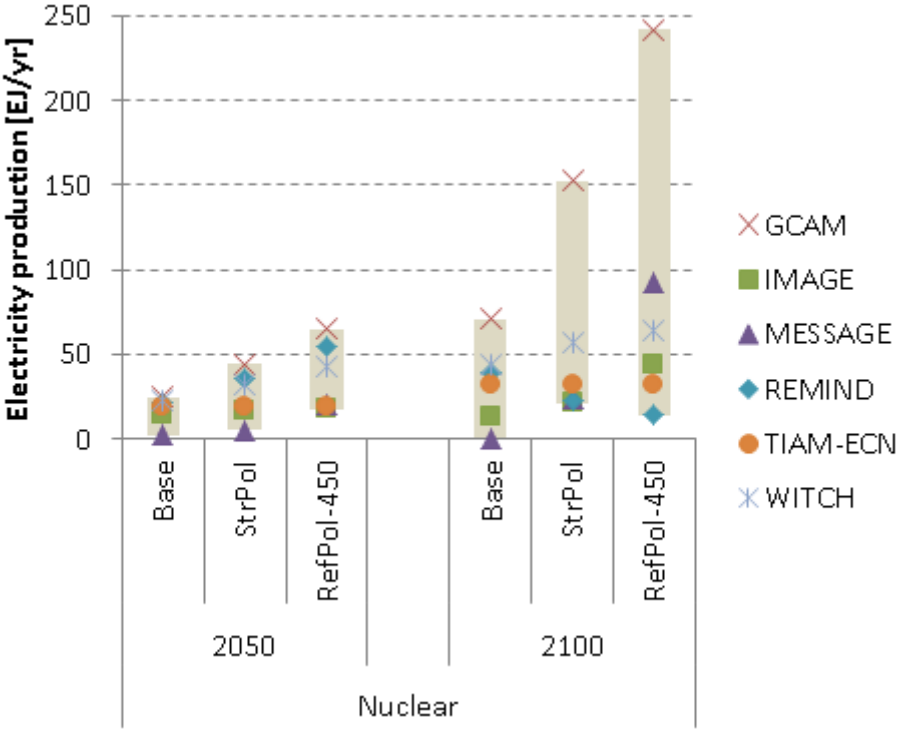


Figure 8. Nuclear power production in 2050 and 2100 in scenarios Base, StrPol and RefPol-450.

1.3.4 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 CO_2 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/m^2 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 CO_2 too high for reaching an ambitious climate control target, whereas CCS associated with biomass as combustion fuel can yield negative emissions.

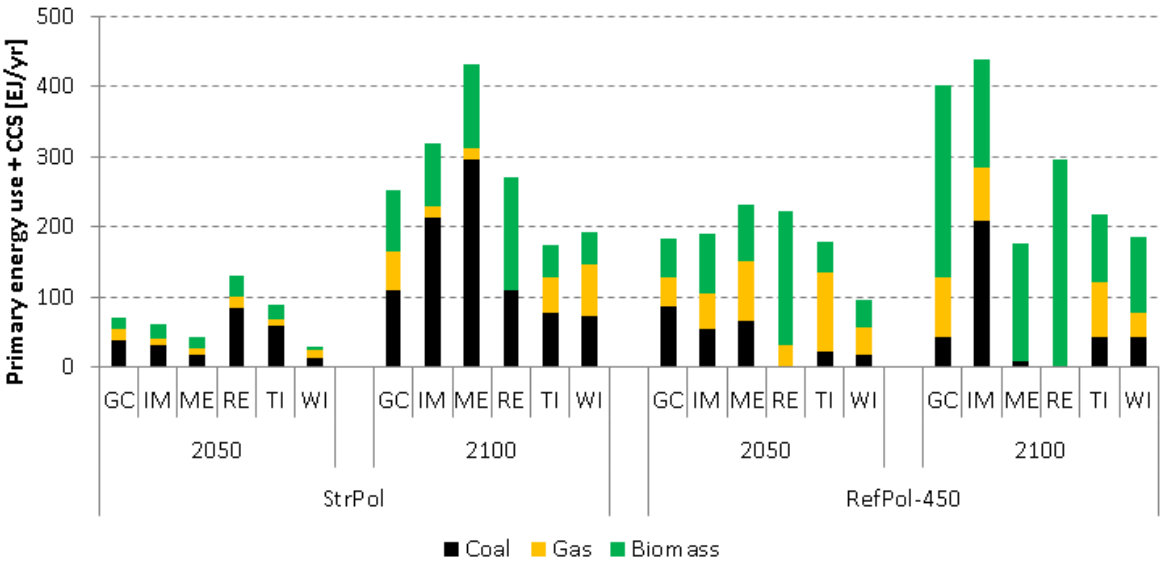
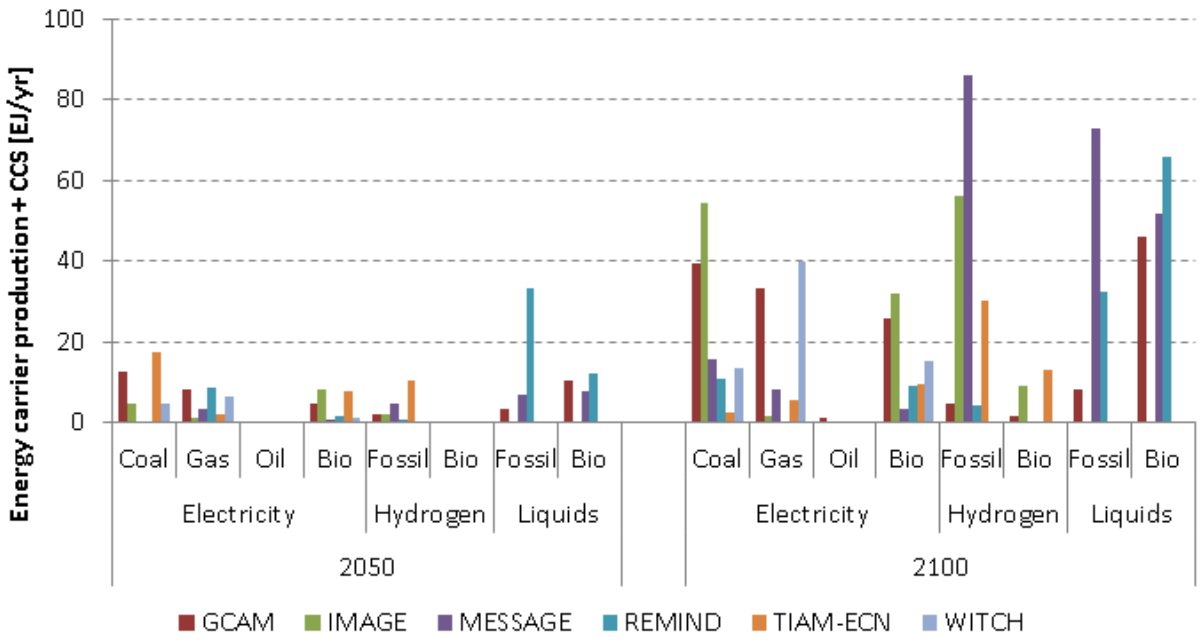
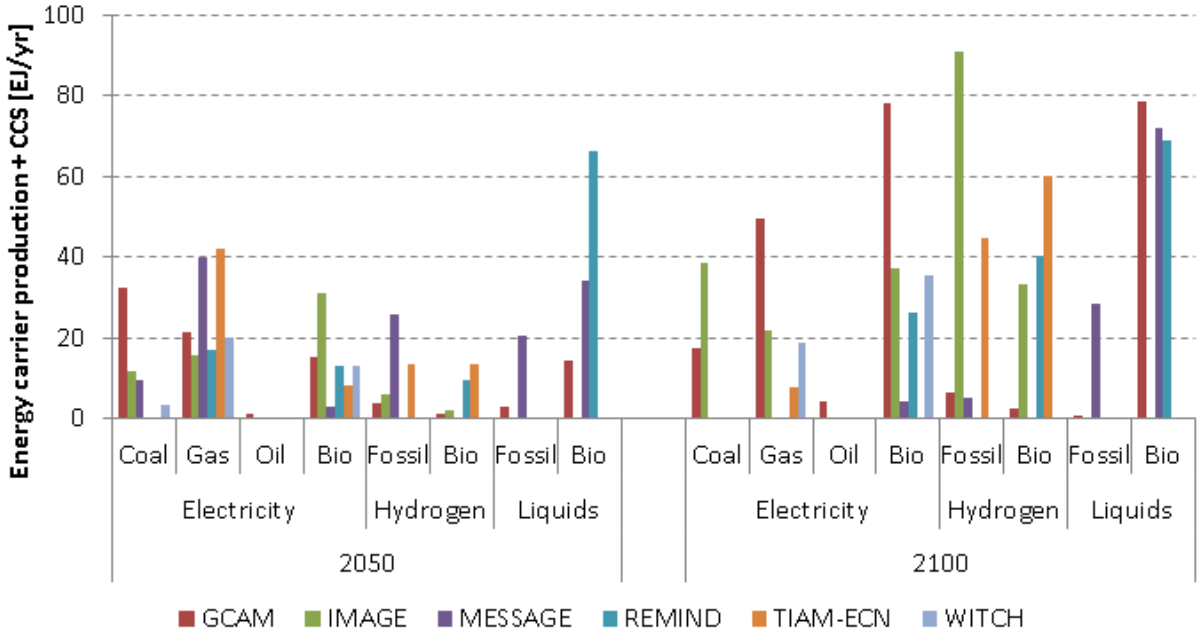


Figure 9. Primary energy use in combination with CCS in scenarios StrPol and RefPol-450.

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 fossil-based electricity production, probably because these models find large roles for renewables in the power sector. Consequently, as also demonstrated in Figure 10, these two models can reserve global geological CO_2 storage capacity to large extents 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) in most cases CCS for fossil options (notably natural gas) increases significantly when tightening CO_2 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/m^2 forcing target scenario, GCAM and IMAGE attain the highest usage of CCS aggregated over all applications.



(a) StrPol



(b) RefPol-450

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

1.3.5 Technology costs of reaching 2˚C

Since other articles in the LIMITS special issue (Kriegler et al., forthcoming) spend sizeable effort on, and/or are especially dedicated to, analysing the various cost dimensions of the energy system transformation required for the scenarios developed in the LIMITS project (such as Aboumahboub *et al*., 2013; Bowen et al., 2013; Kober *et al*., 2013; McCollum *et al*., 2013; Tavoni *et al*., 2013), we here only briefly highlight one main relevant technological economic aspect. For this purpose we add to our scenario set five more scenarios with common global action reaching climate stabilisation by 2100. Below are indicated all of this report's six scenarios in which climate stabilisation is reached, involving either of two distinct values for the radiative forcing target (2.8 W/m^2 resp. 3.2 W/m^2; for more details on these scenarios, see Kriegler *et al*., 2013). A climate stabilisation plan with a radiative forcing target of 3.2 W/m^2 in 2100 corresponds to a GHG concentration of approximately 500 ppmv in that year. In all these scenarios, overshoot in terms of radiative forcing is allowed.

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.

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 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 more deployment with associated 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/m^2 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 pledges type of policies. 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 in both plots, 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 in the right plot, but simulate cumulative installed capacity that diverges by about a factor of two. For nuclear energy, all data points lie pretty much on a linear diagonal through the origin of the plots, implying that the respective models adopt similar cost assumptions for these technologies. For the other energy technologies there is at least one model that deviates from a similar conclusion, indicating that cost assumptions for them may vary significantly across models. The aggregated costs resulting from the deployment of CCS, nuclear power, plus solar and wind energy capacity amount, over the 2010-2050 time frame, 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 a triplet of well-spread data points for solar energy that is more vertically oriented than for other models. This is a recognition of the fact that, with more modest cost reduction assumptions (that are exogenous – and not endogenous, in the absence of learning-by-doing effects), within the cluster of solar technologies larger capacity requirements imply a switch to different (more expensive) options, such as from CSP to PV, or necessitate a transition from low-cost potentials to high-cost potentials, like from solar energy in or close to the built environment to solar plants far away from human habitat.

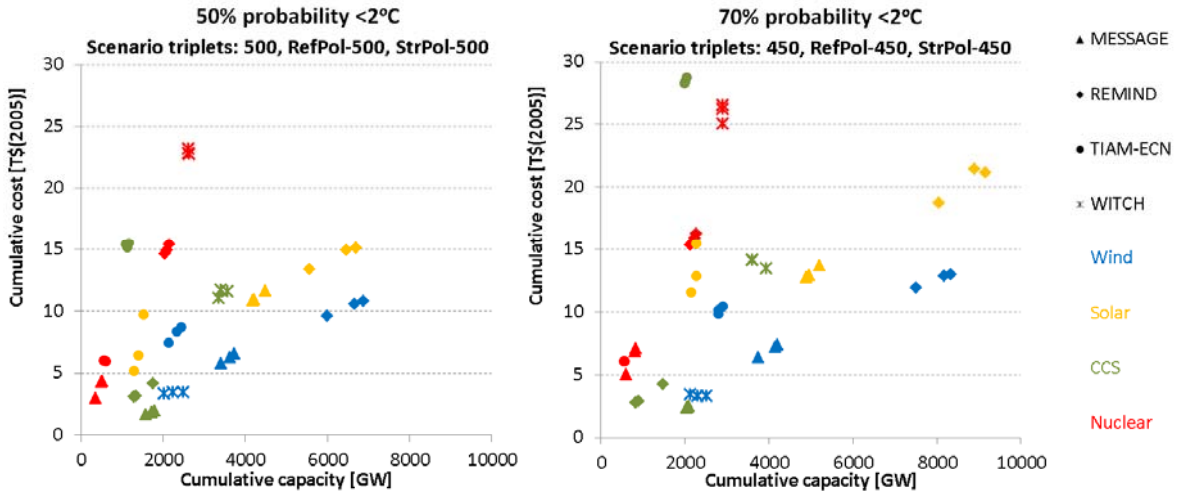


Figure 11. Cumulative cost versus capacity until 2050 for four low-carbon power supply options in scenarios 500, RefPol-500 and StrPol-500, respectively, scenarios 450, RefPol-450 and StrPol-450.

1.3.6 Transport sector

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*., 2013). These models differ thereby fundamentally from models dedicated only to the transport sector, in which new automotive options typically spread more quickly (see, for example, the micro-economic / market approach presented in Schäfer and Jacoby, 2006, and Schäfer *et al*., 2009). This article does not investigate the divergence in results on timing issues between these different methodological frameworks, but rather concentrates on the types of technologies that may, sooner or later, dominate in transportation. While our genre of

models may not be the most suitable to address timing issues regarding the introduction of new vehicle types in transportation, the important benefit of these models is that they are particularly fit for investigating linkages between for instance the energy and transport sectors. With regards to how these linkages are represented and analysed, we refer to, amongst others, Barreto *et al*. (2003), Hedenus *et al*. (2010), McCollum *et al*. (2012), Rösler *et al*. (2012), and Yeh and McCollum (2012).

As with many of the results reported above, our 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).

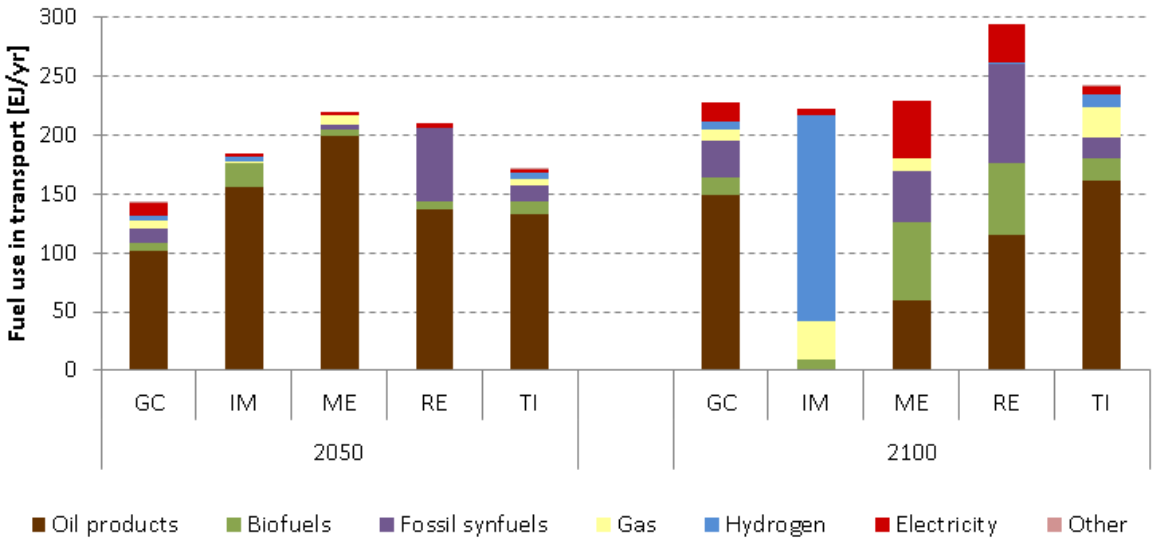


Figure 12. Fuel use in the transport sector in the Base scenario in 2050 and 2100.

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 to alternatives for traditional automotive fuels has been completed (as shown in the results for IMAGE in 2100 under the 2.8 W/m^2 forcing target scenario). All models agree that energy efficiency improvements and fuel savings possess

in the long run a higher importance than fuel switching in order to reach the 2˚C climate change control target. Whether natural gas, biofuels, electricity or hydrogen 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.

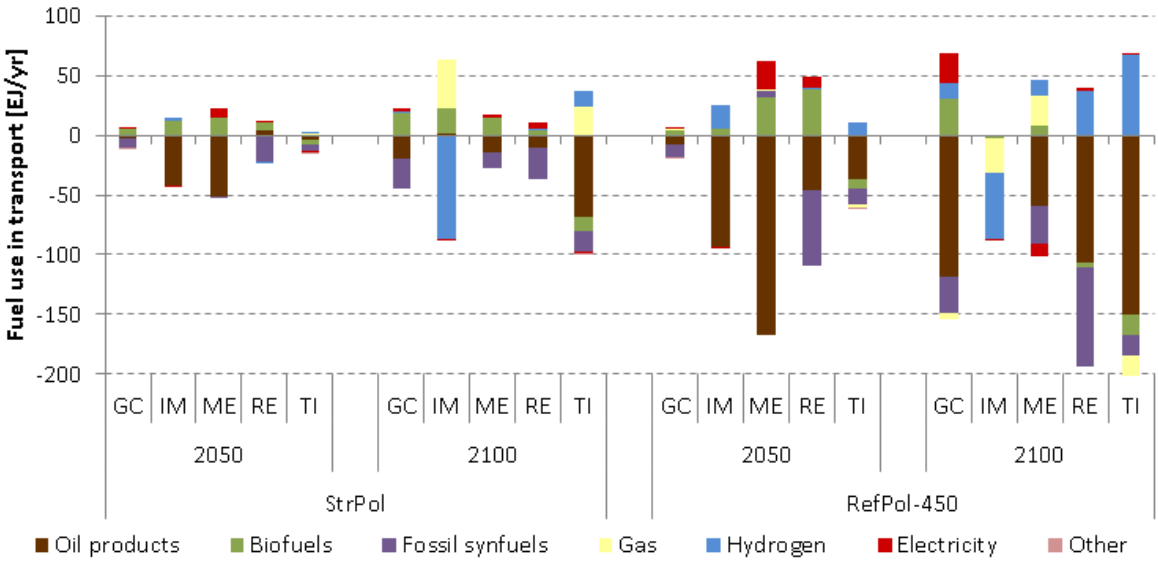


Figure 13. Difference in fuel use for transportation with respect to Base in StrPol and RefPol-450.

1.4 Discussion, conclusions and policy & strategy implications

Our first main finding is that the CO_2 emission reductions needed to reach a high probability to stay below a maximum global temperature increase of 2˚C are much deeper than those that correspond to even a significantly enhanced and extended version of the Copenhagen pledges. Indeed, if we are to stabilize the average anthropogenic temperature increase at 2˚C, CO_2 emissions have to be reduced much more substantially than so far professed: deep negative CO_2 emission values have to be reached during the second half of the century. In other words, not only do policy makers need to ascertain that the fragmented promises made during the UNFCCC summit in 2009 are matched with effective national climate control measures, the international community must imminently act in order to go well beyond these pledges, so as to guarantee the conclusion of a negotiated global climate treaty over the next couple of years that enables achieving much more ambitious emission abatement targets.

We also find that the role of most fossil-based primary energy resources needs to be substantially reduced today, and all of them during the 2nd half of the century. They do not need to be phased out, however, if a large-sale implementation of CCS materializes. In order to reach a broad diffusion of CCS, an important step is to move from the phase of CCS now having been proven on relatively small scales to the stage at which it is put to practice in large CO_2 point sources in industry and power production – we have not analysed the consequences of the possibility that CCS may never reach massive deployment maturity (see e.g. Riahi *et al*., 2013). The power sector should start generating negative CO_2 emissions from around 2050 in order to compensate for GHG emissions in other sectors where abatement is more costly. Such negative emissions can be achieved through e.g. biomass-CCS options in power production (see Calvin *et al*., 2013, this SI). As long as the large-scale use of biomass remains uncertain, however, other options to generate negative CO_2 emissions should also be investigated, including direct air capture devices (Keith *et al*., 2009; Lackner *et al*., 2012).

For large-scale low- or negative-CO_2 electricity generation, renewables like biomass, solar and wind energy dominate our present view of future global energy systems. Other options could also play a significant role, among which hydropower, tidal, wave and geothermal energy. Nuclear power cannot be ruled out, even while it remains troubled by concerns over radioactive waste, reactor accidents and weapons proliferation. Dedicated policy instruments can support the emergence of markets for renewables, such as subsidies, R&D programs, carbon pricing, feed-in 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 necessary changes involve shifts of hundreds of EJ/yr). This is an expression of the multitude of pathways available to establish a climate-neutral energy system. From a technology perspective, our model results strongly diverge in each of the scenarios we developed. This uncertainty in the energy system transformation process yields important implications for the public sector: except when local circumstances so dictate, for instance because of a lack of certain energy resources at the national level, policy makers may not necessarily want to pick winners today, since we do not (yet) know in all countries what the best, optimal, or most cost-effective GHG emissions abatement technology is. Certain is, however, that massive-scale emissions abatement must take place if the 2˚C target is to be met. We surely need to design policies so as to generically

stimulate the deployment of low-carbon energy options, while not *per se* selecting 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 notably wind energy until 2030 needs to be similar to that recently observed for coal-based power plants, and for both solar and wind energy will have to be several times higher than that between 2030 and 2050. Industry needs to prepare for this. According to all modelling teams CCS constitutes a large part of the climate mitigation technology mix and involves hundreds of EJ/yr of primary energy, but CCS may apply to different forms of resources (coal, gas and biomass) and types of energy carrier production (electricity, hydrogen and liquid fuels). Hence industry must undertake R&D to steer its decision process regarding where to commercially invest. Not only does uncertainty abound with regards to the technology type and diffusion extent of low-carbon energy alternatives that need to be deployed until 2050, but also concerning the respective cumulative costs involved. From our cross-model comparison exercise it is clear that high agreement exists in terms of the aggregated 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 e.g. McCollum *et al*., 2013; Kober *et al*., 2013, this SI). Many options exist to decarbonize transportation, but efficiency improvements and energy savings measures are probably of greatest importance to reach stringent climate control targets. Hence, switching to less carbon-intensive fuels has to be accompanied by lower energy consumption levels. It is unclear which of the currently competing new vehicle technologies will ultimately dominate, or whether a mix of options will serve the transformation of this sector best. Private sector R&D can help determining the optimal pathway.

Both the public and private sectors should thus stimulate respectively undertake technology-specific R&D, in order to prepare for the changes the energy sector needs to be subjected to over the next few decades. Modelling exercises like those presented in this report should be pursued to allow for energy systems analysis that instructs both these sectors on how to steer their planning and decision making processes. Subjects abound that are yet to be explored by integrated assessment models like ours. A question closely related to the theme of this article is what the realistically feasible and/or technologically permissible rates of change are that the required energy system transformation demands. Riahi *et al*. (2013), Wilson *et al*. (2010) and the present report proffer analyses inspecting different aspects of this topic – in terms of, respectively, historical values of CO_2 emission reduction rates, empirical numbers for technology diffusion and market share parameters, and observed figures for annual technology capacity deployment levels – which need to be further researched.

Acknowledgements

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References

Anderson, K, Bows-Larkin, A. (2008) Reframing the climate change challenge in light of post-2000 emission trends. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences* vol. 366 (1882) p. 3863-82

T. Aboumahboub, G. Luderer, E. Kriegler, M. Leimbach, N. Bauer, M. Pehl, L. Baumstark, 2013, "On the regional distribution of climate mitigation costs: the impact of delayed cooperative action", *Climate Change Economics*, forthcoming.

Barreto L., Makihira A., Riahi, K., 2003, "The hydrogen economy in the 21st century: A sustainable development scenario", *International Journal of Hydrogen Energy*, 28(3): 267-284.

Bauer, N., L. Baumstark, M. Leimbach, 2012a, The ReMIND-R model: the role of renewables in the low-carbon transformation—first-best vs. second-best worlds. Climatic Change 114:145–168. doi:10.1007/s10584-011-0129-2.

Bauer, N., R.J. Brecha, G. Luderer, 2012b, Economics of nuclear power and climate change mitigation policies. Proceedings of the National Academy of Sciences in press.

Bosetti, V., C. Carraro, M. Galeotti, E. Massetti and M. Tavoni (2006), "WITCH: A World Induced Technical Change Hybrid Model", *The Energy Journal*, Special Issue. Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down, 13-38.

Bosetti, V., E. De Cian, A. Sgobbi and M. Tavoni (2009), "The 2008 WITCH Model: New Model Features and Baseline", FEEM Working Study N. 85.2009.

Bowen, A., E. Campiglio, M. Tavoni, 2013, "A macroeconomic perspective on climate change mitigation: meeting the financing challenge", *Climate Change Economics*, forthcoming.

Calvin, K.V., *et al*., 2011, GCAM Wiki Documentation, https://wiki.umd.edu/gcam/.

Calvin, K.V., *et al*., 2013, "What is the role of bioenergy carbon mitigation?", *Climate Change Economics*, forthcoming.

Clarke, L., Krey, V., Weyant, J., Chaturvedi, V., 2012. Regional energy system variation in global models: Results from the Asian Modeling Exercise scenarios. Energy Econ. 34, S293–S305.

ENGO, 2012, "Perspective on Carbon Capture and Storage", Environmental Non-Government Organisation, ENGO Network on CCS, downloadable from www.engonetwork.org.

EPIA, 2012, European Photovoltaic Industry Association, *Global Market Outlook for Photovoltaics until 2016,* Brussels, Belgium.

GEA, 2012, *Global Energy Assessment*, IIASA (Laxenburg, Austria), Cambridge University Press, Cambridge, UK.

Glaser, A., 2011, "After Fukushima: Preparing for a More Uncertain Future of Nuclear Power", *The Electricity Journal*, July, 24, 6, 27-35.

GWEC, 2013, Global Wind Energy Council, Global Annual Installed Wind Capacity, obtained from: http://gwec.net/wp-content/uploads/2012/06/7Glob_ann_inst_wind_cap_1996-2011.jpg.

Hedenus, F., S. Karlsson, C. Azar, F. Sprei, 2010, "Cost-effective energy carriers for transport – the role of the energy supply system in a carbon-constrained world", *International Journal of Hydrogen Energy*, 35, 4638-4651.

IEA-CCS, 2012, International Energy Agency (IEA), OECD, *CCS RETROFIT Analysis of the Globally Installed Coal-Fired Power Plant Fleet*, Paris, France.

IEA-ETP, 2012, International Energy Agency (IEA), OECD, *Energy Technology Perspectives (ETP)*, Paris, France.

IEA-WEO, 2012, International Energy Agency (IEA), OECD, *World Energy Outlook (WEO)*, Paris, France.

IPCC, 2005, *Special Report on Carbon Dioxide Capture and Storage*, Working Group III, Intergovernmental Panel on Climate Change, Cambridge University Press.

IPCC, 2011, *Special Report on Renewable Energy Sources and Climate Change Mitigation*, Working Group III, Intergovernmental Panel on Climate Change, Cambridge University Press.

Keppo, I. and B.C.C. van der Zwaan, 2012, "The Impact of Uncertainty in Climate Targets and CO_2 Storage Availability on Long-Term Emissions Abatement", *Environmental Modeling and Assessment*, 17, 1/2, pp.177-191.

Keith, D.W., 2009, "Why capture CO_2 from the atmosphere?", *Science* 325:1654–1655.

Kober, T., B.C.C. van der Zwaan, H. Rösler, 2013, "Regional Burden Sharing Regimes for reaching a global long-term 2˚C Climate Change Control Target", *Climate Change Economics*, forthcoming.

Kriegler, E., M. Tavoni, T. Aboumahboub, G. Luderer, K. Calvin, G. DeMaere, V. Krey, K. Riahi, H. Rösler, M. Schaeffer, D. van Vuuren, 2013, "Can we still reach 2 degrees? The LIMITS study on mitigation pathways towards the 2 degree climate target", *Climate Change Economics*, forthcoming.

Lackner, K.S., S.A. Brennan, J. Matter, A.-H. A. Park, A. Wright, B.C.C. van der Zwaan, 2012, "The Urgency of the Development of CO_2 Capture from Ambient Air", *Proceedings of the National Academy of Sciences*, 109, 33, 13156-13162.

Leimbach, M., *et al*., 2010a, Mitigation Costs in a Globalized World: Climate Policy Analysis with ReMIND-R. Environmental Modeling and Assessment 15:155–173. doi:10.1007/s10666-009-9204-8.

Luderer, G., *et al*., 2012, Description of the ReMIND-R model. Technical Report, Potsdam Institute for Climate Impact Research. http://www.pik-potsdam.de/research/sustainable-solutions/models/remind/REMIND_Description.pdf.

McCollum, D., C. Yang, S. Yeh, J. Ogden, 2012, "Deep greenhouse gas reduction scenarios for California – strategic implications from the CA-TIMES energy-economic systems model", *Energy Strategy Reviews*, 1, 19-32.

McCollum, D., Nagai, Y., Riahi, K., Marangoni, G., Calvin, K., Pietzcker, R., van Vliet, J., van der Zwaan, B., 2013, "Investments, offsets, and incentives: an analysis of the 2°C target and what it takes to achieve it", *Climate Change Economics*, forthcoming.

MNP, 2006, Eds. A.F. Bouwman, T. Kram and K. Klein Goldewijk, "*Integrated modelling of global environmental change. An overview of IMAGE 2.4*." Netherlands Environmental Assessment Agency (MNP), Bilthoven, The Netherlands.

Platt's, 2013, World Power Plant Database, Scaling Dynamics of Energy Technologies Model, obtained from: International Institute for Applied System Analysis (IIASA), Vienna, Austria, http://www.iiasa.ac.at/web/home/research/researchPrograms/TransitionstoNewTechnologies/Scaling-Dynamics-of-Energy-Technologies1.en.html.

Riahi, K., A. Grübler, N. Nakicenovic, 2007, "Scenarios of long-term socio-economic and environmental development under climate stabilization", *Technological Forecasting and Social Change*, 74:887-935.

Riahi, K., E. Kriegler, N. Johnson, C. Bertram, M. den Elzen, J. Eom, M. Schaeffer, J. Edmonds, M. Isaac, V. Krey, T. Longden, G. Luderer, A. Méjean, D. L. McCollum, S. Mima, H. Turton, D.P. van Vuuren, K. Wada, V. Bosetti, P. Capros, P. Criqui, M. Kainuma, 2013, "Locked into Copenhagen Pledges – implications of short-term emission targets for the cost and feasibility of long-term climate goals", *Technological Forecasting and Social Change*, under review.

Rösler, H., B.C.C. van der Zwaan, I.J. Keppo and J.J.C. Bruggink, 2013, "Two Types of Transportation: Electricity versus Hydrogen under Stringent Climate Change Control", *under review*.

Schäfer, A., H.D. Jacoby, 2006, "Vehicle Technology Dynamics under CO2-Constraint: A General Equilibrium Analysis", *Energy Policy*, 34(9), 975-985.

Schäfer, A., J.B. Heywood, H.D. Jacoby, I.A. Waitz, 2009, *Transportation in a Climate-Constrained World*, MIT Press.

Staub-Kaminski, I, Zimmer, A, Jakob, M., Marschinski, R (Forthcoming) 'Climate Policy in Practice: A Typology of Obstacles and Implications for Integrated Assessment Modeling", *Climate Change Economics*, forthcoming

Sue Wing, I., 2006, "The synthesis of bottom-up and top-down approaches to climate policy modeling: Electric power technologies and the cost of limiting US CO_2 emissions", *Energy Policy*, 34, 18, 3847-3869.

Tavoni, M., E. Kriegler, T. Aboumahboub, K. Calvin, G. De Maere, J. Jewell, T. Kober, P. Lucas, G. Luderer, D. McCollum, G. Marangoni, K. Riahi, D. van Vuuren, 2013, "The distribution of the major economies' effort in the Durban platform scenarios", *Climate Change Economics*, forthcoming.

UN, 2012, "Sustainable Energy for All: A Framework for Action", United Nations, The Secretary-General's High-level Group on Sustainable Energy for All, New York.

UNEP, 2011, United Nations Environment Programme, "Bridging the Gap Report".

UNEP, 2012, United Nations Environment Programme, "The Emissions Gap Report 2012".

van der Zwaan, B.C.C., I.J. Keppo and F. Johnsson, 2013, "How to Decarbonize the Transport Sector?", *Energy Policy*, forthcoming.

van der Zwaan, B.C.C., "The Role of Nuclear Power in Mitigating Emissions from Electricity Generation", *Energy Strategies Review*, 1, 2013, 296-301.

van Vuuren, D.P., 2007, *"Energy systems and climate policy: Long-term scenarios for an uncertain future"*, PhD Dissertation, Utrecht University, The Netherlands.

van Vuuren, D.P., Hoogwijk, M., Barker, T., Riahi, K., Boeters, S. Chateau, J. Scrieciu, S., Vliet, J. van, Masui, T., Blok, K., Blomen, E., Kram, T., 2009, "Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials", *Energy Policy*, 37, 5125–5139.

van Vuuren, D., E. Stehfest, M.G.J. den Elzen, T. Kram, J. van Vliet, S. Deetman, M. Isaac, K. Klein Goldewijk, A. Hof, A. Mendoza Beltran, R. Oostenrijk, B. Ruijven, 2011, "RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C", *Climatic Change*, 109, 95–116.

Vuuren, D.P., Stehfest, E., 2013. If climate action becomes urgent: the importance of response times for various climate strategies. Clim. Change.

Wilson, C., A. Grübler, N. Bauer, V. Krey, K. Riahi, 2012, "Future capacity growth of energy technologies: are scenarios consistent with historical evidence?", *Climatic Change*, DOI 10.1007/s10584-012-0618-y.

Yeh, S., D. McCollum, 2011, "Optimizing the transportation climate mitigation wedge", ch.10 in *Sustainable Transportation Energy Pathways*, J. Ogden and L. Anderson, eds., Institute for Transportation Studies, UC Davis, California.

2 The feasibility and implications of future technology trajectories in 2°C scenarios

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2.1 Introduction

Implementing strategies in order to keep temperature increase to less than 2°C will require substantial changes in the energy infrastructure and land use patterns in major economies. Integrated assessment studies on mitigation scenarios can provide insights into the required changes in terms of emissions, the energy portfolio and land use – based on the type of factors accounted for in these models and the key assumptions that are made. In this context, it should be noted that most of the IAM models mostly focus on technological and economic factors. There is wide literature of studies based on these IAMs that conclude that the required transition for reaching the 2˚C target is feasible, obviously based on the factors taken into account these models and assuming that emission reductions can be reduced in the relative short-term in all important regions and sectors (e.g. Clarke *et al.* 2007, Kriegler *et al.* 2013, n.d., Riahi *et al.* 2013a, Weyant and Kriegler 2014). Models have also been used to test the feasibility of such changes under less idealised circumstances, for instance, assuming limits in technology availability or reduced participation in international climate policy. In those cases, some models would conclude that the 2˚C cannot be achieved, while other models would still be able to reduce emissions in line with the 2˚C target.

In the assessment of the "feasibility" of a target by IAM models several factors are accounted, such as constraints by technology lifetime, mitigation potential, inertia in investments patterns and costs constraints. However, many other factors are not included – such as for instance societal inertia, the time associated with decision-making prcesses etc. As such factors also played a role in historical rates of change, it is possible to get some insight into the "rate" of change in models by comparing them to historical changes. While there are many reasons why future changes may be different from those occurred in the past, at very least the historically observed rates of change may guide as an important reference in assessing the difficulties associated with these rates of change. Such comparison have been made in a number of recent studies using indcators that can be derived from the model results and from historical data (Wilson *et al.* 2012, Riahi *et al.* 2013, Van Vuuren *et al.* 2013, Zwaan *et al.* 2013). The methods in these studies are significantly different and lead to contrasting conclusions about the pace of change under 2°C. The former two elaborate on the pace of change by looking into changes in emissions per year either as absolute numbers or in terms of carbon intensity while comparing them to historical values. The latter two studies focus on the scale of change in capacity over time, for which (Zwaan *et al.* 2013) focus on the annual capacity expansion of various energy technologies in absolute terms on the medium-term while (Wilson *et al.* 2012) focus on the speed and extent of diffusion over the full lifecycle of technologies in comparison to historical achievements.

The goal of this study is to systematically compare various methods that use historical evidence as a basis for analysing scenario results and contrasting these different methods in a multi-model set-up. Questions that are addressed are:

- How do historical technology growth rates compare to future growth rates required in mitigation scenarios?
- Do various indicators of technology change depict a coherent storyline?

2.2 Methodology

2.2.1 Comparing historical and future rates of change

Comparing future patterns of energy system changes with what has been observed in the historical record offers a reference point of what is achievable. In literature, various change indicators have been developed for comparing historical to future rates of change, varying in terms of aggregation (technology-specific or energy system wide), time scale (short or long-term), representation (relative or absolute) and speed (per year or over a lifetime) and extent (single year or over a period of time) (for an overview, see table 1 and 2).

For example, (Zwaan *et al.* 2013) investigate historical and future capacity growth by comparing the average annual capacity additions (in GW/yr) for low-carbon technologies for the short-term (2010-2030) and medium-term (2030-2050). The study focuses on the rate of change required under 2°C assumptions compared to actual rates experienced during historical periods of rapid expansion for established technologies (e.g. natural gas power) or recent build rates for newer technologies (e.g., solar power). The comparison delivers a clear idea about the needed sustained expansion rate for future deployment and values are easily comparable to historical figures published in literature and online databases (e.g. (Platt's 2013, EPIA 2014, US EIA 2014)). However, although the methodology of (Zwaan *et al.* 2013) is rather straight-forward, the analysis is not embedded in a clear theoretical framework. The comparison of absolute future rates with historical rates can become less meaningful as it does not correct for the stage of development for specific technologies or the general growth in the size of the power system as historical experience suggests that energy transitions are characterized by massive increases in energy consumption (Fouquet and Pearson 2012). By using this approach (Zwaan *et al.* 2013) conclude, using this approach, that future global expansion rates need to increase significantly, reaching expansion rates beyond those observed historically in order to reach the 2°C target. In particular, the expansion of renewable energy technologies would be several fold the historical rate.

Wilson et al. (2012), compare historical and future dynamics of technological diffusion in the energy system by fitting logistic growth curves to cumulative capacity time series describing technologies' full lifecycle from early innovation to saturation. The advantage of using cumulative capacity over the technology lifecycle, as opposed to installed capacity or growth rates during particular time periods, is that short-term volatility and potential selection biases in the comparison periods are avoided. The logistic function parameters describing extent and duration of diffusion also allow cross-technology as well as within-technology comparisons. To account for the changing size and structure of the energy system, Wilson et al. (2012) normalize the extent of diffusion by the size of the energy system output at the inflection point of the logistic growth curve. The main disadvantage of this methodology is that it is not readily comparable to recent observations or to maximum short-term growth rates. Moreover, only historical and future technologies of which diffusion approximates known logistic growth profiles can be included in the analysis. This excludes, for example, wind and solar power with historical growth remaining broadly exponential with no evidence of a slowdown towards saturation. The results from the methodology by Wilson et al. (2012) show that the full lifecycles of power generation technologies diffusing in many scenarios have longer durations than those observed historically for any given

diffusion phase. However, the authors acknowledge several caveats, including the possibility that comparing long-run historical growth with long-run future growth in this way is problematic. Specifically for coal or nuclear power, which combine historical and future growth dynamics in the

Emissions decline rate or the decarbonisation rate (change in the emissions-GDP rate are also indicators that can be compared to historically observed values (Riahi *et al.* 2013, Van Vuuren *et al.* 2013). The advantage of using such highly aggregated indicators is that they capture all underlying detail, implicitly encompassing socio-economic dynamics like lifetime of technologies and infrastructure, scale effects, technological interrelatedness, the existence of niche markets, and the relative advantage of new versus incumbent technologies. The downside of this, is obviously that several details on underlying trends are not visible. Moreover, as emission reduction and decarbonization have not been policy goals in the past, the comparison to historical reference can be regarded as having limited relevance. The study by (Van Vuuren *et al.* 2013) concludes that on the basis of comparing to historical achievements, that emission reductions as well as decarbonization rates can be regarded as extremely rapid.

Table 1- overview of technology change indicators

Theme	Technology change indicator	Metric
Annual capacity addition [1]	Average annual capacity addition	GW/yr
Technology diffusion [2]	Eventual saturation of capacity growth	MW
	Size of the energy system (to normalize growth dynamics)	EJ
	Duration of capacity growth over full technology lifecycle	Years
Decarbonization rate [3]	Decadal average emission reduction rate	%
	Decarbonization rate	mtCO2/EJ

[1] (Zwaan *et al.* 2013)
[2] (Wilson *et al.* 2012)
[3] (Riahi *et al.* 2013, Van Vuuren *et al.* 2013)

Table 2- overview of applied comparison methodologies

Method	Aggregation	Time scale	Growth	Speed	Extent
Annual capacity addition	Technology specific	Variable (short-to-medium term)	Absolute	Annual	Cumulative
Technology diffusion	Technology specific	Full technology lifecycle	Relative	Lifetime	Cumulative
Decarbonization rate	Energy system	Variable (short-to-medium term)	Relative	Annual	N/A

2.2.2 Comparing future technological change to historical references

To assess how well scenario results compare to historical evidence, we apply a multi-model approach to provide projections of three scenarios with varying assumptions on long-term international climate policy. We use cumulative capacity data for coal, oil, gas, solar, wind nuclear and biomass to describe growth trajectories generated by five global energy-environment models with centennial timescales (e.g. REMIND: (Luderer *et al.* 2013); MESSAGE: (Messner and Strubegger 1995); IMAGE: (Bouwman *et al.* 2006); WITCH: (Bosetti *et al.* 2006); TIAM-ECN: (Keppo and Zwaan 2011)) (see table 3). The five energy-environment models represent a wide range of different approaches, including general equilibrium, partial equilibrium, dynamic recursive, perfect foresight and systems engineering. Moreover the models differ in model characteristics, coverage of sectors, disaggregation and definitions (economy wide or energy system) and baseline assumptions, to get an indication of the robustness in responses on the feasibility of the required changes in the energy infrastructure in a 2°C context.

Table 3 - key model characteristics

Name	Time horizon	Model category	Intertemporal Solution Methodology
IMAGE	2100	Partial equilibrium	Recursive dynamic
MESSAGE	2100	General equilibrium	Intertemporal optimization
REMIND	2100	General equilibrium	Intertemporal optimization
TIAM-ECN	2100	Partial equilibrium	Intertemporal optimization
WITCH	2100	General equilibrium	Intertemporal optimization

The scenarios that are used in this study are based on different policy assumptions for long-term international climate policy and have been developed as part of the LIMITS project (Kriegler, Tavoni, *et al.* 2013). The baseline (Base) scenario addresses the future energy system and emission developments in the absence of climate policy. Secondly, we assume a scenario that reflects current day (unilateral) climate policy implementation (RefPol), which is based on formulated 2020 national energy and climate targets reflecting the unconditional Copenhagen pledges. The scenario is extended after 2020 by assuming a similar national effort in the subsequent decades. Lastly, we assume a cost-optimal mitigation scenario that assumes immediate global cooperation (450).

The methods summarised in section 2.1 are systematically tested and comparatively assessed on a similar set of scenarios. To reconstruct a similar analysis as by (Zwaan *et al.* 2013), we compare the projections to historical rates of change over 10-year averages of maximal capacity expansion rates. For PV the historical rate of change is based on the total new installed capacity over 2003-2013 (EPIA 2014). Wind energy is based on the time period 2003-2013 (GWEC 2014), nuclear on 1980-1990 (Platts 2013), biomass on 2005-2011 (US EIA 2014) and fossil power on 2003-2012 (Platts, 2013). To accommodate for the methodology as described by Wilson et al. (2012) we have combined historical and future time series that began as early as the 1900s (natural gas and coal power), the 1950s (nuclear power), the 1970s (wind power and solar PV), or the 2020s or later (CCS). To compare with decarbonization rates, in line with (Van Vuuren *et al.* 2013), we depict 10-year average emission reduction rates in the 2010–2050 period. In parallel, we also look at the change in CO_2 emission reductions, similar to (Riahi *et al.* 2013).

2.3 Results

The following paragraphs focus on the depicted rate of change in future projections per methodology. Results are structured in such a way that historical achievements provide a benchmark value to which scenario outcomes are compared.

2.3.1 Annual capacity change

Fossil energy technologies are currently the dominant energy source in power production and remain in this position under limited or no climate policy. In the Base scenario the expansion rates in the 2010-2030 interval are more or less comparable as observed historically. Coal without CCS maintains a constant expansion rate whereas gas without CCS will nearly double its current annual capacity rate, matching and overtaking coal without CCS over time. Under climate constraints we find that coal without CCS is gradually phased out while gas is used as a transition fuel (RefPol) or follows a similar pathway as coal (450). In the medium-term (2030-2050) we find that projections of fossil fuel demand deviate more from historical observations. Under Base assumptions, both coal and gas without CCS will expand its growth to unprecedented levels. In the case of a 2°C objective, capacity growth of fossil fuels will gradually decrease or be supplemented with CCS facilities. CCS in particular, will make room for natural gas in the first half of the century, remaining within the limits of historical peak values. However, literature is indecisive if CCS can be employed sufficiently rapid on the short-term given issues with legal permission, business development, and public opinion. These are expected to be the main determinants of technological growth and not the technology in itself (Haszeldine 2009).

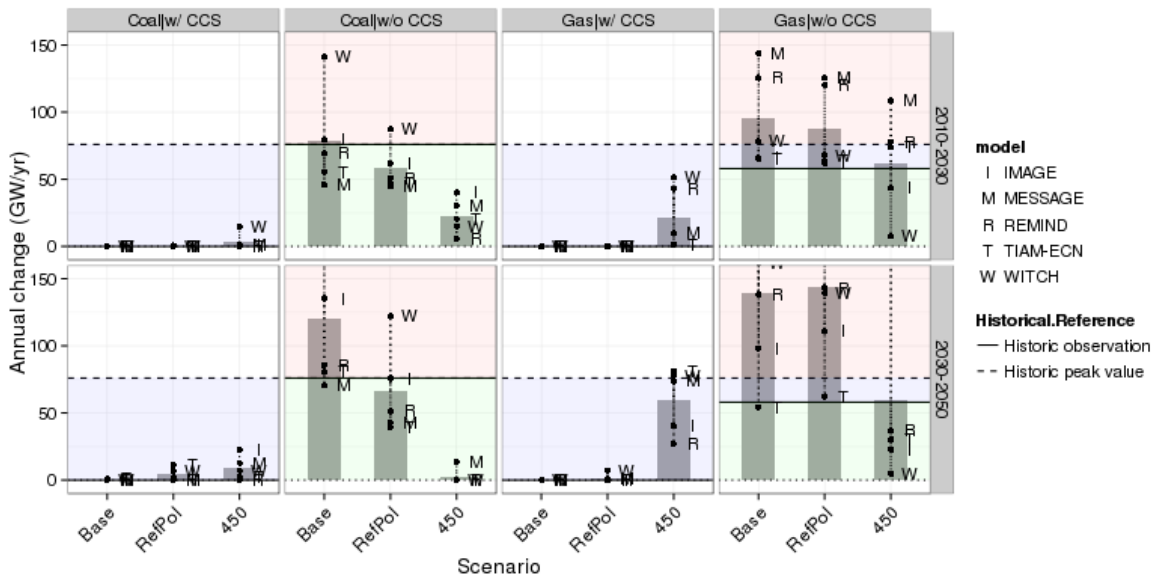

Figure 1 - Average annual capacity additions (over the 2010-2030 and 2030-2050 period) for various fossil-based energy technologies under various climate policy assumptions. Historical observation (solid line) represents the highest growth rate observed for the specific technology looked at, the historical peak value (dotted line) represents the highest reported growth rate(found in coal w/o CCS). Green area implies consistency with historical evidence, blue represents values within historic bounds and red implies beyond historic reference.

If we consider the short-term (2010-2030) average for non-hydro renewables, we find that the LIMITS models depict a modest growth for the coming decades. Although the expansion rates for PV wind and biomass seem to be in line with the historical 10-year average values, these do not compare to more recent developments. For example, already in 2013, 8 GW of non-hydro renewable technologies has been added globally, which is mainly due to favourable market conditions for solar PV created by feed-in tariffs in China and Japan (39 GW) (OECD/IEA 2014). This is in sheer contrast to model outcomes, which range between 55GW/yr (450) and 72GW/yr (RefPol) for non-hydropower technologies, despite having expanded 3-fold (RefPol) to 7-fold (450) in total cumulative capacity in 2030.

Nuclear projections seem in line with historically observed expansion rates. Short-term expansion rate projections may however be questioned considering the long lead-time for planning and building a nuclear plant and the increasing concerns about operational safety and proliferation risks. For example, the World Nuclear Association (World Nuclear Association 2014) reports that currently 52 reactors are under construction with a total capacity of 50 GWe and another 15 plants (covering in total 10 GWe) for planned construction starting between 2015-2019. From this, it can be concluded that the expansion rate will most likely not exceed the 3GW/yr on average under any climate objective for 2010-2030, which is much lower than the modeled 20-30 GW/yr.

On the longer term, during the 2030-2050 period, mitigation efforts increase as the annual additional non-hydro renewable energy capacity needs to have expanded to 152 GW/yr (RefPol) or 345 GW/yr (450). This doubles the annual capacity growth under unilateral conditions and leads to a 7-fold increase under 2C constraints compared to earlier decades. Across all models, the growth of solar and wind capacity is particularly strong, showing deployment rates above the historical peak value while even surpassing fossil power capacity under stringent climate policy assumptions. Hence, by strictly comparing these numbers to historically observed averages, it leads to believe that these values are beyond reach for the following decades. For nuclear energy, concerns exists regarding the feasibility of such annual additional capacity between 2030-2050, as governments would need to commit to a 40-fold increase in current nuclear capacity expansion within the next decade to materialize such a growth rate by 2030.

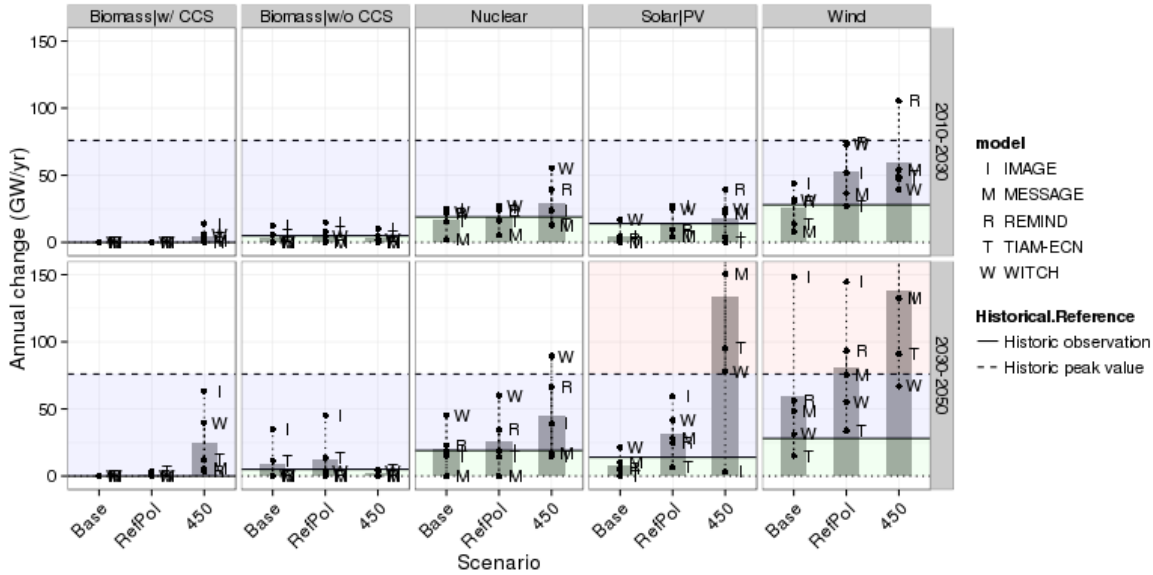

Figure 2 - Average annual capacity additions for various low-carbon energy technologies under various climate policy assumptions (over the 2010-2030 and 2030-2050 period). Historical observation (solid line) represents the highest growth rate observed for a technology, the historical peak value (dotted line) represents the highest reported growth rate (found in coal w/o CCS). Green area implies consistency with historical evidence, blue represents values within historic bounds and red implies beyond historic reference

2.3.2 Technology diffusion

Technology growth dynamics are characterized by S-shaped curves that follow step-wise stages of invention, innovation, and diffusion over time. Growth rates vary over the course of a lifecycle, showing to be slow at first until a lift-off point has reached and growth is accelerating. After some time technological development passes an inflection point after which growth rates levels-off and saturate (reducing growth to zero). We analyze the LIMITS scenario data with a similar methodology as applied in Wilson et al. (2013), by extracting parameters from the earlier mentioned S-curve logistic functions fitted to cumulative total capacity data (with a confidence level of 98% or higher). These parameters respectively represent the duration of growth (Δt, between 10% to 90% of saturation), the saturation point (the theoretical asymptote denoted as K) and the year of largest growth (Tm, inflection point)(see table 4 in Annex I).

We construct an extent - duration relationship (normalized K vs. Δt) of all electricity generation technologies for three LIMITS scenarios as shown in Fig. 3. Compared to historical extent-duration relationships, the scenarios show some conservatism, similar as observed in Wilson et al (2013). This becomes apparent from the longer than historically observed duration of growth of technology lifecycles in the scenarios (with maximum growth beyond 2100) at a similar extent. The stringency of climate policy shifts the construction of capital stock of coal without CCS, and to a smaller extent also gas without CCS. This results in a lower capacity saturation level, a shorter lifecycle, and some capacity reduction in the year in which maximum growth is achieved (see annex I).

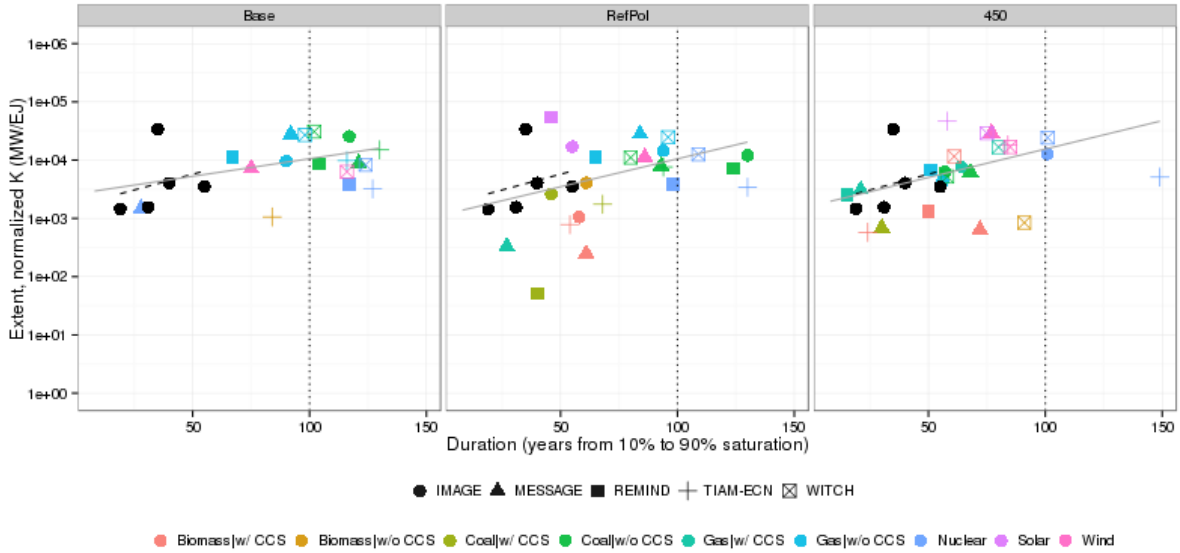

Figure 3 - Capacity growth of 9 energy technologies in 4 future scenarios of the 21st century: extent vs. duration of growth using fitted logistic function parameters. Grey line = linear regression line through all energy supply technologies. Dotted black line is a linear regression line through historical data of energy supply technologies.

Based on the results it can be seen that coal with CCS and biomass with CCS have the shortest duration ranges in the 450 scenario. If we consider stringent climate policy scenarios, then coal CCS reaches its global capacity saturation point within 30 years, whereas fossil CCS has an overall range of 20–75 years. This is similar to the historical range of saturation duration values across all technologies of 19–64 years. Moreover, biomass with CCS is projected to be fully materialized within a 25-72 years duration. Renewable energy technologies show a saturation range of 60-80 years for solar PV and 75-90 years for wind, under stringent climate policy considerations. Nuclear energy has its capacity saturation much later, even beyond the 21st century, due to its long lead-times and high costs relative to other low carbon electricity generation technologies. Differences between scenarios are greatest for fossil CCS and solar PV as these are most influenced by climate policy assumptions.

2.3.3 Decarbonization rates

By plotting the average decarbonization rate (carbon intensity reductions) compared to CO2 emission reductions we find that decarbonization rates are increasing under increasing climate policy assumptions. The decarbonization rates show a range of 1.4-2.3% under RefPol assumptions whereas the margins have expanded to 6-11% by 2050 if 2°C is to be attained at the end of the century. Historically, the global decarbonization rate has been around 0.5% over the period 1900–2010 and around 1% over the 1970–2010 (driven by technological improvement and sectoral shifts) (Van Vuuren *et al.* 2013). As only some Asian regions have managed to achieve decarbonization rates of 3–5% per year during the late 1980s/early 1990s, it would not only imply that the global community needs to match such rate by 2030 but also that the highest known decarbonization rate of today needs to be doubled by 2050 and maintained at the global scale.

In terms of average annual emission reductions, the range varies between 0-6% annually over the decades till 2050. In literature the highest values over a 50 year average under the 2°C objective is found to be around the order of 3.5-3.7% per year over the 2030-2050 interval (Riahi *et al.* 2013, Van Vuuren *et al.* 2013). Up till today only historical occurrences on a national level have led to higher reduction rates than the global average, such as observed in Sweden from 1974 to 2000 as a result of policy impulses on greening the Swedish energy system after the oil crisis in 1973 (2-3% per year). Another example is the emission decline of 2-4% per year for Eastern European and former Soviet Union countries after the collapse of the Soviet Union (Riahi *et al.* 2013). This gives the suggestion that sustained annual emission reductions will be difficult to attain.

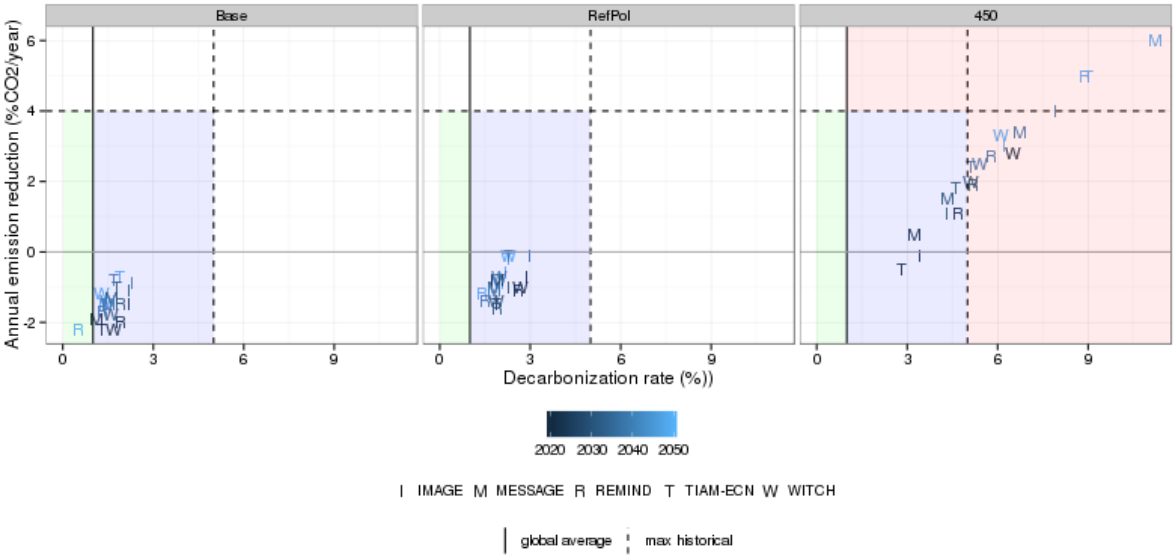

Figure 4 – Average annual emission reductions (per decade) versus average annual decarbonization rate per decade from 2010 to 2050. Negative numbers indicate emission increase. Green area implies consistency with historical evidence, blue represents values within historic bounds and red implies beyond historic reference

2.4 Discussion

2.4.1 Ambiguity in assessment methodologies

This study focuses on three different methods to assess the feasibility of technological change as depicted in 2°C constrained scenarios by looking at how well future rates of change compare to historical observed rates. Overall, we observe ambiguity in the results as one methodology emphasizes how expansion requirements go beyond rates ever experienced before, whereas the other methodology gives a more moderate view about the aspired changes in the energy supply and infrastructure. The differences in results can partially be explained by several limitations, such as (1) methodological and (2) modeling shortcomings, next to critical implementation barriers in real world situations that hamper technological growth that are currently not taken into consideration.

2.4.1.1 Methodological shortcomings

Some bias could be involved in the outcomes of the demonstrated comparison methodologies, as each method compares to various scopes in available historic data and controls only for a limited set of indicators that drive system transformations. For example, the chosen scope for study influences what rate of change is taken into consideration, as rates of change generally tend to be more rapid when the analysis is (1) technology-specific rather than system-wide (2) over the short-term (3) over smaller spatial scales. This is in particular true if one considers more absolute values for technological growth (such as the case if looking at absolute expansion rates) or when one benchmarks on more local achieved peak values (such as the case for the emission reduction rate).

Moreover, by selecting and using historical growth rates as reference points for future growth may not provide sufficient guidance on how technologies will evolve in the future. Projections of future technological growth may, for example, be biased towards incumbent technologies with rich historical data and historical comparison studies than highly innovative technologies, as projected growth is highly sensitive to both market size and stage of the diffusion lifecycle. This becomes in particular apparent in the Wilson et al (2013) comparison methodology, favouring technology projections with a very clear logistic growth profile. Similar holds true for historical emission reduction rates (or decarbonization rates), which may not be comparable to future projections as emission reductions were not incentivized in the past and thus give no clear indication of possible attainability of such rates of change.

Moreover, several indicators describing system transformations are currently not included in the demonstrated methodologies. For example, neither methodology provides any substantive insights on the economics of technological change (e.g. the steering of investments, economic constraints or the relation to overall regional economic developments). Moreover, by scrutinizing (additional) capacity growth it passes over technological decline rates which could be considered an important indicator of technological viability. For example (Höök *et al.* 2011) argue growth of the global energy system will become more challenging to sustain with increasing size.

2.4.1.2 Modeling shortcomings

Models are inherently limited in their representation of global dynamics, and highly dependent on the level of included technological detail (number of technologies included), underlying assumptions (on e.g. capital replacement) and structure of the model. Some authors therefore express criticism by posing that institutional conservatism plays a large role in the way technological developments of emerging energy technologies are modeled. This leads to a structural underestimation of utilizable technical potentials. It can therefore be argued that short-term projections of stringent climate policy scenarios are more in line with current day technology growth developments than actually considered under current day policies (De Vos and De Jager 2014). This position is supported in numerous studies that continuously report higher renewable energy or electricity penetration levels (>70%) across various regions throughout the world than originally projected (e.g. ECF 2010, German Advisory Council on the Environment 2011, Greenpeace 2012, Eurelectric 2013, IRENA 2014), implying that projections can potentially misrepresent available potential.

Moreover, models may not be able to anticipate on real world barriers such as technological, manufacturing, economic, institutional and socio-cultural barriers, which could become critical in achieving a transition that is consistent with the 2°C objective. For example:

- Technological barriers: 2°C scenarios depict a strong dependence on emerging renewable energy technologies and yet unproven technologies like bioenergy and carbon capture and storage (BECCS). These technologies contain several implementation and/or sustainability issues that could limit the price-competitiveness and performance on the market (IRENA 2014) and thereby influence the rate of potential change.
- Manufacturing barriers: Technological innovations have often led to greater resource consumption (UNEP International Resource Panel 2011). For most materials used in energy technologies, global stocks are still sufficient to meet the increasing future demand, but are rapidly becoming critical. Specifically for the production of solar photovoltaic and wind power technologies relatively large quantities of rare elements are used, of which several elements pose a high risk in jeopardizing the 2°C target due to shortages of resources (Moss *et al.* 2011).
- Institutional barriers: continuous changes in (1) the technology investment climate due to inconsistencies in governmental policy (IEA and International Energy Agency 2012) and (2) the movement away from state involvement towards more privatized and liberalized energy markets, could also pose a clear challenge in attaining the 2°C objective. It is therefore argued that much greater (sustained) governmental encouragement is required than ever employed in most past transitions (Fouquet and Pearson 2012). Several governmental tools can be employed, such as blending mandates, quotas, portfolio obligations, tax credits and feed-in tariffs (IEA 2013), to create a 'protected space' for new technologies to improve on price and performance (Jacobsson and Lauber 2006).
- Socio-cultural barriers: Another constraining factor in achieving ambitious government targets to increase the share of renewable energy in electricity production is social acceptance. Several renewable and carbon-free technologies have become subject of controversy in several countries, such as wind energy due to the visual impact on landscapes (the so-called NIMBY effect - Not In My Back Yard) and the negative effects on biodiversity (Wüstenhagen *et al.* 2007). Similar acceptance issues exist for carbon

capture and storage due to NIMBY-attitudes for storage related safety considerations (Terwel *et al.* 2012).

2.4.2 Expanding the scope of research

Lack of knowledge on complex and uncertain issues may lead to widely divergent outcomes of comparison methods. Hence, to further expand the knowledge on critical implementation barriers several prospective studies on technology development use expert elicitation protocols as a research tool to assess the feasibility of emerging (carbon-free) energy technologies (see for example Bosetti *et al.* 2012, Jenni *et al.* 2013, Fiorese *et al.* 2014). Experts can provide probabilistic information on the likelihood that technologies will overcome particular hurdles and estimate the overall probability of success for each technology (Baker *et al.* 2009).

Further study could also be included by expanding on the application of growth dynamic theories. For example (Kramer and Haigh 2009) describe two 'fundamental laws' that limit the build rate of new and existing energy technologies which have been fairly consistent across energy technologies. The first law describes how technologies grow for two decades at exponential rates (+/-26%/yr) until reaching 'materiality', defined as a +/-1% share of the global energy system. The second law states that after materiality, growth rates slow linearly to an eventual equilibrium market share. Although the expansion phase and the maturing growth phase characterized by (Wilson *et al.* 2012) broadly correspond with these 'fundamental laws', this could be studied in more detail.

2.5 Conclusion

In this study we have assessed the feasibility of 2°C scenarios by comparing future scenarios to historical trends. The analysis confronts scenario data from the LIMITS project to three methodologies that focus on different historical indicators of technology change, such as capacity expansion and changes in emission trends. The main conclusions of this analysis are:

How do historical technology growth rates compare to future growth rates required in mitigation scenarios?

We find that modeled rates of change for capacity expansion are within the range of those historically observed for the coming decade. On the short-term projections are considered more conservative than currently observed in reported achievements, but these increase to unprecedented levels after 2030. Across all models the growth of solar and wind capacity is particularly strong under 2°C constraints, showing deployment rates above the historical peak value of fossil fuels. By strictly comparing these numbers to historically observed averages, it leads to believe that these values are beyond our reach from 2030 and onwards. Specifically for nuclear energy, concern exists on the feasibility of such sustained annual additional capacity by 2030-2050 as governments would need to commit to a 40-fold increase in current nuclear capacity expansion rates within the next decade to materialize such a growth rate by 2030.

In terms of technology diffusion we find that modeled technology diffusion are considered more conservative, this becomes apparent in the longer durations of growth over full technology lifecycles than observed historically in future scenarios at a similar extent. The stringency of climate policy may influence the duration of technology diffusion but has a marginal effect on the extent to which technologies are employed. Coal with carbon capture and storage (CSS) and biomass with CCS show to have the shortest diffusion lifecycle, whereas renewable energy technologies require nearly a century to fully materialize (ranging between 60-80 years for solar PV and 75-90 years for wind). This suggests that to fully utilize the technological potential under 2°C objectives it would require nearly a century of technological growth and development.

On the more aggregate level we observe that transformations in the energy system under 2°C constraints are increasingly diverging from historical references. This poses several challenges for the global community, as the highest decarbonization rate ever achieved is exceeded already by 2030. Moreover, the highest known decarbonization rate of today needs to be doubled by 2050 and maintained at the global scale in order to attain the 2°C target.

Do various indicators of technology change depict a coherent storyline?

Overall we observe ambiguity in the results, as one methodology emphasizes how expansion requirements go beyond rates ever experienced before, whereas the other methodology gives a more moderate view about the projected changes in the energy supply and infrastructure. The studies have, however, several limitations due to the differences in, and restricted scope of, the comparison methodologies. Comparing historical growth with future growth is by its very nature a risky exercise, as technological

growth in scenarios are highly dependent on the scope of study in terms of underlying economic and technological assumptions, model structures and the included level of technological detail. Moreover, historic occurrences may provide only limited information on the achievable rate of change. Comparing to historic values may give confidence for future trends on the short term, but do not provide any further insight on the possibility of attaining rates of change that are unprecedented to current day practice.

Lack of knowledge on complex and uncertain issues may lead to deviating outcomes than presented in this study. Further research could be performed on the likelihood that technologies will overcome particular hurdles in these domains.

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References

Baker, E., Chon, H., and Keisler, J., 2009. Advanced solar R&D: Combining economic analysis with expert elicitations to inform climate policy. *Energy Economics*, 31, S37–S49.

Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., and Tavoni, M., 2006. WITCH: A World Induced Technical Change Hybrid Model. The Energy Journal, Special Issue: Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down.

Bosetti, V., Catenacci, M., Fiorese, G., and Verdolini, E., 2012. The future prospect of PV and CSP solar technologies: An expert elicitation survey. *Energy Policy*, 49, 308–317.

Bouwman, A.F., Kram, T., and Klein Goldewijk, K., 2006. *Integrated modelling of global environmental change. An overview of IMAGE 2.4*. Netherlands Environmental Assessment Agency. available at: www.mnp.nl\en, Bilthoven, The Netherlands.

Clarke, L., Kim, S.H., Edmonds, J.A., and Dooley, J., 2007. *Model Documentation for the MiniCAM Climate Change Science Program Stabilization Scenarios: CCSP Product 2.1a*.

ECF, 2010. *Roadmap 2050: A practical Guide to a Prosperous, Low-Carbon Europe*. 2010. European Climate Foundation, Brussels.

EPIA, 2014. *Global Market Outlook for Photovoltaics 2014-2018*.

Eurelectric, 2013. *Utilities: Powerhouses of Innovation - Full Report*.

Fiorese, G., Catenacci, M., Bosetti, V., and Verdolini, E., 2014. The power of biomass: Experts disclose the potential for success of bioenergy technologies. *Energy Policy*, 65, 94–114.

Fouquet, R. and Pearson, P.J.G., 2012. Past and prospective energy transitions: Insights from history. *Energy Policy*, 50, 1–7.

German Advisory Council on the Environment, 2011. Pathways Towards a 100% Renewable Electricity System [online]. Available from: http://www.umweltrat.de/SharedDocs/Downloads/EN/02_Special_Reports/2011_10_Special_Report_Pathways_renewables.pdf?__blob=publicationFile [Accessed 13 Sep 2014].

Greenpeace, 2012. *Energy Revolution: A Sustainable World Energy Outlook*.

GWEC, 2014. *Global Wind Statistics 2013*.

Haszeldine, R.S., 2009. Carbon capture and storage: how green can black be? *Science (New York, N.Y.)*, 325 (5948), 1647–52.

Höök, M., Li, J., Johansson, K., and Snowden, S., 2011. Growth Rates of Global Energy Systems and Future Outlooks. *Natural Resources Research*, 21 (1), 23–41.

IEA, 2013. *World Energy Outlook 2013*.

IEA and International Energy Agency, 2012. World Energy Outlook 2012, 1–690.

IRENA, 2014. *REmap 2030: A Renewable Energy Roadmap*.

Jacobsson, S. and Lauber, V., 2006. The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology. *Energy Policy*, 34 (3), 256–276.

Jenni, K.E., Baker, E.D., and Nemet, G.F., 2013. Expert elicitations of energy penalties for carbon capture technologies. *International Journal of Greenhouse Gas Control*, 12, 136–145.

Keppo, I. and Zwaan, B., 2011. The Impact of Uncertainty in Climate Targets and CO2 Storage Availability on Long-Term Emissions Abatement. *Environmental Modeling & Assessment*, 17 (1-2), 177–191.

Kramer, G.J. and Haigh, M., 2009. No quick switch to low-carbon energy. *Nature*, 462 (7273), 568–9.

Kriegler, E., Riahi, K., Bosetti, V., Capros, P., van Vuuren, D.P., Edenhofer, O., and Weyant, J., n.d. Editorial. *Climate Change Economics*.

Kriegler, E., Tavoni, M., Aboumahboub, T., Luderer, G., Demaere, G., Krey, V., Riahi, K., and Rosler, H., 2013. Can we still meet 2 ° C with global climate action ? The LIMITS study on implications of Durban Action Platform scenarios 1. *Climate Change Economics*, 282846.

Kriegler, E., Weyant, J.P., Blanford, G.J., Krey, V., Clarke, L., Edmonds, J., Fawcett, A., Luderer, G., Riahi, K., Richels, R., Rose, S.K., Tavoni, M., and Vuuren, D.P., 2013. The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*.

Luderer, G., Leimbach, M., Bauer, N., and Kriegler, E., 2013. *Description of the REMIND model (Version 1.5)*.

Messner, S. and Strubegger, M., 1995. *User's guide for MESSAGE III. Working Study WP-95-069. International Institute for Applied Systems Analysis (IIASA)*.

Moss, R., Tzimas, E., Kara, H., Willis, P., and Kooroshy, J., 2011. *Critical metals in Strategic Energy Technologies - Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies*.

OECD/IEA, 2014. *Renewable energy Medium-Term Market Report 2014*.

Platt's, 2013. *World Power Plant Database, Scaling Dynamics of Energy Technologies Model*.

Riahi, K., Kriegler, E., Johnson, N., Bertram, C., Den Elzen, M., Eom, J., Schaeffer, M., Edmonds, J., Isaac, M., Krey, V., Longden, T., Luderer, G., Méjean, A., McCollum, D., Mima, S., Turton, H., Van Vuuren, D.P., Wada, K., Bosetti, V., Capros, P., Criqui, P., Hamdi-Cherif, M., Kainuma, M., and Edenhofer, O., 2013. Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*.

Terwel, B.W., ter Mors, E., and Daamen, D.D.L., 2012. It's not only about safety: Beliefs and attitudes of 811 local residents regarding a CCS project in Barendrecht. *International Journal of Greenhouse Gas Control*, 9, 41–51.

UNEP International Resource Panel, 2011. *Decoupling natural resource use and environmental impacts from economic growth*.

US EIA, 2014. International Energy Statistics [online]. Available from: http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=2&pid=28&aid=7&cid=CG6,CG5,&syid=2005&eyid=2011&unit=MK [Accessed 5 Sep 2014].

De Vos, R. and De Jager, D., 2014. World Energy Outlook hides the real potential of renewables - EnergyPost.euEnergyPost.eu [online]. *Energy Post*. Available from: http://www.energypost.eu/world-energy-outlook-hides-real-potential-renewables/?utm_source=Energydesk+Daily+Email&utm_campaign=7cb3690e8c-Energydesk_Dispatch5_9_2013&utm_medium=email&utm_term=0_ad1a620334-7cb3690e8c-6099429 [Accessed 18 Sep 2014].

Van Vuuren, D.P., Stehfest, E., and Vuuren, D.P., 2013. If climate action becomes urgent: the importance of response times for various climate strategies. *Climatic Change*.

Weyant, J. and Kriegler, E., 2014. Preface and introduction to EMF 27. *Climatic Change*, 123 (3-4), 345–352.

Wilson, C., Grubler, a., Bauer, N., Krey, V., and Riahi, K., 2012. Future capacity growth of energy technologies: are scenarios consistent with historical evidence? *Climatic Change*, 118 (2), 381–395.

World Nuclear Association, 2014. WNA Reactor Database [online]. Available from: http://world-nuclear.org/nucleardatabase/rdResults.aspx?id=27569 [Accessed 21 Sep 2014].

Wüstenhagen, R., Wolsink, M., and Bürer, M.J., 2007. Social acceptance of renewable energy innovation: An introduction to the concept. *Energy Policy*, 35 (5), 2683–2691.

Zwaan, B.C.C. Van Der, Rösler, H., Kober, T., Aboumahboub, T., Calvin, K. V, Gernaat, D.E.H.J., Marangoni, G., and McCollum, D., 2013. A Cross-model Comparison of Global Long-term

Technology Diffusion under a 2 ˚ C Climate Change Control Target. *Climate Change Economics*, 1–17.

3 The implications of lifestyle change in 2°C scenarios

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3.1 Introduction

Scenario analysis shows that substantial emission reductions are required in order to not exceed 2˚C temperature increase. This will, in turn, require substantial changes in energy demand and supply and land-use. Overall, decrease rates of carbon intensity over the next three decades are needed that go well beyond historically observed rates (Kriegler et al. 2013; Van Vuuren and Stehfest 2013). Most model studies require very ambitious changes to be implemented to be able to meet the target, such as negative emissions from bioenergy with carbon capture and storage (BECCS), introduction of advanced technologies for energy efficiency and energy supply and increased material efficiency. It should be noted that most modeling studies explore such scenarios under so-called first-best world assumptions – expressing the mitigation potential under the assumption of full participation in climate policy and coverage of all sectors. However, implementation of necessary changes will be limited by various obstacles such as economic (e.g. vested interests and sunk investments), social (e.g. values and lifestyles, cognitive routines, alignment between social groups) and political factors (e.g. opposition to change from vested interests, uneven playing field) (Geels 2005; Hof et al. 2013; Cagno et al. 2013; Staub-Kaminski et al. 2014). In the past, this has often led to a reformulation of policy ambitions, such as the recent amendment of the European Union of their Energy Efficiency Directive in response to the lag in achieving the primary energy consumption reduction target of 20% by 2020 (EEA 2013). As a result, modeling studies have started to explore non-optimal situations (e.g. limitations in joint international commitments, instrumentation and availability of technologies) – which could potentially make the 2°C target unattainable (Rao et al. 2008; Tol 2009; Clarke et al. 2009; IEA and International Energy Agency 2012; van Vuuren et al. 2012; Stocker 2013). Interestingly, while the current debate on sustainable energy systems and climate change mitigation is largely dominated by technical and economic efficiency and clean energy strategies (Metz et al. 2007; Roy 2012), it may be questioned whether the global mitigation rates associated with the 2°C target can be met by focusing on technological changes alone.

Although assessment reports mention the notion of lifestyle change as an alternative way to reduce carbon emissions (Fisher et al. 2007), very little studies have evaluated the potential or implications of lifestyle and lifestyle change in global assessment modeling (Weber and Perrels 2000; Bernstein et al. 2007; Metz et al. 2007). As a result, it is also not clear how lifestyle changes relate to technical measures under strict climate control scenarios. This aim of this study is to explore the potential and the implications of lifestyle change in mitigation scenarios and to highlight the limitations of energy demand modelling. As we will discuss in Section 2, we are limited here by the possibility to represent lifestyle measures in models. Still, we contribute to the aim by exploring the following research questions:

- How can a specific set of lifestyle change measures contribute to reducing greenhouse gas emissions?
- How can lifestyle and lifestyle change be included in integrative assessment modeling?
- What barriers need to be overcome in order to successfully implement lifestyle measures in climate policies?

In section 2 we will address the research boundaries and introduce a framework of lifestyle change measures. Section 3 discusses scenario results, followed by contextual limitations in section 4. Section 5 will finalize with overall conclusions.

3.2 Methodology

3.2.1 Modelling framework

In order to explore the potential of changes in consumer behaviour and lifestyle change, we apply the Integrated Model to Assess the Global Environment (IMAGE) modeling framework. Within the IMAGE integrative assessment framework, long term dynamics of global change are modelled as a function of socioeconomic drivers (population, GDP) while given biophysical constraints and developments in the energy and agricultural system (Bouwman et al. 2006) are explored.

The framework consists of various system-dynamic sub-models, such as, among others, the energy model TIMER (van Vuuren et al. 2006), coupled to the climate policy model FAIR(SiMCaP) (den Elzen et al. 2007) and the land use model IMAGE (Bouwman et al. 2006). Within the energy model TIMER, the annual demand and supply of different energy carriers is described for a set of 26 world regions spanning till the end of the century. Changes in energy demand within the available sectors (industry, transport, residential, services, non-energy and other) are related to structural changes, autonomous and price-induced changes in energy intensity and price-based fuel substitution. The share of a certain service or technology in an economy are determined by a multinomial logit (MNL) equation, distinguishing for differences in relative costs and preferences per option (Van Vuuren et al. 2011). The FAIR model calculates the difference between baseline and global emission pathways using a cost-optimal approach involving regional marginal abatement cost (MAC) curves and combined with the SiMCaP pathfinder module uses an iterative procedure to find multi-gas emission paths that correspond to a predefined climate target (Van Vuuren et al. 2007). In the land use model of IMAGE, interactions between society, the biosphere and the climate system are represented to assess sustainability issues such as climate change, biodiversity and human well-being. Key inputs are the demand for food, feed, bio-energy and animal products.

3.2.2 Lifestyle change measures in integrative assessment modeling

Lifestyle is described by how individuals consume products and services, and the pattern of action involved in the consumption and disposal of these products and services (Bedford et al. 2004; DEFRA 2008; Roy and Pal 2009). The energy requirement to fulfill this pattern is considered an outcome of contemporary choices, preferences and decisions that do not comprise convenience and comfort of life. Changes in lifestyle are commonly embedded within changes in consumption patterns which can be expressed in changes in energy demand either through more (1) physically efficiency boosting actions or (2) curtailment measures (Gardner and Stern 2008; Gutowski et al. 2008) (von Borgstede et al. 2013). We consider physical energy efficiency improvement measures as options that require a single decision and up-front monetary costs. These behaviours are one-shot behaviours, typically involving the adoption of new technologies. Furthermore we define curtailments measures as options that requires some conscious effort to alter lifestyle and consumption levels, such as travel mode changes or downsizing on households size and cars (Dietz et al. 2009).

In this study we zoom in on curtailment measures as we consider this more true to conscious change in one's lifestyle, whereas energy efficiency improvement measures are considered to overlap with the more frequently studied technological improvements. However, global Integrated

Assessment Models (IAMs) are tools used for analytical projections of policy impacts and generally do not explicitly model individual behavioural decision making. In the IMAGE integrative assessment framework behavioural decision making is represented by (multinomial) logit functions which assign (market) shares to all the options based on relative costs of the service - thus imposing a price-based preference order. To some degree these costs are influenced by incorporating factors that represent non-energy related prices (such as consumer preferences or governmental policies in so-called 'preference' or 'premium' factors) although these originate from rather arbitrary calibration factors representing empirically unquantifiable (market) externalities (De Vries et al. 2001).

We classify curtailment behaviour as decisions determined by considerations other than costs, and thus incongruent with the classic method of behavioural decision making in energy modeling as described above. Some degree of non-price-based behavioural heterogeneity is integrated in the IMAGE-framework, but in a more static and ad-hoc way, such as calibrating on differences in energy demand per region (e.g. refrigeration energy use is explicitly different in the USA than for other regions, whereas floor space per capita is significant lower in Japan (Daioglou et al. 2012)) or applying constants that represent a certain exogenous trend within the model structure (e.g. fixed vehicle occupancy rates, discount rates, lifetimes).

3.2.3 Framework of lifestyle change measures

For the purpose of energy demand modeling we frame lifestyle change as an dependent variable for which housing, transport and waste recycling are considered the main drivers (Bedford et al. 2004; Daioglou et al. 2012; Girod et al. 2013) (OECD 2008). Below we describe the lifestyle change measures that have been selected from the literature and how these are translated to IMAGE integrative assessment framework model parameters. In Table 1 summarizes the key measures.

3.2.3.1 Residential energy

Space heating

- Reducing demand for cooling and heating

  The most common climatic indicator of the demand for heating and cooling services is the degree day (DD, in °C/yr), describing the number of degrees per day above or below a certain base temperature (which may vary for heating and for cooling) (Isaac and van Vuuren 2009). We assume a behavioural change in which a user accepts a difference to the desired (room) temperature by adapting the base temperature of 18 degrees by 1°C downwards (for space heating) or 1°C upwards (for space cooling).
- Capping household dimensions

  For most countries, larger dwelling sizes (0.7% increase in energy demand per annum) and lower occupancy rates (0.5% increase in energy demand per annum) have tended to drive up energy demand for space heating, offsetting reductions achieved through efficiency gains. Hence, limiting home size has been suggested as a measure in literature (Dietz et al. 2009). To approach this lifestyle change, we assume that with increasing affluence, the increase of floor space per capita is limited to 2010 levels of a representative developed region (EU). This scenario also explicitly differentiates between urban and rural regions, of which the values are set at 40 m^2/cap for urban households

and 50 m^2/cap for rural households (allowing regions with greater values to converge within a decade) (OECD/IEA 2004; Daioglou et al. 2012). The measure can also be seen as a limitation to the heated and/or air conditioned surface area in homes.

Water heating

- Reduced use of heated water

  Heating water uses about a third of the annual gas used for space heating, and is mainly done for activities such as, among others, showering, bathing and hand-washing. To reduce the energy needed for heating water, we assume a reduction of shower time of 2 minutes by applying a correction factor in total energy demand for water heating based on an estimate calculated from literature. By assuming an 8 minute shower, with a water throughput of 15 L/min (Wright 2011), an required temperature elevation of 50°C, and a 0.0011 kWh/L energy consumption per degree of water heating (Goodall 2007), on average, this could lead to a 25% energy reduction.

Appliance use

- Reduced rate of appliance ownership per household

  Large appliances such as refrigerators, freezers, washing machines, dishwashers and televisions account for around 50% of household electricity consumption in appliances. An important driver of appliance energy use is the rate of ownership. We adjust the ownership rate by fixing saturation levels for major domestic appliances and entertainment devices to current day ownership rates (irrespective of regional differentiation). For tumble dryers we assume they are gradually phased out over the decade leading to 2025 (Daioglou et al. 2012).
- Switch off standby mode

  Between 3 and 13% of residential electricity use in high-income regions can be attributed to standby power consumption (EEA 2005; de Almeida et al. 2011). Specifically office equipment (such as information and communication technologies) and entertainment devices (such as consumer appliances) have the largest share in standby energy demand (de Almeida et al. 2011). We assume an appliance standby energy use as listed in (Lawrence Berkeley National Laboratory 2013), and deduct this from the total average energy consumption per appliance category as described in (Daioglou et al. 2012).
- More efficient or smarter use of appliances

  A number of energy-conscious behaviour options can be considered for appliance, such as choosing different wash temperatures, maximizing washing load per cycle, switching off the oven or the hotplates before the end of a cooking period, locating 'cold' appliances wisely (e.g. not near an oven), cooling hot food before storing or thawing food in the refrigerator and keeping it filled up (or not to use 'over-dimensioned' appliances) (Wood and Newborough 2003; Geppert and Stamminger 2010). Due to varying reduction potentials in the various measures (see for an overview Geppert and Stamminger, 2010), we assume the BAT energy consumption for technology functions as a proxy for possible reduced energy demand per appliance category to simulate more effective use (Goodall 2007; Daioglou et al. 2012; Lawrence Berkeley National Laboratory 2013).

3.2.3.2 Transportation

- Reduced vehicle use

  As described in (Schafer and Victor 2000; Schäfer et al. 2009), individuals reserve a fixed proportion of income to traveling (travel money budget, TMB), which increases as the motorization rate (number of light duty vehicles per 1000 inhabitants) of a region increases. With increasing ownership of cars, the TMB increases till saturation is reached at 10-15%, as opposed to 3-5% in non-motorized (developing) regions. In order to dampen the increase of motorization (e.g. representing car sharing or carpooling), we cap the TMB to the reported value for Japan (7%) - as lowest value reported in literature for a developed region[1]- and allow the model to adjust to this value over an interval of a decade. Moreover, to slow down the decrease in vehicle occupancy with rising income, we introduce an income elasticity of -5% for all transport modes (Girod et al. 2013).
- Modal shift to public transport

  Despite limiting the available TMB, the continuous increase of income leads simultaneously to a higher preference for faster modes. To reduce high-impact traveling we influence the mode split by differentiating non-monetary preferences per mode, in favour of the bicycle and railway transportation similarly to (Girod et al. 2013). Moreover, to correspond with the increase in the preference for slower modes, we allow an additional 0.5 minute per year on the traveling time budget (TTB).

3.2.3.3 Waste management

- Reduced demand for consumer plastic

  Waste management is expected to be an increasing challenge, as the generation of municipal waste is projected to increase within the OECD regions (OECD 2008). Reusing plastic bags or using durable plastic products rather than disposables could reduce the total volume of municipal waste. This measure is implemented by reducing the intensity of useful energy demand in the industry and non-energy sectors to represent reduced material processing. We reduced the energy intensity of demand for the ethylene sector with 15-20% to depict reduced energy demand for plastics production, while remaining within plausible bounds of empirical regional data (Daioglou et al. 2014). This in turn reduces the demand of primary energy to be used as feedstock, but also process energy in the form of heat and electricity.
- Plastic waste recycling

  In order to assess possibilities of material efficiency improvement throughout the lifecycle of non-energy products (such as recycling and incineration with electricity generation), we also account for possible routes of post-consumer plastic waste (PCW). It is assumed that 50% of plastic production can be recycled since not all plastics can be collected as PCW. The volume of PCW undergoing mechanical recycling is capped at 30% in order to account for decreased material properties (downcycling), the remaining PCW undergoes chemical recycling processes.

[1] Driven by an exceptional large share of public high-speed transport in Japan, due to e.g. the *Shinkansen* high-speed rail way (Schafer and Victor 2000).

Table 4: Overview table of implementable changes in lifestyle and the energy reduction potential considered. Name in brackets denotes the scenario short name used in figures.

Aggregate theme	*Measure*	*Implementation*	*Source*
Transport	*Reduced vehicle use [passload]*	*Capping the travel money budgetChanging income elasticity to -5% to prevent lower passenger load per mode*	*TIMER/IMAGE* (Girod et al. 2013)
	Mode shift to public transport [modalshift]	*Change of perceived price*	*TIMER/IMAGE* (Girod et al. 2013)
Residential energy use	*Reduced heating / cooling demand [CoolHeatDemand]*	*Change of base temperature by 1 degree, reducing the number of heating degree days or cooling degree days.*	*TIMER/IMAGE* (Isaac and van Vuuren 2009)
	Reduced appliance ownership [AppleOwn]	*Reduced ownership levels for 'luxury goods' to zero (no tumble dryers, dish washers etc . Maximum ownership rates for other major domestic appliances are fixed to 2013 values.*	*TIMER/IMAGE* (Daioglou et al. 2012)
	More efficient use of appliance [EffAppl]	*BAT energy consumption estimates and make appliances converge to these new levels gradually over time.*	(Goodall 2007) (Daioglou et al. 2012)
	Switch off stand-by mode [standbymode]	*Reduce annual appliance energy consumption based on estimations of standby mode energy consumption per appliance*	(Lawrence Berkeley National Laboratory 2013)
	Reduces water heating [showerless]	*A correction factor in total energy demand for water heating (based on cutting down 2 min of shower time), based on an estimate in literature.*	(Goodall 2007) (Daioglou et al. 2012)
	Capping household dimensions [floorspace]	*Floor space (m^2/cap) is fixed to a representative 2010 value, differentiating for rural (50m^2/cap) and urban households(40 m^2/cap)*	*TIMER/IMAGE* (Daioglou et al. 2012) (OECD/IEA 2004)
Waste management	*Reduced plastic consumption [nonenergy]*	*Reduce intensity of useful energy demand in ethylene production by 15-20%*	*TIMER/IMAGE*
	Plastic waste recycling [nonenergy]	*Assuming active household plastic waste separation from general waste. Assuming available infrastructure in which max. 20% is mechanically recycled and max 30% chemically recycled.*	TIMER/IMAGE (Daioglou et al. 2014)

The aim of the study is to explore how lifestyle measures could contribute to emission reductions, which is considered a more difficult exercise in energy modeling as (1) such decisions are much less influenced by direct costs considerations and (2) are generally not standard included in models. Moreover, there is not a set of commonly accepted lifestyle measures, hence the proposed framework can be considered an arbitrary selection of an exhaustive list of options. This leads to several implications on the representation of lifestyle change in the model, as ad-hoc model parameterization does not fully cover the interactions of socio-demographic factors (such as low education, income, age, gender, employment status and attitudes) (OECD 2008). For instance, income levels are found to determine the response towards household energy consumption when providing households with frequent feedback (Bittle et al. 1979). However, as key drivers like population and GDP are exogenous (fixed) inputs for the model (derived from external sources such as the IEA and World Bank), the ad-hoc changes simulate behavioural change only to a limited extent. The authors acknowledge these caveats but would like to stress that the purpose of this study is to assess the *implications* of lifestyle change to mitigate emissions rather than quantifying the available potential.

3.2.4 Scenario design

For this study we are introducing four different scenarios to analyse the implications of lifestyle changes in a 2°C scenario (see Table 2). The baseline is a stylized scenario assuming business-as-usual without detailed assumptions on planned (regional) climate policy. Key drivers of the baseline are described in (OECD 2012). Projections for GDP growth rates stem from the OECD environmental outlook (OECD 2010) leading to an average annual global growth rate of 3.5% between 2010 and 2050. Population assumptions are based on the United Nations population prospects (UN 2008), in which the global population reaches 9.55 billion at the end of the century. Increase in energy consumption in the baseline roughly follows the projections of the IEA World Energy Outlook (IEA 2011) and relate to historical trends and the range found in literature as reviewed by (van Vuuren et al. 2012). The second scenario combines the baseline projections together with the lifestyle change measures as described in the framework, to assess the contribution of lifestyle change relative to the baseline. Furthermore, we introduce a cost-optimal mitigation scenario targeted to not exceed the 2°C temperature increase, assuming no lifestyle changes, and one that considers the same lifestyle change measures as implemented in the baseline.

This study focuses on the aggregated (global) level, with a temporal scale up to 2100 and zooms in onto four sectors (energy supply, industry, residential an transport). The energy supply sector accounts for power and heat generation and other energy conversions (e.g. refineries, synfuel production), resource extraction and energy transmission and distribution (e.g. gas pipelines). The industry sector includes heavy industry such as steal and cement production. The residential sector includes both heating and cooling as well as appliance energy use. The transport sector includes freight and passenger travel and bunker fuels. To assess the implications of lifestyle change measures on attaining the 2°C objective as well as initiated energy system transformations, the analysis focuses on CO_2 emission trajectories and secondary energy carriers. Amongst the energy carriers addressed, solid fuel denotes coal (incl. cokes and other commercial solid fuels), liquid fuel denotes oil as light liquid fuel (LLF) or heavy liquid fuel (HLF) and commercial liquid fuel from biomass, gaseous fuel denotes natural gas and gaseous fuel from biomass (BGF). The electricity category in the power sector denotes energy generated from sources other than fossil energy carriers (e.g. wind, solar, hydro-power and nuclear), in any other sector electricity denotes power generated from both fossil and non-fossil sources.

Table 5 - Scenario overview table

Scenario	Description
Baseline (default)	The baseline scenario used throughout this study is described in the OECD Environmental Outlook (OECD 2012).
Baseline + lifestyle	The baseline including all the lifestyle measures addressed in the lifestyle change framework
2 Degrees (default)	A mitigation scenario based on a cost-optimal emission pathway reaching a 450 ppm climate stabilization target with a high likelihood of staying within 2C temperature increase
2 Degrees + lifestyle	A combination of the abovementioned 450 ppm including all the lifestyle measures addressed in the lifestyle change framework

3.3 Results

3.3.1 Implications of lifestyle change

In the following Sections, we discuss the impacts of the lifestyle changes on sectoral energy use and emissions. In order to gain insight in the most dominant measures, we have summarized the individual impacts in Figure 1.

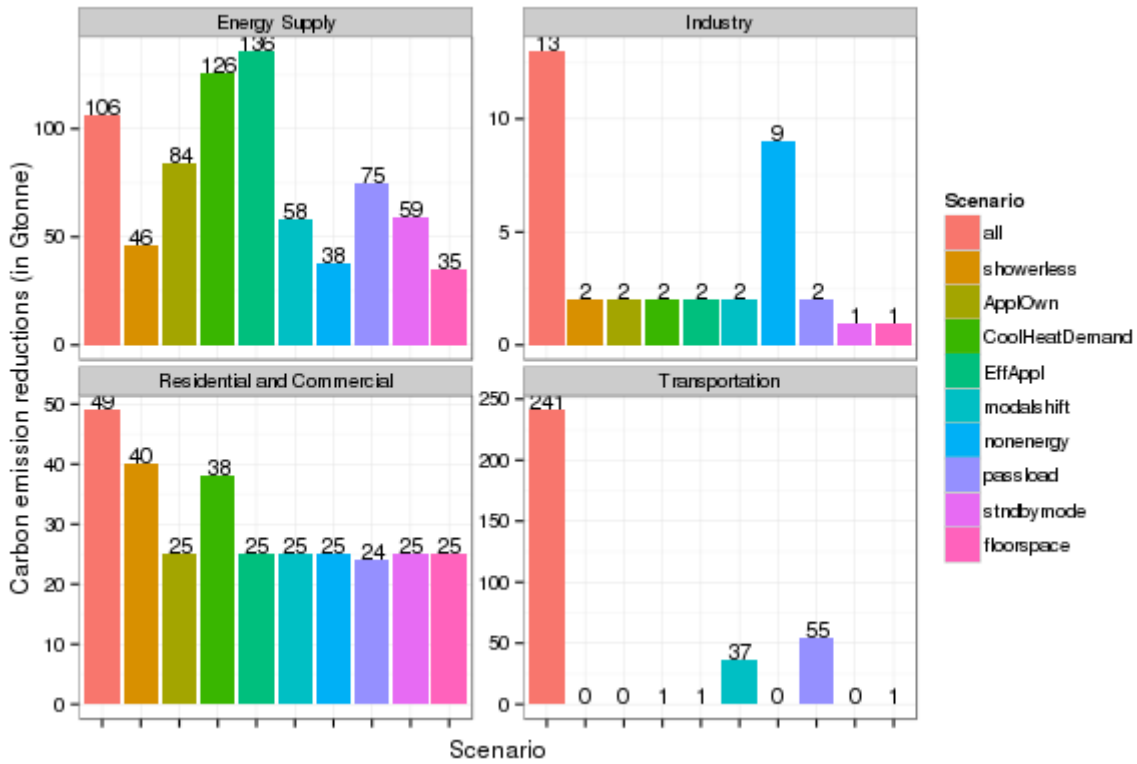

Figure 5 - effect of single lifestyle measures on total cumulative CO_2 emission reductions in 2100.

3.3.2 Direct implications of lifestyle change

Energy demand reduction and changes in travel behaviour have direct implications for the residential and transport sector. We will discuss per sector the implications of lifestyle change:

Residential

The buildings sector is responsible for about 32% of total global final energy use and 19% of energy-related greenhouse gas emissions in 2010 and is expected to double or triple by mid-century due to increasing life-standards in emerging regions. The largest part of GHG emissions are indirect CO_2 emissions from electricity use in buildings and the leading trend to decrease building energy use is by deep retrofits, such as replacing existing equipment with, amongst others, energy efficient appliances and lighting (IPCC AR5 2014). Lifestyle changes can contribute to energy saving strategies through measures affecting appliances use and heating (see figure 3). We find that changing the temperature setting by 1 degree and using appliances more efficiently are the two most effective measures for energy conservation over the considered time horizon (see also figure 1). The lifestyle change measures implemented in the residential

domain may lower CO_2 emissions in the residential sector by 15% and simultaneously could reduce emissions in the energy supply sector by 2-5% compared to baseline emissions in 2100. Together the measures lead to a total fuel consumption that can be considered to be in line with 2°C ambitions. By implementing similar conditions to 2°C mitigation scenarios, this creates greater energy savings that lead up to 26 $GtCO_2$ additional emission reductions throughout the century (or 10 percentage points greater reductions in the residential sector than in the default 2°C mitigation scenario).

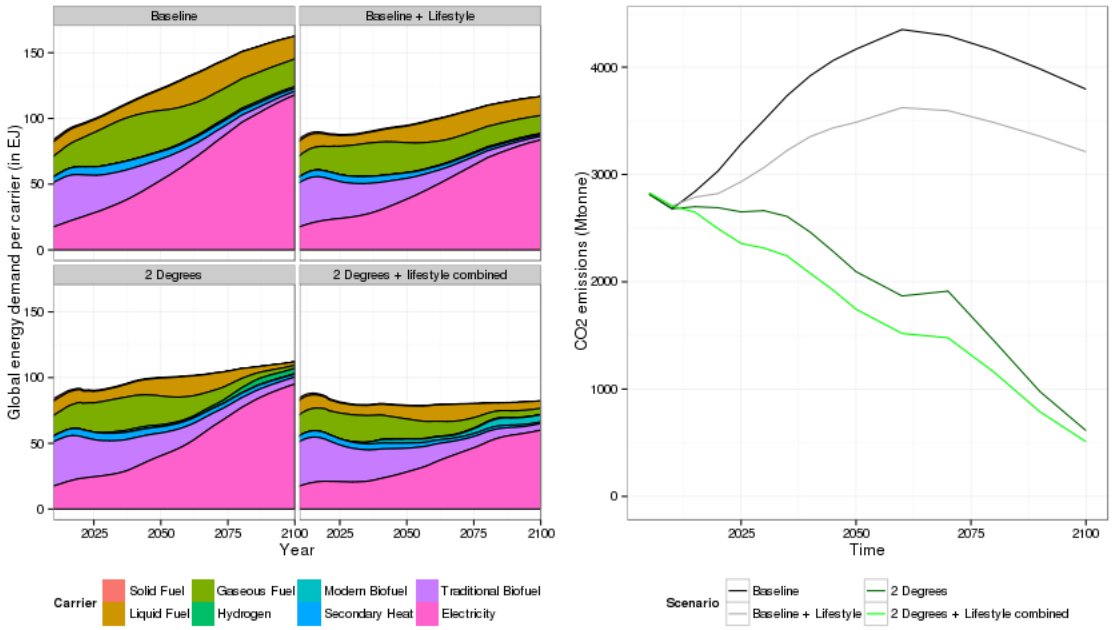

Figure 6 - Overview of the effect on the residential sector of all lifestyle measures on the use of secondary energy carriers (left, in EJ) and emission trajectories (right, in Mtonne CO_2).

Transport

The transport sector poses due to be the most difficult and expensive sector to reduce energy demand and greenhouse gas emission, due to increasing travel behavior and limited mitigation opportunities (Schafer and Victor 2000). Conventional mitigation strategies focus on supply-side vehicle technology efficiency gains and fuel switching as the central theme for this sector – creating several challenges on the short term as most aspired technological changes are not yet commercially available and require major infrastructure investments (Anable et al. 2012). By imposing lifestyle changes we observe that an immediate shift can be realized from a predominant oil and bioenergy orientation under default assumptions to more electrified passenger travel – which opens up opportunities to use renewable energy sources in the transport sector (emission reductions) on the short term without substantial additional changes to the energy infrastructure. Emission reductions up to 9% can be achieved on the short term in the transport sector alone, reaching up to 35% in 2100, compared to baseline emissions in the absence of climate control targets (which translate to respectively 2-4% emissions reductions in total CO_2 emissions). Greater use of public transport is promoted, reducing car travel by 14% by 2030 and 63% in 2100. Long distance air travel is mostly substituted by the high-speed train, reducing global aviation by 22% in the short term (2030) to 84% by 2100 compared to baseline

projections. By implementing similar conditions to 2°C mitigation scenarios, 115 $GtCO_2$ additional emission reductions can be achieved over the century (representing 17 percentage point greater emission reductions in the transport sector than in the default 2°C mitigation scenario) and simultaneously creates a near carbon neutral passenger travel sector, as demand for liquid fuel is significantly dampened and substituted for biofuel.

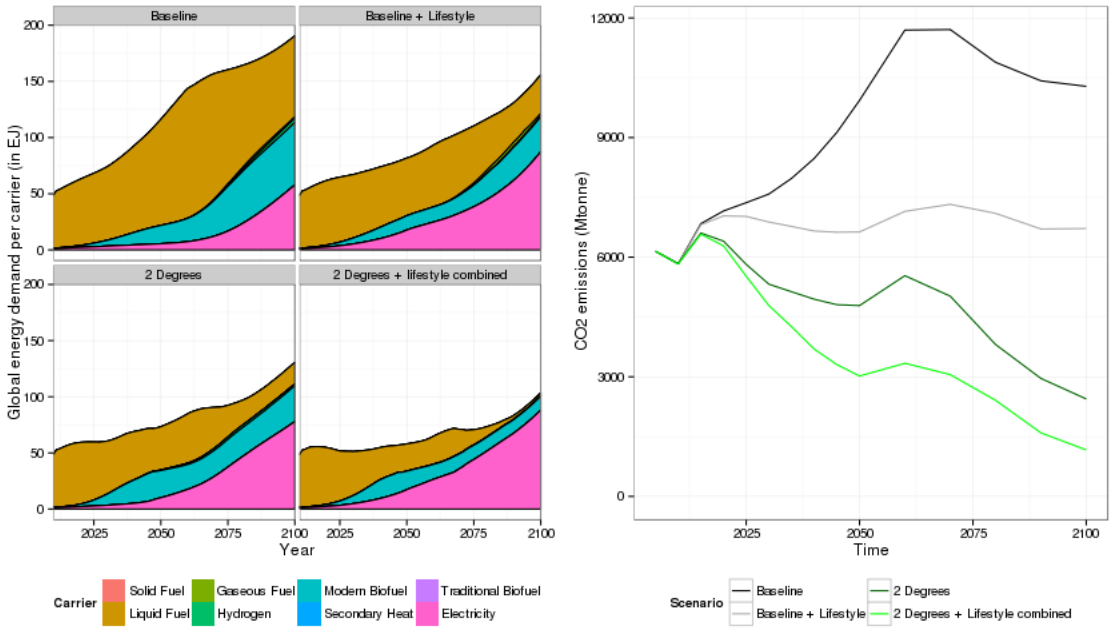

Figure 7 - Overview of the effect on the transport sector of all lifestyle measures on the use of secondary energy carriers (left – limited to passenger travel in EJ) and emission trajectories (right, in Mtonne CO_2).

3.3.3 Indirect implications of lifestyle change

Although lifestyle measures are not implemented in the energy supply and industry sector directly, some of the measures regarding energy and material conservation will lead indirectly to impacts in these sectors.

Power sector

The energy supply sector is acknowledged to be the largest contributor to global greenhouse gas emissions, responsible for 35% of total anthropogenic greenhouse gas emissions in 2010. Although multiple options exist to reduce energy supply sector GHG emissions, the central theme in long-term mitigation scenarios is generally the development and deployment of technology, as fossil-fuel-based energy supply is commonly replaced by new low-carbon energy techniques (IPCC AR5 2014). Lifestyle changes can indirectly impact the power supply sector and the composition of fuel for power generation, leading to an overall emission reduction of 5% by 2030 and 3% over the long term (2100) (see figure 1). By introducing lifestyle changes to the 2°C mitigation scenario an additional 67 $GtCO_2$ emission reductions in the energy supply sector are achieved over the century (representing 2 percentage point greater emission reductions in the transport sector than achieved in the default 2°C mitigation scenario).

Industry

Despite continued improvements in energy and process efficiency in the industry sector, industry related emissions are increasing and represent just over 30% of global GHG emissions in 2010 (IPCC AR5 2014). Lifestyle change measures can indirectly impact the producing industry through reducing material consumptions (e.g. through curtailment and recycling and re-use). The effect of lifestyle change measures on the industry sector are limited in the absence of more stringent climate target strategies (see figure 4). Mainly the organic petrochemical sector is affected through e.g. plastic reuse and recycling – although it covers most of the energy demand in the non-energy sector it shows to have a marginal effect for the total energy demand in the industry sector as a whole. On the short term (2030), about 12% less energy is used for polymers produced by steam cracking with respect to the baseline, with a 28% long term potential by 2100. These reductions lead to a near negligible effect in the total industry energy mix, translating to reductions of about 0.2% by 2030 and 4% by 2100 compared to baseline emissions in the industry sector. By implementing similar conditions to 2°C mitigation scenarios an additional 6 $GtCO_2$ is reduced in the industry sector over the century (representing 1 percentage point greater emission reductions in the industry sector than achieved in the default 2°C mitigation scenario).

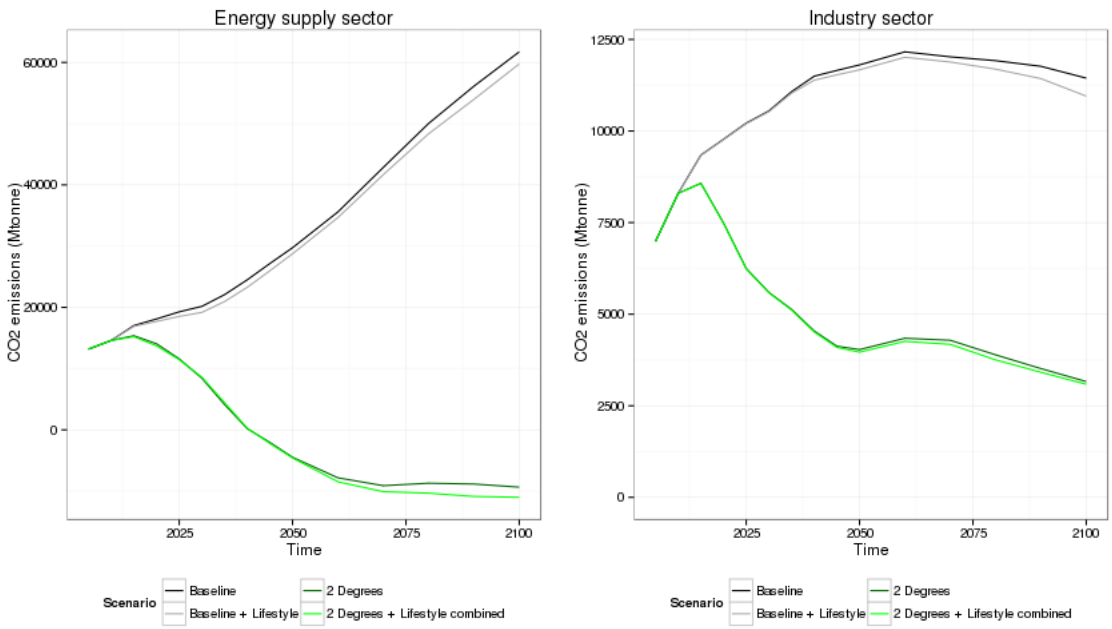

Figure 8 - Overview of the effect of all lifestyle measures on the power sector (left) and industry (right) emission trajectories (in Mtonne CO_2).

3.3.4 Implications of lifestyle change on 2°C mitigation

By introducing lifestyle change measures under similar mitigation efforts as required under default 2°C, an additional emission reduction of 80GtC is observed (see figure 6). As this shifts the climate target downward, we also assess the implications of lifestyle change under similar climate target control measures. We find then that the pathway under the +lifestyle scenario leads to greater cumulative emissions throughout the first half of the century, as an effect of extending the use of fossil fuel use. In the second half of the century the +lifestyle pathway follows a similar route as under default 2°C settings but needs to compensate for the additional emissions emitted earlier in the century by reaching more negative emissions eventually.

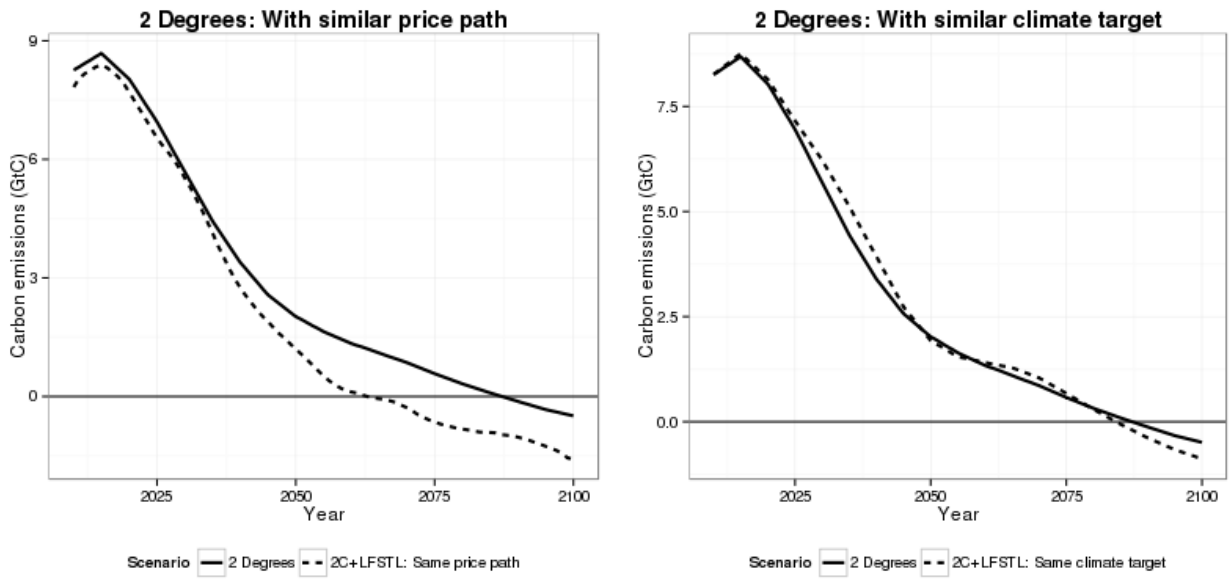

Figure 9 - CO_2 emission trajectories for similar carbon pricing (left, in GtC) and similar climate target (right, in GtC).

As described in the previous paragraph, lifestyle change measures mostly affect the end-use sectors directly in the absence of more stringent climate target, and alone show to be insufficient to meet the 2˚C climate objective. However, by preemptively reducing the energy demand and transitioning to electricity-driven sectors, multiple opportunities are unlocked to mitigate in (1) more resilient sectors and subsequently (2) allow more cost-efficient mitigation without additional radical changes in energy infrastructure (see figure 7). This is represented by a carbon price value of about USD$600/t$CO_2$ in 2100 whereas in similar respect the carbon price is nearly USD$100/t$CO_2$ lower throughout the century leading to a cut of about 15% in the total mitigation costs under +lifestyle considerations.

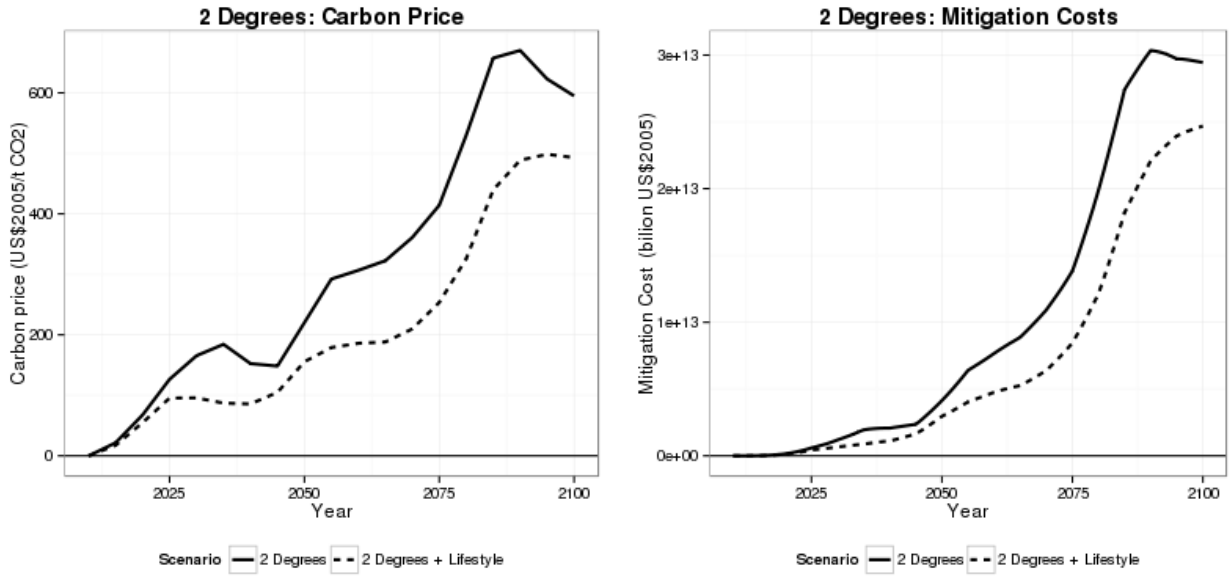

Figure 10 - Differences in required carbon tax projections (left, in US$2005) and total mitigation costs (right, in US$2005) for the 2 Degrees and 2 Degrees + lifestyle scenario

As most cost-optimal deep mitigation studies depend on the utilization of key energy technologies (i.e. bioenergy, renewable energy) at the second half in the century, the higher cumulative emissions throughout the first half of the century pose significant implications on the rate and extent these technologies need to be developed and employed. Under +lifestyle change assumptions we observe an initial lower implementation rate than under the default 2˚C settings – but appears to show greater dependence on bioenergy and carbon capture and storage (BECCS) as opposed to other clean tech energy technologies during the second half of the century.

3.4 Discussion

3.4.1 Barriers and policies for lifestyle measures

Suboptimal behaviour and barriers to adopt behavioural change limit the extent of how much lifestyle change can influence the required transformation towards a 2°C objective. In this section we discuss the main barriers for each sub-section addressed. Three main categories of barriers have been identified within each domain: (i) Sociocultural barriers, those related to habits and socio-demographic factors; (ii) Knowledge barriers which are related to the level of information and understanding and (iii) Structural barriers which are obstacles in the environment of the individual influencing the willingness to change its behavior. In the following paragraphs we will address several international examples of policy instruments and programs to address these barriers. An overview table is presented in Table 3.

3.4.1.1 Residential domain barriers

Within the residential domain, measures are aimed at increasing the level of awareness on consequences for energy use from personal behaviour. This given fact indicates the need for tailored and repeated knowledge until the desired change is acquired or in line with current (energy saving) trends (Lindén et al. 2006). Typical barriers that hamper lifestyle energy savings in the residential sphere are:

- Sociocultural barriers: Habits, daily routines, the attribution of the responsibility to others and poor environmental attitudes (Rohde et al. 2012) are preventing inhabitants to reduce their energy use at household level. Financial instruments targeting specifically households with high energy demand, as demonstrated in e.g. the ecological tax reform in Germany (or 'Ökosteuer'), have been implemented before to level off the effect of this barrier (ODYSSEE-MURE 2014)
- Knowledge barriers: Lack of knowledge about one´s own energy consumption restricts the individuals' reduction potential. Information about energy consumption conveyed to households through informative billing, mass campaigns, workshops and home audits could increase awareness, allowing savings up to 13% per household (Darby 2006). Economic incentives for energy-monitoring appliances (e.g. smart-meters, set-back thermometers) and for water-efficient showerheads can achieve emissions reductions.
- Structural barriers: As described in (Gatersleben et al. 2002; Csutora 2012; Tabi 2013) the energy demand for heating and electricity seems to be more closely related to socio-economic and demographic factors (e.g. income, household size, family composition) creating limited space for the pro-environmentalist to dissociate itself from environmental indifferent behaviour.

3.4.1.2 Transport domain barriers

The transport sector is considered as the most difficult sector for mitigating carbon emissions, due to the rapid growth of the sector and the relative lack of low-cost and carbon neutral options. Changes in demand are therefore vital in reducing transport emissions, yet several impediments may prove to prevent the sector from achieving its potential;

- Sociocultural barriers: Shifting from one to the other transport mode entails a social and psychological choice such as habits and driving mode preference. Ways to overcome this sociocultural barrier is by employing instruments that would reduce the convenience and necessity of using polluting modes of transport, such as introducing parking restrictions, car-free residential areas and imposing traffic restraints (Crawford 2013). Land-use projects such as the restriction of out-of-town shopping centers and mixed-use zoning projects have also demonstrated to be very effective in reducing motorized transport (e.g. HafenCity in Germany, reducing the share of individual motorized transport to 20-25%) (HafenCity Hamburg GmbH 2014).
- Knowledge barriers; Car users might not be aware of the potential of shifting to a more sensible (fuel-efficient) driving style. Communication could raise awareness on the costs and benefits of driving a car and the possibilities of switching to alternative modes or ways of reducing travel and advantages of eco-driving. Examples can be found in programs such as *TravelWise* (Hampshire County Council 1993), *Travel Smart* (DfT Western Australia 2008), *Travel Blending* (Rose and Ampt 2001), the *Travel Feedback Program* (Taniguchi et al. 2003) and the *Dutch Eco Driving campaign "HNR"* (Smokers et al. 2006).
- Structural barriers: Physical impediments such as a poor transport infrastructure and difficult accessibility to jobs, services and education also prevent users from changing their lifestyle. Investment in public transport infrastructure to improve service (frequency, punctuality, comfort, convenience, safety, etc.) and offering adequate infrastructure for cycling and walking by providing park and ride facilities are essential to offer users a more environmentally-friendly transport network (e.g. the Rapid Transit systems in Brazil and Colombia and the Marikina bikeways network in the Philippines) (Nurul Amin 2009).

3.4.1.3 Waste management barriers

Governments have become gradually more concerned with their waste disposal financing options, and are more interested in inducing people to produce less waste and to engage them in recycling activities. Three main impediments for waste reduction and recycle can be identified.

- Sociocultural barriers: Related to behaviour, perceptions and habits prevent people from further progressing waste disposal behaviour (e.g. high levels of consumption per capita, not accepting there is an environmental benefit, being too busy with other preoccupations). Regulatory policy instruments could help increase the participation rate of citizens, such as obligating the collection of waste as well as capping the use of plastic per capita. Examples can be found in e.g. limiting the use of ultra-thin plastic bags in China (Wang 2008). The effect of economic instruments are found to be more dichotomous, either leading to successful decline in plastic bag demand (Wang 2008) or to opposition from the retail (Ohtomo and Ohnuma 2014) .
- Knowledge barriers: Recycling programs may fail if users do not know which fractions or products can be recycled. Information campaigns about how to recycle and the environmental impact of waste generation will be an effective instrument, as demonstrated by the *Envirowise program* in the UK (Fry 2007).
- Structural barriers: Physical impediments can be lack or shortage of adequate containers, a lack of space for storage at home and the inability to bring waste to the recycling site (Pocock et al. 2008). On the macro level the absence of adequate infrastructure for e.g.

deposit/refund or recycling systems inhibit people to sensibly dispose of their plastic waste.

Overall it can be concluded that a combination of regulatory, economic and information-based instruments ("policy packages") are observed to work more efficiently than just individual ones (Rohde 2012; OECD 2008; Abrahamse 2005). The design of a successful policy strategy requires knowledge of all these factors that determine the changes in specific behaviours. Policy makers need a better understanding of how the traditional policy tools can be complemented by insights from behavioural change theory and evidence at various levels (individual, interpersonal and community). Another challenge is how to maintain these behavioural changes in the long-term and to avoid that people fall back into their old habits (such as described by the drawback effect (EEA 2013)), various compensating behaviours (such as observed with the so-called rebound effect (Madlener and Alcott 2009) and boomerang effect (Harding and Rapson 2013)) or moral licensing (Tiefenbeck et al., 2013)).

Table 6 - Overview of barriers per domain and available (crystallized) policy instruments.

	Domain		
Barrier	Residential	Transport	Waste
Sociopsychological	- Obligatory energy performance certificates with display of inhabitant's energy use - Installation of smart meters	- Convenience reduction: parking restrictions, car-free residential areas and traffic restraint - Necessity reduction: land-use policies such as mixed-use zoning, requiring public transport access to new developments, restricting out-of-town shopping centers	- Mandatory separate collection of waste fractions - Regulation to minimize waste and to promote closed-product cycles - Limits on the amount of plastic used among manufacturers (e.g. packages) and consumers (e.g. plastic carrier bags)
Financial	- Higher energy prices - Taxation of household with comparatively high heating/ electricity consumption - Economic incentives for energy-monitoring appliances (e.g. smart-meters, set-back thermometers) and water-efficient showerheads	- Economic incentives for cleaner and more efficient vehicles, for limiting cars and for cleaner modes of transport (e.g. Subsidies for public transport) - Taxes over the variable costs of car use (fuel taxation, kilometer tax, road pricing, congestion charging, parking charges, insurance tax) - Taxes over the fixed costs of car ownership (car purchase tax, annual road tax, residential parking fees or tax)	- Instruments based on the "polluter pays" principle such as taxes to force polluters to bear the costs of their waste generated - Deposit/refund type scheme, which consists of an advanced disposal fee applied either at the production or the purchase point of the product. - Quantity-base fees - Recycling subsidies fund type scheme (subsidy to households that recycle or firms that purchase recycled materials) - Landfill bans on biodegradable waste - Landfill and incineration taxes
Knowledge	- Information about energy consumption conveyed to households through mass campaigns, workshops and home audits - Heating and electricity billing at more frequent periods	Raise awareness on the problems caused by car use, of the possibilities of switching to alternative modes, of ways of reducing travel and advantages of eco-driving	- Information campaigns about the environmental impact of waste generation - Information campaigns about waste minimization and increase recycling (e.g. by removing desk-side bins in offices) - Recycling labelling
Structural	- Investments in infrastructure such as smart-meters	Investment in public transport infrastructure to improve service (frequency, punctuality, comfort, convenience, safety, etc.), and offering adequate infrastructure for cycling and walking by providing park and ride facilities.	- Investment in a well-functioning waste recycled system with collection containers close to the generation points and adequate processing facilities

3.4.2 Beyond energy system lifestyle change measures

This study has mostly focused on lifestyle change and mitigation measures within the energy system and does not impose changes in the land system. Yet, about 18% of the global greenhouse gas emissions are caused by livestock production, for which ruminants constitute for the largest anthropogenic source of forcing agents, followed by manure, fertilizer and land-use and agricultural emissions. By including lifestyle change measures beyond the energy domain within the scope of study, for example by reducing meat consumption, the implications of lifestyle change in 2˚C scenarios are expected to be greater. (Stehfest et al. 2009) introduce a 'healthy diet' scenario that describes reduced meat consumption, limited to once per week consumption of ruminant meat and pork, while consumption of fish, poultry and eggs with zero to two servings per day. The healthy diet leads to a decrease in demand for ruminant meat (specifically sheep and goats) reducing livestock size and simultaneously leading to a total reduction of greenhouse gas emissions of about 10% compared to baseline projections. It is assumed that including these reductions will amplify the patterns observed under current 2°C objective scenarios.

However, changing behaviour for meat consumption contains socio-cultural barriers as meat is considered a main ingredient in many cultures. Regulatory instrument could achieve changes in consumption patterns (e.g. by limiting the quantities served, as demonstrated in New York city on the serving sizes of soda and other sugary drinks) (Jacobson 2012). The rich availability and lower priced unhealthy products in the market is also an important structural barrier to change consumer's diets. The first world *fat food tax* was introduced in Denmark (BBC world news Europe 2011), where a surcharge was applied to products such as butter, milk, cheese, pizza, oils and meat with more than 2,3% saturated fats. Although this tax was set to reduce obesity rates and not to preserve the climate, the implementation for an environmental goal could be similar. Consumers ignoring the healthiness or sustainability of specific (food) products could be persuaded through information provision via e.g. sustainability (footprint) labelling or education (e.g. Mass-media campaign, school intervention programs (For an overview of all programs see (Evans et al. 2012)).

3.5 Conclusion

This study aimed to explore the contribution of various low-cost and directly implementable lifestyle changes and the implications on an ambitious climate stabilization target. By using the IMAGE integrative assessment framework, we have compared four scenarios in terms of carbon emission reductions and their economic potential to their reference case. One scenario includes business as usual assumptions and one full global mitigation, in both cases we impose a set of lifestyle change measures that reduce primary energy consumption to understand the role of lifestyle changes in mitigation scenarios.

How can lifestyle changes contribute to achieving 2˚C climate targets?

We find that each of the lifestyle change measures included in the framework decrease the global energy demand compared to baseline projections. In the power sector, as well as the industry sector, lifestyle changes generally have an indirect impact due to energy conservation – leading to marginal changes in fuel composition and emission reductions (ranging between 0-2% in total CO_2 emissions). For the residential sector lifestyle change can impact fuel demand and emissions both directly and indirectly, mainly through changing our (water) heating habits (reducing direct emissions in the residential sector by 15% by 2100) and by reducing appliance energy use (reducing emissions in the energy supply sector by 2-5% compared to baseline emissions by 2100). Furthermore, structural changes in travel behaviour in the transport sector could also alleviate the environmental pressure by about 9% in 2030 and 35% by 2100. Under 2°C ambitions we find that lifestyle change measures alone are insufficient to meet the 2˚C climate objective. However, by preemptively reducing the energy demand and transitioning to a greater electrified system, opportunities are unlocked for greening the more resilient sectors (specifically in the transport sector with considerable additional emission reductions over the century) or for more cost-efficient mitigation under 2°C ambitions without introducing additional major changes to the energy infrastructure.

How is lifestyle and lifestyle change included in integrative assessment modeling?

Integrated assessment models generally do not explicitly model behavior. Within the IMAGE framework behavioral heterogeneity is generally embedded through mechanisms causing a specific order of preference based on (non-) energy prices or through calibrating to historic trends using (arbitrary) calibration parameters to generate (regional) diversity. Moreover, as socio-economic trends and the interactions with lifestyle are not dynamically captured in the model, study designs like these are inherently reduced to ad-hoc adjustments and highly stylized assumptions. In order to conduct proper behaviourally-realistic modeling, information needs to become available on the diversities and heterogeneities of behavior (e.g. preferences, agents, geographies) and included in the model. Further expansion of scope could also be sought in domains beyond the energy domain, such as changing the extent of livestock by reducing meat consumption.

What barriers that need to be overcome in order to successfully implement climate policies?

Only a certain level of non-optimality is taken into consideration in the scenarios under study – as a variety of real world challenges to move people to, and to sustain, behavioural changes is not taken into further consideration. Strong barriers, such as split incentives (tenants and builders),

fragmented markets and inadequate access to information and financing, hinder the uptake of opportunities. A combination of regulatory, economic and information-based instruments are considered to work more efficiently in moving individuals into (sustained) appropriate behaviour than single measures. The design of a successful policy strategy requires knowledge of all socio-demographic factors, correlated to the barriers. Policy makers need a better understanding of how the traditional policy tools can be complemented by insights from behavioural change theory and evidence at various levels (individual, interpersonal and community).

Acknowledgements

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References

De Almeida A, Fonseca P, Schlomann B, Feilberg N (2011) Characterization of the household electricity consumption in the EU, potential energy savings and specific policy recommendations. Energy Build 43:1884–1894. doi: 10.1016/j.enbuild.2011.03.027

Anable J, Brand C, Tran M, Eyre N (2012) Modelling transport energy demand: A socio-technical approach. Energy Policy 41:125–138. doi: 10.1016/j.enpol.2010.08.020

BBC world news Europe (2011) Denmark introduces world's first food fat tax. http://www.bbc.co.uk/news/world-europe-15137948.

Bedford T, Jones P, Walker H (2004) " Every little bit helps …" Overcoming the challenges to researching , promoting and implementing sustainable lifestyles. 1–48.

Bernstein L, Bosch P, Canziani O, et al. (2007) Climate Change 2007 : Summary for Policymakers. 12–17.

Bittle R, Valesano R, Thaler G (1979) The Effects of Daily Feedback on Residential Electricity Usage as a Function of Usage Level and Type of Feedback Information. J Environ Syst 9:275–287. doi: 10.2190/91AA-P97G-JF92-T7EJ

Von Borgstede C, Andersson M, Johnsson F (2013) Public attitudes to climate change and carbon mitigation—Implications for energy-associated behaviours. Energy Policy 57:182–193. doi: 10.1016/j.enpol.2013.01.051

Bouwman AF, Kram T, Klein Goldewijk K (2006) Integrated modelling of global environmental change. An overview of IMAGE 2.4. Netherlands Environmental Assessment Agency. available at: www.mnp.nl\en, Bilthoven, The Netherlands.

Cagno E, Worrell E, Trianni a., Pugliese G (2013) A novel approach for barriers to industrial energy efficiency. Renew Sustain Energy Rev 19:290–308. doi: 10.1016/j.rser.2012.11.007

Clarke L, Edmonds J, Krey V, et al. (2009) International climate policy architectures: Overview of the EMF 22 International Scenarios. Energy Econ 31:S64–S81. doi: 10.1016/j.eneco.2009.10.013

Crawford J (2013) Cities - Carfree Places. In: 2013. http://www.carfree.com/carfree_places_old.html.

Csutora M (2012) One More Awareness Gap? The Behaviour–Impact Gap Problem. J Consum Policy 35:145–163. doi: 10.1007/s10603-012-9187-8

Daioglou V, Faaij APC, Saygin D, et al. (2014) Energy demand and emissions of the non-energy sector. Energy Environ Sci 7:482. doi: 10.1039/c3ee42667j

Daioglou V, van Ruijven BJ, van Vuuren DP (2012) Model projections for household energy use in developing countries. Energy 37:601–615. doi: 10.1016/j.energy.2011.10.044

Darby D (2006) The effectiveness of feedback on energy consumption - a review for DEFRA of the literature on metering, billing and direct displays. 1–24.

DEFRA (2008) A FRAMEWORK FOR PRO- ENVIRONMENTAL BEHAVIOURS.

DfT Western Australia (2008) TravelSmart. http://www.travelsmart.gov.au/about.html. Accessed 12 Feb 2014

Dietz T, Gardner GT, Gilligan J, et al. (2009) Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. Proc Natl Acad Sci U S A 106:18452–6. doi: 10.1073/pnas.0908738106

EEA (2013) Achieving energy efficiency through behaviour change: what does it take?

EEA (2005) EEA Report 11/2005 - Household consumption and the environment.

Evans CEL, Christian MS, Cleghorn CL, et al. (2012) Systematic review and meta-analysis of school-based interventions to improve daily fruit and vegetable intake in children aged 5 to 12 y. Am J Clin Nutr 96:889–901. doi: 10.3945/ajcn.111.030270

Fisher BS, Nebojsa N, Alfsen K, et al. (2007) Issues related to mitigation in the long-term context. Clim. Chang. 2007 Mitigation. Contrib. Work. Gr. III to Fourth Assess. Rep. Inter-governmental Panel Clim. Chang. Cambridge University Press, Cambridge, p 82

Fry C (2007) Case study: Helping UK Industry Save over £1 billion through improved resource efficiency.

Gardner BGT, Stern PC (2008) The Short List - The Most Effective Actions U.S. Households Can Take to Curb Climate Change. Environ Mag 50:12–26.

Gatersleben B, Steg L, Vlek C (2002) Measurement and Determinants of Environmentally Significant Consumer Behavior. Environ Behav 34:335–362. doi: 10.1177/0013916502034003004

Geels FWWT (2005) Processes and patterns in transitions and system innovations: Refining the co-evolutionary multi-level perspective. Technol Forecast Soc Change 72:681–696. doi: 10.1016/j.techfore.2004.08.014

Geppert J, Stamminger R (2010) Do consumers act in a sustainable way using their refrigerator? The influence of consumer real life behaviour on the energy consumption of cooling appliances. Int J Consum Stud 34:219–227. doi: 10.1111/j.1470-6431.2009.00837.x

Girod B, van Vuuren DP, de Vries B (2013) Influence of travel behavior on global CO2 emissions. Transp Res Part A Policy Pract 50:183–197. doi: 10.1016/j.tra.2013.01.046

Goodall C (2007) How to Live a Low-Carbon Life: The Individual's Guide to Stopping Climate Change. 320.

Gutowski T, Taplett A, Allen A, et al. (2008) Environmental Life Style Analysis (ELSA). 1–5.

HafenCity Hamburg GmbH (2014) HafenCity Hamburg. http://www.hafencity.com/en/home.html. Accessed 10 Oct 2014

Hampshire County Council (1993) TravelWise. http://www.hertsdirect.org/travelwise. Accessed 12 Feb 2014

Harding M, Rapson D (2013) Does Absolution Promote Sin ? The Conservationist ' s.

Hof A, Sluisveld MAE Van, Deetman S (2013) feasibility of transitions in 2 degree scenarios '.

IEA (2011) World Energy Outlook 2011.

IEA, International Energy Agency (2012) World Energy Outlook 2012. 1–690.

IPCC AR5 (2014) Chapter 9: Buildings. http://report.mitigation2014.org/drafts/final-draft-postplenary/ipcc_wg3_ar5_final-draft_postplenary_chapter9.pdf. Accessed 12 Oct 2014

Isaac M, van Vuuren DP (2009) Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy 37:507–521. doi: 10.1016/j.enpol.2008.09.051

Jacobson M (2012) New York City Health Board Caps Soda Serving Sizes. In: Cent. Sci. Public Interes. http://www.cspinet.org/new/201209131.html. Accessed 12 Feb 2014

Kriegler E, Tavoni M, Aboumahboub T, et al. (2013) Can we still meet 2 ° C with global climate action ? The LIMITS study on implications of Durban Action Platform scenarios 1. Clim. Chang. Econ. 282846:

Lawrence Berkeley National Laboratory (2013) Standby Power Summary Table. http://standby.lbl.gov/summary-table.html. Accessed 22 Nov 2013

Lindén A-L, Carlsson-Kanyama A, Eriksson B (2006) Efficient and inefficient aspects of residential energy behaviour: What are the policy instruments for change? Energy Policy 34:1918–1927.

Madlener R, Alcott B (2009) Energy rebound and economic growth: A review of the main issues and research needs☆. Energy 34:370–376. doi: 10.1016/j.energy.2008.10.011

Metz B, Davidson OR, Bosch PR, et al. (2007) Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.,

Nurul Amin A (2009) Reducing Emissions from Private Cars: Incentive measures for behavioural change. Econ Trade Branch, Div Technol Ind Econ United Nations Environ Program 1–172.

ODYSSEE-MURE (2014) ODYSSEE-MURE Database. http://www.measures-odyssee-mure.eu/.

OECD (2008) Household Behaviour and the Environment, reviewing the evidence.

OECD (2012) OECD Environmental Outlook to 2050 - THE CONSEQUENCES OF INACTION. doi: http://dx.doi.org/10.1787/9789264122246-en

OECD (2010) OECD Environmental Outlook to 2050: The Consequences of Inaction.

OECD/IEA (2004) Oil Crises & Climate Challenges - 30 years of energy use in IEA countries.

Ohtomo S, Ohnuma S (2014) Psychological interventional approach for reduce resource consumption: Reducing plastic bag usage at supermarkets. Resour Conserv Recycl 84:57–65. doi: 10.1016/j.resconrec.2013.12.014

Pocock R, Stone I, Clive H, et al. (2008) Summary Report - Barriers to recycling at home. doi: Project code: CDC405-001

Rao S, Riahi K, Stehfest E, Vuuren D Van (2008) Interim Report IMAGE and MESSAGE Scenarios Limiting GHG Concentration to Low Levels. 2008

Rohde C, Dütschke E, Gigli M, Bles M (2012) Behavioural Climate Change Mitigation Options - Domain Report Housing. 1–102. doi: Publication code: 12.7316.01

Rose G, Ampt E (2001) Travel blending: an Australian travel awareness initiative. Transp Res Part D Transp Environ 6:95–110. doi: 10.1016/S1361-9209(00)00015-8

Roy J (2012) Lifestyles, Well-Being and Energy. Glob. Energy Assess. pp 1527–1548

Roy J, Pal S (2009) Lifestyle approach to climate mitigation: Cross country empirical evidence. IOP Conf Ser Earth Environ Sci 6:262006. doi: 10.1088/1755-1307/6/6/262006

Schäfer A, Heywood JB, Jacoby HD, Waitz IA (2009) Transportation in a Climate-constrained World. MIT press

Schafer A, Victor DG (2000) The future mobility of the world population. Transp Res Part A Policy Pract 34:171–205. doi: 10.1016/S0965-8564(98)00071-8

Smokers R, Vermeulen R, Van Mieghem R, et al. (2006) Review and analysis of the reduction potential and costs of technological and other measures to reduce CO2-emissions from passenger cars - Final Report. 1–303. doi: Contract nr. SI2.408212

Staub-Kaminski I, Zimmer A, Jakob M, Marschinski R (2014) Climate Policy in Practice: A Typology of Obstacles and Implications for Integrated Assessment Modeling. Clim. Chang. Econ.

Stehfest E, Bouwman L, Vuuren DP, et al. (2009) Climate benefits of changing diet. Clim Change 95:83–102. doi: 10.1007/s10584-008-9534-6

Stocker TF (2013) Climate change. The closing door of climate targets. Science 339:280–2. doi: 10.1126/science.1232468

Tabi A (2013) Does pro-environmental behaviour affect carbon emissions? Energy Policy 1–10. doi: 10.1016/j.enpol.2013.08.049

Taniguchi A, Hara F, Takano S, et al. (2003) Psychological and Behavioral Effects of Travel Feedback Program for Travel Behavior Modification. Transp Res Rec J Transp Res Board 1839:182–190. doi: 10.3141/1839-21

Tol RSJ (2009) The feasibility of low concentration targets: An application of FUND. Energy Econ 31:S121 – S130.

UN (2008) World Population Prospects, The 2008 Revision.

De Vries B, Van Vuuren D, Den Elzen M, Janssen M (2001) Technical Documentation November 2001 The IMAGE Project Department of International Environmental Assessment National Institute of Public Health and the Environment (RIVM) P . O . Box 1 3720 BA Bilthoven The Netherlands. 0:

Van Vuuren DP, Riahi K, Moss R, et al. (2012) A proposal for a new scenario framework to support research and assessment in different climate research communities. Glob Environ Chang 22:21–35. doi: 10.1016/j.gloenvcha.2011.08.002

Van Vuuren DP, Stehfest E (2013) If climate action becomes urgent: the importance of response times for various climate strategies. Clim Change. doi: 10.1007/s10584-013-0769-5

Van Vuuren DP, Stehfest E, Elzen MGJ, et al. (2011) RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. Clim Change 109:95–116. doi: 10.1007/s10584-011-0152-3

Van Vuuren DP, VanRuijven B, Hoogwijk M, et al. (2006) TIMER 2: model description and application. Integr. Model. ofG lobal Environ. Chang. An Overv. IMAGE 2.4

Van Vuuren DPD, Elzen MGJ den, Lucas PLP, et al. (2007) Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Clim Change 81:119–159. doi: 10.1007/s10584-006-9172-9

Wang H (2008) China to limit use of plastic bags from June 1. http://english.gov.cn/2008-01/09/content_853755.htm. Accessed 12 Feb 2014

Weber C, Perrels A (2000) Modelling lifestyle e ! ects on energy demand and related emissions. 28:

Wood G, Newborough M (2003) Dynamic energy-consumption indicators for domestic appliances: environment, behaviour and design. Energy Build 35:821–841.

Wright RL (2011) Unilever Sustainable Living Plan - Inspiring Sustainable Living, Expert insights into consumer behaviour & Unlever's Five Levers for Change. 1–45.

4 Understanding the contribution of non carbon dioxide gases in deep mitigation scenarios.

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4.1 Introduction

In the discussion of climate change and climate policy, most of the attention is focused on reducing carbon dioxide (CO_2) emissions. And indeed, CO_2 forms currently around two-thirds of equivalent emissions and forcing. Accordingly, the reduction potential for CO_2 emissions (as part of more comprehensive climate policy strategies) has been extensively looked at in several comparison projects using scenarios reaching 2 degrees (Kriegler, 2013; Kriegler et al., 2013; Riahi et al., 2013). Many of the deep mitigation scenarios use negative emissions technologies to mitigate CO_2. Interestingly, in these scenarios non-CO_2 emissions tend to show less ambitious reduction levels. As these could contribute significantly to climate change at the time, it is very policy relevant to look deeper into the non-CO_2 emission reduction strategies.

Integrated assessment analyses already rely on mitigating non-CO_2 greenhouse gas (GHGs) as part of cost-efficient climate mitigation strategies (van Vuuren et al., 2006; Weyant et al., 2006). There are several reasons for this. First of all, the main non-CO_2 GHGs (CH_4, N_2O and the F-gasses) covered under the Kyoto Protocol contribute to about 20-30% of the total 2010 CO_2-equivalent emissions and to about 30% of the total radiative forcing (IPCC, 2007). Second, some non-CO_2 GHGs have relatively short lifetimes, thereby creating the option of a short-term climate benefits (Shindell et al., 2012). Third, some of the options to reduce non-CO_2 gases are relatively inexpensive, providing an option to reduce overall mitigation costs (Weyant, 2006; van Vuuren et al., 2006). Finally, a larger portfolio of mitigation options increases flexibility (van Vuuren et al., 2006; Weyant et al., 2006). At the moment, non-CO_2 GHGs are already covered in most climate policies, including the Kyoto protocol and several country pledges under the Cancun agreements (UNFCCC, 2005; UNFCCC, 2009).

As indicated above, non-CO_2 gases have received much less attention in multi-model studies. The last model comparison study to specifically address non-CO_2 gases was the EMF21 study (Weyant et al., 2006). This study looked into the benefits of a multigas strategy over a CO_2-only reduction strategy. The study, however, paid little attention to comparing sectoral strategies across models, and only looked at relatively modest climate targets.

In this report, we focus on sectoral mitigation potential and specifically address the role of the remaining non-CO_2 emissions (CH_4, N_2O and F-gases) in deep mitigation scenarios in order to discuss their relevance for climate policy. To show some of the relevant uncertainty, we use a set of different integrated assessment models (IAMs). The analysis uses the results of the recent LIMITS model comparison study (Kriegler, 2013) for six different IAMs. Appendix A provides a brief overview of the participating models: GCAM (Calvin, 2011), IMAGE (MNP, 2006; van Vuuren, 2007), MESSAGE (Riahi et al., 2007), REMIND (Luderer. et al., 2011), TIAM-ECN (Kober et al., 2013; van der Zwaan et al., 2013; Rösler et al., 2014) and WITCH (Bosetti et al., 2006; Bosetti et al., 2009). In the LIMITS study, several scenarios were run by these models, including no policy scenarios and scenarios aiming at a 2100 forcing level of 2.8 W/m^2. Using the LIMITS scenarios, this report looks into the following questions:

(1) What is the role of the remaining non-CO_2 emissions for reaching ambitious climate targets?
(2) How do mitigation strategies compare across models in reducing non-CO_2 emissions at a sectoral level?

First, in Section 2, we discuss the methodology of the study. In Section 3.1, we compare the overall response for non-CO_2 emissions in the different models for deep mitigation scenarios. In a subsequent analysis, we look into the sectoral emissions sources (Section 4.3.2 to Section 3.4). and regional results (Section 3.5). After which we compare emissions under similar conditions in section 3.6. Finally, in Section 3.7 we look into the potential implications for climate change. Section 4 presents the conclusions.

4.2 Methodology

4.2.1 Comparison of mitigation potential

The LIMITS study (Kriegler, 2013) developed different scenarios to look into the question what would be required to meet the 2°C target. Here, we use two scenarios from the LIMITS project:

- B*aseline*: This scenario assumes that no new climate policies are implemented. Assumptions on the development of trends in socio-economic parameters, energy and land-use and derived emissions were left to the individual models teams, resulting in a range of 2100 emission levels of 90-110 $GtCO_2$-eq/yr (Kriegler, 2013).
- The *450* scenario: This scenarios aims to achieve a radiative forcing target of 2.8 W/m^2 in 2100 by starting with immediate full global cooperative action. The scenario is regarded to have a likely (>70%) chance of reaching the 2°C target (Kriegler, 2013). The policy target assumed for the depicted scenarios refers to the aggregate radiative forcing from the following substances: Kyoto gases (CO2, CH4, N2O, HFCs, PFCs, SF6), Non-Kyoto gases (substances controlled under the Montreal protocol, i.e. chlorides, halons, bromine; tropospheric and stratospheric ozone; stratospheric water vapor), and aerosols (sulfate, black and organic carbon from fossil fuel and biomass burning, indirect aerosol forcing).

All six IAMs included in this study have partly based their information on mitigation potential and costs on the US-EPA MAC curves (Weyant et al., 2006) to estimate the marginal abatement costs of non-CO_2 GHGs. This includes the information presented by Delhotal et al., (2006) for methane and nitrous oxide emissions from waste, energy and industry, DeAngelo et al., (2006) for methane and nitrous oxide mitigation from agriculture, and Schaefer et al., (2006) for emissions from the f-gases (HFCs, PFCs, and SF6). IMAGE and REMIND use a set of MAC curves that also try to capture dynamic changes over time as described in Lucas et al., (2007). This set combines information from the US-EPA curves with information taken from Graus et al., (2004) and extends the abatement potential over time using a technological development factor. The abatement potential is reformed with first-order estimates on future maximum attainable reduction potentials combined with an inertia effect representing implementation barriers. GCAM and MESSAGE have implemented the information underlying the US-EPA MAC curves, but at the level of underlying technologies. The MAC curves in these models are held constant over time. TIAM-ECN uses a combination of DeAngelo et al., (2006) and Lucas et al., (2007).

In the analysis, we compare models for three different Kyoto non-CO_2 gases in different sectors and regions. In implementing a multi-gas strategy, all models considered here use Global Warming Potential (GWPs) as reported by IPCC's Fourth Assessment Report (AR4) (IPCC, 2007) to determine the relative value of reducing 1 kg of each gas. Here, we report the emissions of all sources in terms of CO_2-eq using AR4 GWPs. For the sectoral comparison, we compared the models with respect to the emission trends for the following sectors: 1) energy production; 2) energy end-use; 3) livestock production; 4) rice production; 5) fertilizer use; 6) deforestation, including savannah burning; 7) solvents; and 8) waste. Specific definitions can be found in Appendix B. In order to compare in the regional dimension, we defined a set of 5 aggregated world regions for comparison: OECD90, Asia, Latin America, Middle East and Africa, and the

reforming economies of Eastern Europe and the Former Soviet union, see Appendix C for specifics.

Finally, it should be noted that the two scenarios above do not provide information on the underlying marginal abatement curves across the models – as they will use different carbon taxes to achieve a similar climate target (2.8 W/m^2). In order to systematically compare the potential across the models, we have therefore also look into non-CO_2 emission reduction using scenarios with the same carbon tax. For the comparison we have used diagnostic scenarios developed in the AMPERE project (Kriegler et al., in press). One of the scenarios in this set, starts with US$12.50/ton CO_2eq in 2010, increasing 4% per year to around $426/ton CO2-eq in 2100. The scenarios used harmonized population and GDP data (OECD, 2012) and are therefore very suitable to compare emission reductions across the models. We look at the reductions in this scenario compared to the baseline, plotting the value of the tax against the emission reduction.

4.2.2 Simple climate model runs exploring implications of non-CO_2 reduction potential

In order to get further insight into the importance of the findings regarding non-CO_2 abatement we have performed an additional set of experiments using the MAGICC model (version 6) (Meinshausen et al., 2011). In the experiments we used different assumptions on the mitigation potential of non-CO_2 gases, by either assuming: 1) no further reductions than the *Baseline*, 2) using the non-CO_2 results of the different models in combination with a standard CO_2 scenario (IMAGE), 3) assuming that emissions can be reduced to zero and 4) by combining the different assumptions of the non-CO_2 gases with perturbed IMAGE output of the *450* scenario in which the negative CO_2 emissions were removed in order to compare the impacts of non-CO_2 assumptions against the influence of negative CO_2 emissions.

4.3 Results

4.3.1 Non-CO_2 impact on global emissions

In the six LIMITS models, non-CO_2 Kyoto gas emissions account for 26-29% of global GHG emissions in 2005 (Figure 1). In the *Baseline* scenario, the share declines to 16-27% in 2100 as a result of a more rapid increase of CO_2 emissions (98-181%) compared to non-CO_2 (23-148%). A key reason for this difference in growth rates is that the main driver of CO_2 emissions (energy use) is expected to grow faster than the main driver of non-CO_2 emissions (for a significant part land-use), as will be discussed further in the sectoral analysis.

Interestingly, for the *450* scenario an opposite trend can be noted (Figure 1Figure). As discussed by van Vuuren and Riahi, (2011); and Kriegler, (2013), in deep mitigation scenarios, CO_2 emissions tend to be reduced to negative numbers (by using bio-energy in combination with carbon capture and storage (CCS)). At the same time, reductions of non-CO_2 gases are assumed to be constrained (see Sections 3.2 – 3.4). In total, across the different models the non-CO_2 Kyoto gas emissions in a 450 scenario are reduced by 16-47% compared to the *Baseline* scenario in 2050 and further reduced by 46-72% 2100. This means that by 2100, the non-CO_2 Kyoto emissions amount to 11-14 Gt CO_2-eq/yr across the models, which are comparable to 2005 levels (12-13 Gt CO_2-eq/yr). A remarkable result is that in the mitigation scenario (*450)* the contribution of non-CO_2 gases in emissions tend to increase over time (assuming the reduction of CO_2 emissions is implemented) – even going to levels above 100% of total emissions, as a result of total emissions becoming net negative. At the same time, in terms of forcing, CO_2 remains the most important contributor to climate change. Figure 1 thus emphasizes that assumptions on the mitigation of non-CO_2 gases become increasingly important over time. Certainly if the option to further create negative emissions from CO_2 is constrained (due to limitations on bio-energy availability or CCS), assumptions on the non-CO_2 gases thus become critically important in achieving low concentration targets.

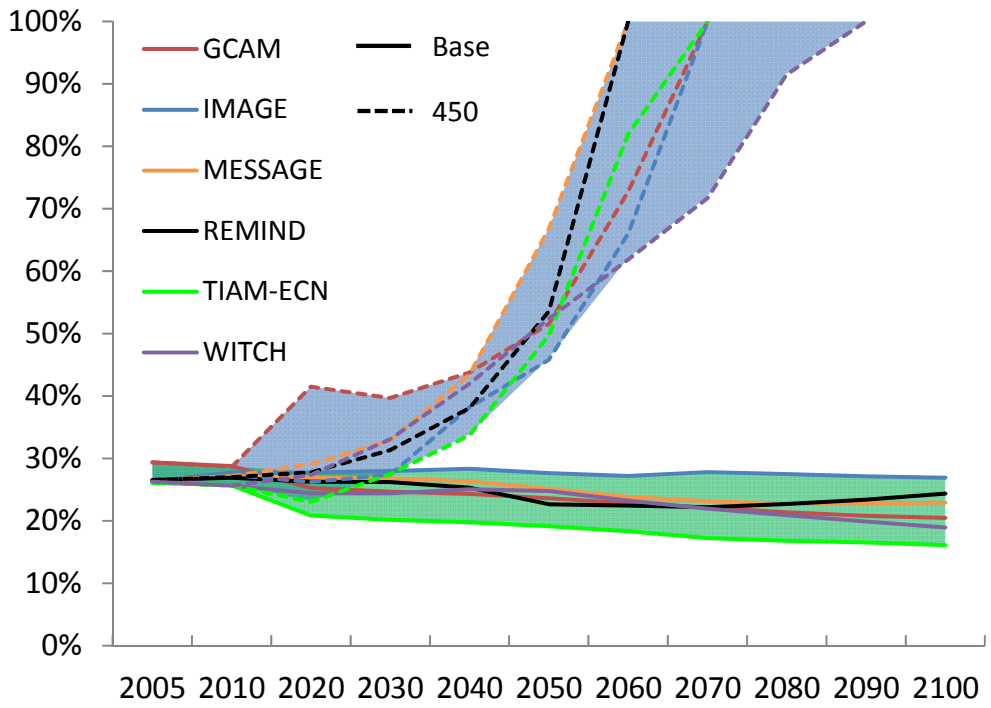

Figure 1: Non-CO_2 emissions as fraction of total Kyoto gases in *Baseline* and *450* scenario.

In Figure 2, we have broken down the emissions by gas. Across the different LIMITS models, the 2005 methane emissions account for approximately 66-74% of the non-CO_2 emissions, the N_2O emissions for 26-29% and the emissions of F-gasses for 5-6%. The overall growth of 23-148% by 2100 in the *Baseline* scenario is a result of a growth of methane emissions of 20-88%, for N_2O -8-101% and for F-gases 19-1269%. The reduction in the *450* scenario results from a reduction of all gases: the emission reductions of methane range from 52% to 74% compared to the *Baseline* scenario in 2100. For N_2O, the numbers are 46% and 72% and for F-gases 50% and 90%. This implies that across all models an overall reduction potential is seen comparable to Lucas et al., (2007). At the same time, however, large differences can be noted across the models at a sectoral level which we will discuss in more detail in sections 3.2-3.4.

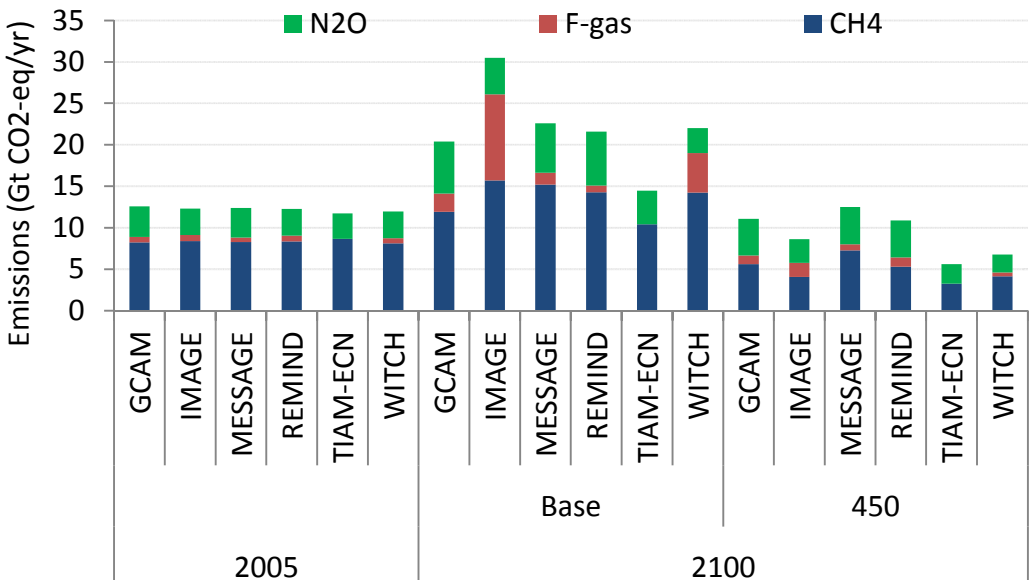

Figure 2: Contribution of CH_4, N_2O and F-gases to total non-CO_2 emissions for the *Baseline* and *450* scenarios in the year 2005 and 2100.

4.3.2 Methane emissions

4.3.2.1 Overall trends in emissions

In 2005, methane emissions in the models are 8-9 Gt CO_2-eq/yr. Similar differences have been reported for historical inventories (Höglund-Isaksson, 2012), so the range is consistent with the uncertainty in emission data. In the *Baseline* scenario, the models project an increase to 10-16 Gt CO_2-eq/yr in 2100 (Figure 3) (38-79% increase over 2005). In all cases, first a faster increase in the 2005-2050 period is noted, followed by relatively small changes in the 2050-2100 period (except for REMIND, which even shows a relatively rapid decline in the second period).

Methane emissions in the *450* scenario shows a reduction across models ranging from 13-58% in 2050 and 35-71% in 2100 compared to the *Baseline* scenario. This implies that, on average, compared to 2005 the models show a slow decline with some model showing nearly constant emissions (MESSAGE) and other models showing a >50% reduction. Figure 4 shows that the most important sectoral emissions sources in 2005 are the energy supply (24-30%), agricultural livestock (31-35%), agricultural rice fields (8-14%) and the waste sector (17-23%). Of the remaining emissions in 2100 in the *450* scenario (Figure 4), the livestock sector is the most important remaining methane source (49-76%).

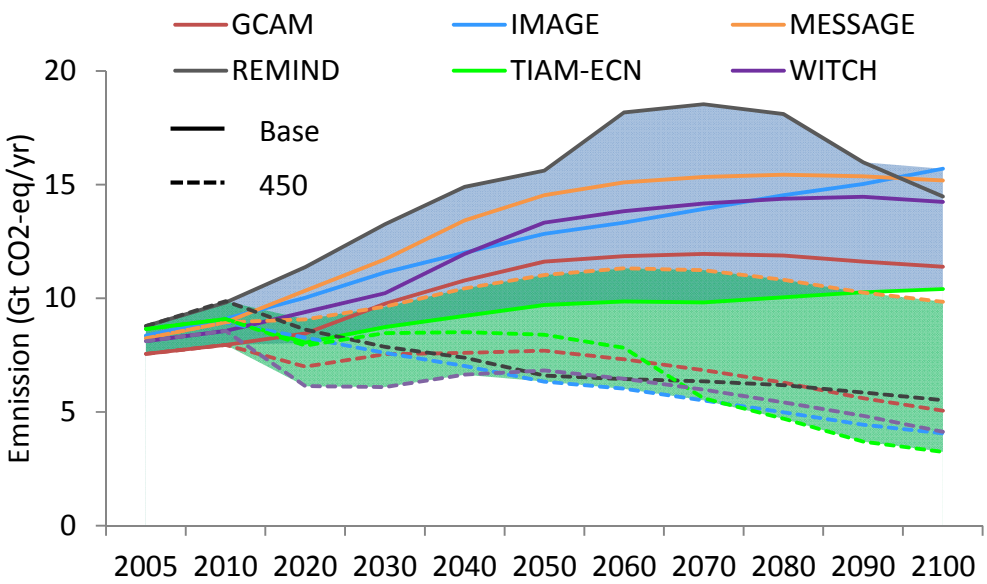

Figure 3: Global CH_4 emissions for *Baseline* and *450* scenario.

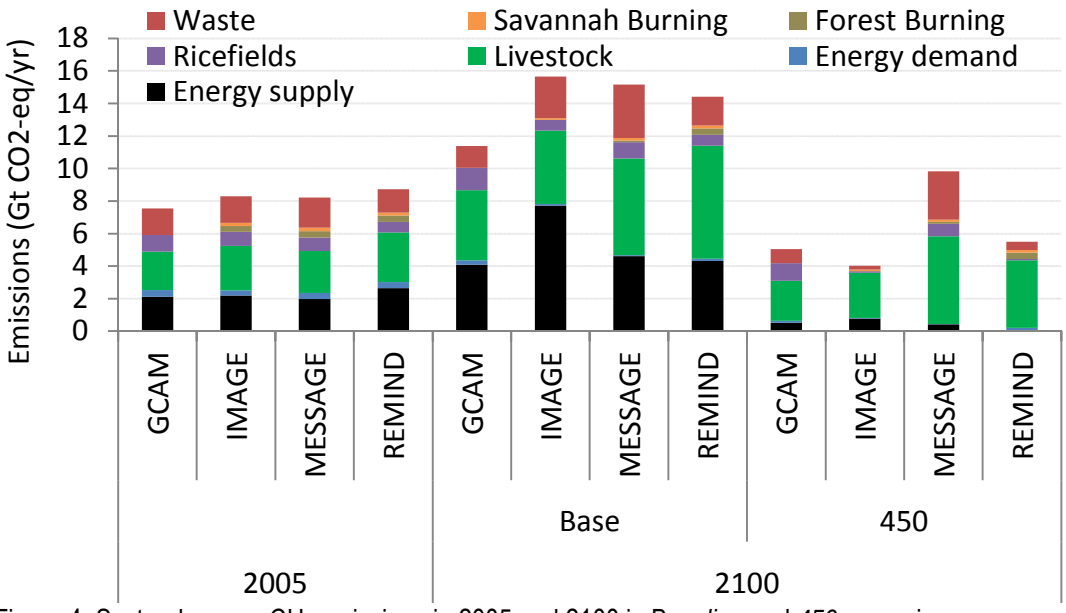

Figure 4: Sectoral source CH_4 emissions in 2005 and 2100 in B*aseline* and *450* scenario.

4.3.2.2 Detailed discussion by sector

Methane emission reductions in the energy supply sector are considerable: across the models a reduction potential for the *450* scenario can be noticed of 87-99% compared to the *Baseline* scenario in 2100 (Figure 5). Within this category, the two main sources are coal mining and oil and gas production emissions. Emission reductions in this sector occur as a result of 1) specific reduction of methane emissions by end-of-pipe measures and 2) reduction of fossil fuel use as a result of climate policy. Together these factors explain the large part of the emissions reduction.

For underground mining, a key "end-of-pipe" measure is methane recovery (Hendriks and de Jager, 2001). There is a trend towards more surface mining, which is harder to mitigate but for the baseline scenario emits less methane emissions (factor 10) compared to underground mining. The abatement options taken into account for oil and gas production are better leakage management and co-production of gas and flaring (US-EPA, 1999; Hendriks and de Jager, 2001). Most emissions sources in energy supply can be mitigated at low cost.

The agricultural livestock sector shows significantly lower reduction potential ranging from 9-43% across the models. Three models (IMAGE, REMIND and GCAM) show a reduction of 39-43% while MESSAGE shows a more constrained reduction of only 9%. The two sources in this sector are enteric fermentation and animal waste emissions. Abatement options to reduce enteric fermentation emissions are dietary change and the use of more productive animal types (Riemer, 1999; Graus et al., 2004). The animal waste abatement option is the capture and use of methane emissions through anaerobic digesters (Graus et al., 2004).

Emissions from agricultural rice fields show a very large uncertainty range for reduction potential across the models ranging from 22 to 88%. While all models include emission reductions in this sector based on assumed changes in rice varieties and changing water management (see also Lucas et al (2007)), they vary with respect to assumptions on the future technical improvements in these mitigation options and the degree with which these technical measures can be implemented (given the large amount of actors involved). Some models (IMAGE/REMIND) assume significant changes in the potential of these options – in particular related to the potential to implement existing options. Two models (MESSAGE/GCAM) only show a reduction of 21-24%. Clearly, agricultural rice emissions are strongly regionally related, with 80-93% of global emissions occurring in Asia throughout the century (see section 3.5).

The waste sector shows very large differences across the models. The MESSAGE model shows a reduction potential of only 10% (starting from a high *Baseline*), while the IMAGE and REMIND models show 90% and 72% reduction potential in 2100 compared to the *Baseline*. GCAM shows a 34% reduction. The two sources in this sector are landfill and sewage and waste water emissions. Landfill emissions can be abated by either the reduction of organic material in landfills or by landfill gas recovery (Bates, 2001). Sewage and waste water emissions can be abated by more waste water treatment plants in combination with methane recovery and aerobic waste water treatment (Lucas et al., 2007).

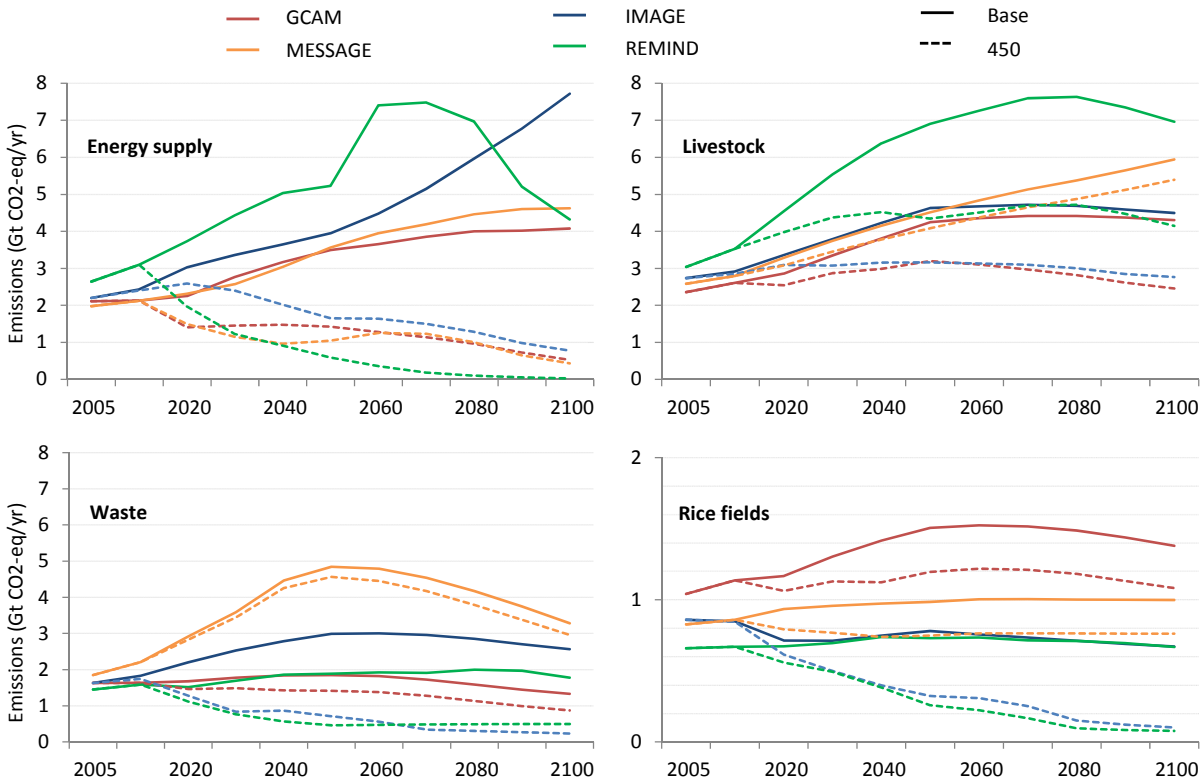

Figure 5 a) CH_4 emissions from energy supply sector. b) CH_4 emissions from agricultural livestock sector. c) CH_4 emissions from the waste sector, d) CH_4 emissions from agricultural rice fields. Note the TIAM-ECN and WITCH model lack sectoral detail to be included in this analysis.

4.3.3 N_2O Emissions

4.3.3.1 Overall trends in emissions

In 2005, N_2O emissions in the models are 2.3-3.6 Gt CO_2-eq/yr. The range is consistent with historical emission inventories (Granier et al., 2011). In the *Baseline* scenario, the models project a growth of 32-108% by 2100, except for WITCH that shows a decline in the second half of the century to -8% in 2100 compared to 2005 (Figure 6). In the *450* scenario, three models (IMAGE, TIAM-ECN and WITCH) show a reduction of 9-34% by 2100 compared to 2005 emissions, while the three other models (GCAM, MESSAGE and REMIND) show an increase of 26-42%. In terms of reduction compared to *Baseline* in 2100 the range is 10% (MESSAGE) to 42 % (TIAM-ECN). The overall reduction potential for N_2O is, thus, smaller than for CH_4 (35-71%), partly related to the much smaller role of the energy sector. The most important sectoral sources for N_2O emissions in 2005 are the livestock (37-77%) and fertilizer sector (27-49%)[2] (Figure 7), both sectors are discussed in detail below. The livestock range excludes the MESSAGE model as emissions from manure management are reported as part of the fertilizer sector, while the other models include this in the livestock sector. For MESSAGE the livestock sector accounts for 7% and the fertilizer sector for 82%.

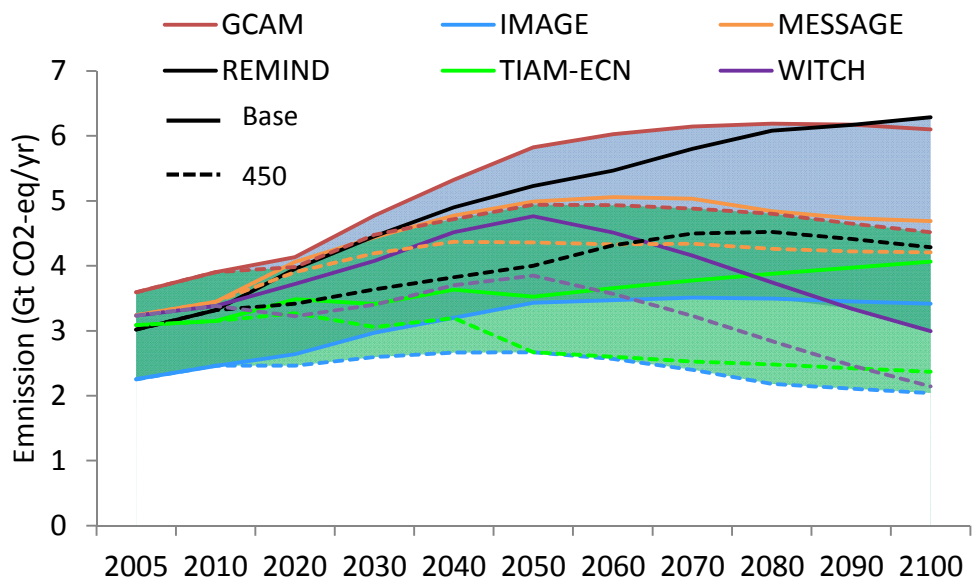

Figure 6: N_2O emissions for *Baseline* and *450* scenario.

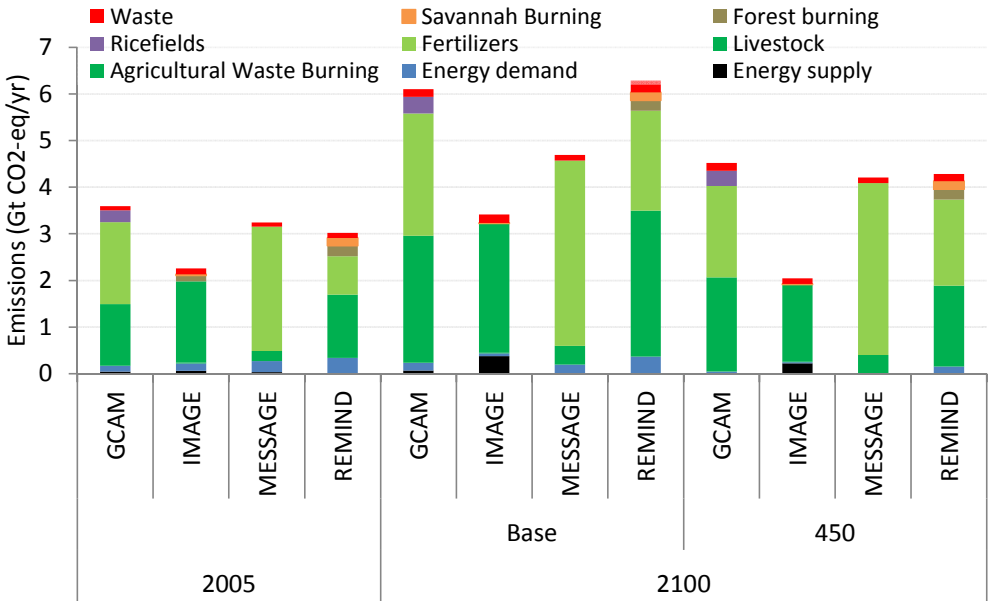

Figure 7: Sectoral source N_2O emissions in 2005 and 2100 in *Baseline* and *450* scenario. Note: Manure management emissions for the MESSAGE model are accounted for in the fertilizer sector.

4.3.3.2 Detailed discussion by sector

Agricultural livestock emissions (Figure 8) are projected to increase by 59-130% in the *Baseline* scenario in the 2005-2100 period compared to 2005, driven by increasing demand for dairy products and meat. The emission reduction in the *450* scenario in 2050 ranges from 16 to 35% compared to the *Baseline* scenario and from 26 to 45% in 2100. It should be noted that for MESSAGE, emissions reduction for this sector are actually accounted for in the fertilizer sector[2]. Abatement options for the livestock sector are dietary changes, increasing animal productivity,

optimizing manure management and limiting the free–grazing share of livestock (Clemens and Ahlgrimm, 2001; Brink, 2003). Most of the emissions are projected in the Asia and OECD region, together around 70% of global 2010 emissions.

The emissions from agricultural fertilizer (Figure 8) increase by 49-160% in 2100 in *Baseline* compared to 2005 for most models, only the IMAGE model projects a slight decline of 4%. Here fertilizer use is the most important driver. The sector shows relatively low emission reduction potential in the *450* scenario compared to *Baseline* with ~7% in 2100 for MESSAGE and IMAGE, and 14-25% for REMIND and GCAM. Abatement options for this sector are improving fertilizer use efficiency, restricting the use of fertilizer in time, using fertilizer-free zones and replacing current fertilizer with new types with lower emissions (Hendriks et al., 1998; Mosier et al., 1998; Graus et al., 2004).

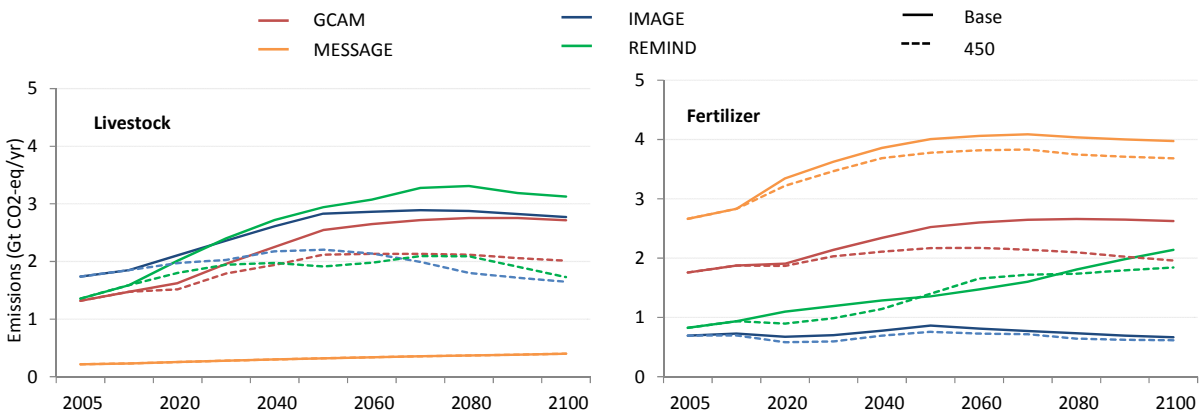

Figure 8 a) N_2O emissions from the agricultural livestock sector. b) N_2O emissions from agricultural fertilizers use.

4.3.4 F-gases

In 2005, F-gas emissions in the models are 0.5-0.8 Gt CO_2-eq/yr. In the *Baseline* scenario, they are projected to increase to 0.8-10 Gt CO_2-eq/yr in 2100 (12-1269% increase over 2005) (Figure 9). Two models (IMAGE and WITCH) project significantly higher increase of emissions (1269% and 677%) than the other models (GCAM 237%, MESSAGE 162%). REMIND shows an increase of 11%. The *450* scenario shows reduction across models ranging from 52-90% in 2100 compared to *Baseline.* In REMIND, F-gas emissions are exogenous and show, therefore, no change in the mitigation scenario as a result of a carbon tax. The projections are left out of further analysis.

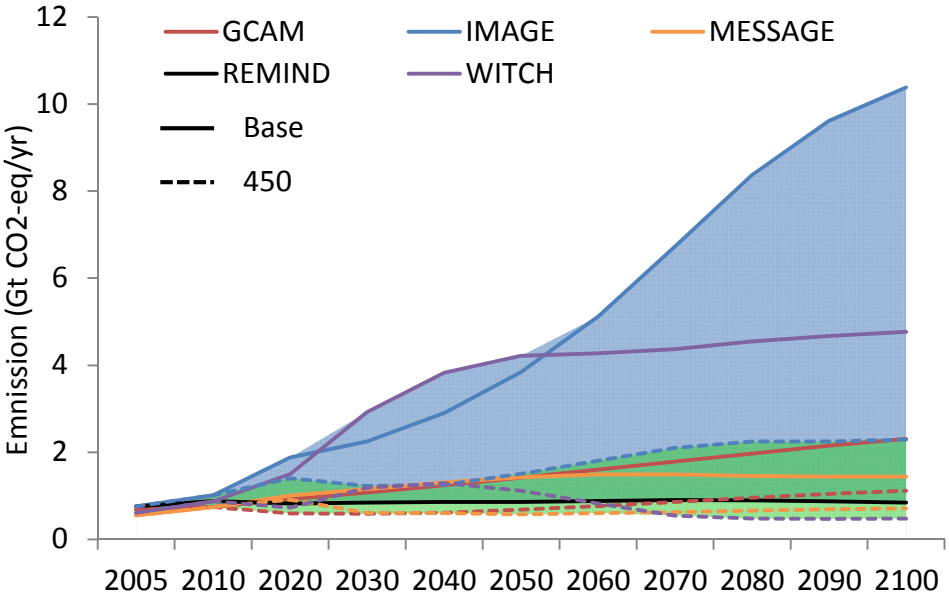

Figure 9: F-gas emissions for *Baseline* and *450* scenario

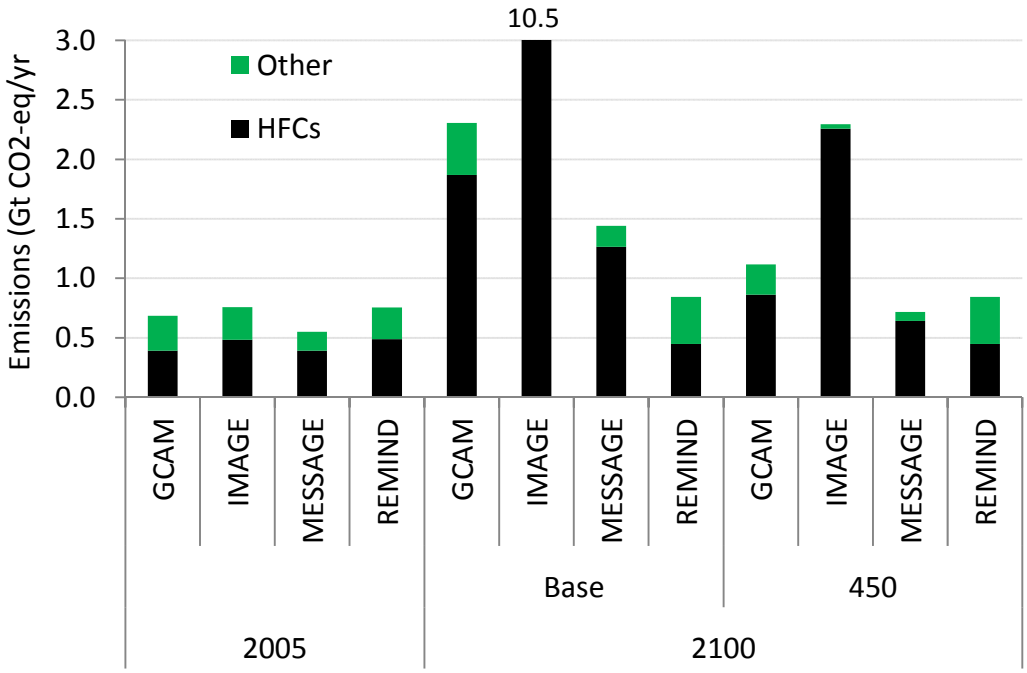

Figure 10: Sectoral source F-gas emissions in 2005 and 2100 in *Baseline* and *450* scenario. In REMIND, F-gas emissions are implemented exogenously and show, therefore, no change as a result of carbon tax. IMAGE F-gas emission are 10.5 Gt CO_2-eq in total, of which the majority (97%) are HFC emissions.

In 2005, HFCs account for 57-71% of total F-gas emissions (Figure 10). Most of the growth in the F-gas emissions over the century is driven by HFC gases. As a result their share increases over

time to 81-97% in 2100 in *Baseline* scenario due to a growth of 222-1968% in 2100 compared to 2005. HFC emissions in the IMAGE model follow projections developed by Velders et al., (2007) suggesting significant emission growth without policy intervention. The main driver for growth is the refrigeration and air conditioning industry. In the 450 scenario strong reduction of 49-77% are seen for the HFC emissions. Abatement options are 1) thermal destruction of HFC emissions during production (Irving and Branscombe, 2002; Klein Goldewijk et al., 2005), 2) better sealed applications to prevent leakages (Schwarz and Leisewitz, 1999), 3) HFC recovery of disposed products, and 4) substitution by substances with zero GWP (Heijnes, 1999).

The "other" F-gases consist of mainly PFC and SF6 gases that are used in the semiconductor, magnesium, aluminum, foam and solvent industry. In 2005, combined PFC and SF6 emissions consist of 29-43% of total F-gas emissions. In the *Baseline* scenario, emissions increase by 13-50% in 2100. Their relative contribution to the total F-gas emissions becomes smaller due to the strong growth of HFC emissions. Reductions in the *450* scenario compared to *Baseline* range between 41% and 58% in the year 2100. For PFC, the abatement options are (a) the use of modern process technology for aluminum production (Heijnes, 1999) (b) emission capture and (thermal) destruction in semiconductor manufacture (Heijnes, 1999); and (c) replacing the use of PFCs as solvents. For SF6 the abatement options are (a) improved recovery; (b) minimization of leakage; and (c) optimization of use (Heijnes, 1999; Wartmann and Harnisch, 2005).

4.3.5 Regional distribution of emissions

In 2005, 31-44% of global methane emissions come from Asia (see Table 1). This is mainly due to emissions from rice production, that are much more prominent in Asia. Also methane emissions from energy supply and livestock play a role but these are more evenly spread across the regions. In the *Baseline* scenario, in 2100, the share in global methane emissions increases in the Middle East and Africa and decreases in Asia, compared to their 2005 shares, in particular due to an increase in the energy supply and livestock sector. In three models (MESSAGE, IMAGE and GCAM) Asia will remain the most important methane emitter (37-44%), while the other models (WITCH and REMIND) show that the Middle East and Africa region would become the largest emitting region. In the *450* scenario, in 2100, the share of global methane emissions is not much different than in the baseline scenario for most regions. Methane emissions decrease in all regions except the Middle East and Africa region (92%-189%), where emissions from livestock still increase significantly.

For N_2O emissions, both Asia (25-41%) and the OECD90 region (23-30%) were the largest emitters in 2005, with no clear difference in sectoral sources. Similar to methane, also the N_2O share of the Middle East and Africa in global emissions increases compared to 2005, in both the *Baseline* and the *450* scenario.

For the F-gas emissions the OECD90 region is clearly the largest emitter (47-62%). Towards 2100, however, the share in global F-gas emissions in the OECD90 region decreases significantly, while the share of Asia and the Middle East and Africa increases. The increase of F-gases in the latter two regions is largely related to increased use of air conditioning by their increasing and more affluent populations. For the *450* scenario, most regions would still see an

increase compared to 2005 levels. Reduction levels are similar across the regions, leaving the global distribution almost unchanged.

		Asia	Latin America	Middle East and Africa	OECD90	Reforming Economies
CH_4	2005	39 [31 - 44]	13 [13 - 14]	16 [13 - 20]	19 [15 - 24]	10 [9 - 14]
	2100 base	35 [24 - 44]	11 [8 - 16]	27 [18 - 36]	17 [10 - 22]	9 [6 - 11]
	2100 450	37 [23 - 47]	15 [8 - 25]	31 [23 - 42]	12 [6 - 16]	5 [2 - 9]
N_2O	2005	34 [25 - 41]	14 [13 - 16]	18 [14 - 25]	25 [23 - 30]	7 [4 - 9]
	2100 base	32 [29 - 36]	14 [12 - 16]	30 [25 - 37]	17 [13 - 21]	6 [2 - 10]
	2100 450	27 [18 - 37]	15 [12 - 18]	32 [19 - 46]	17 [11 - 27]	6 [3 - 13]
F-gases	2005	25 [18 - 30]	5 [3 - 6]	5 [2 - 7]	55 [47 - 62]	7 [6 - 9]
	2100 base	42 [30 - 57]	7 [3 - 11]	17 [2 - 29]	26 [12 - 50]	5 [3 - 8]
	2100 450	41 [30 - 57]	7 [3 - 12]	17 [2 - 29]	27 [11 - 50]	5 [3 - 8]

Table 1: Regional share in percentages of global emissions per gas, in 2100 for the *Baseline* and *450* scenario.

Figure 11 shows the share of non-CO_2 emissions in total regional GHG emissions. This share is around 23-50% in 2005, except for OECD90 where it is much smaller (14-23%). For most regions, the high share of CH_4 emissions come from land-use sources, while in the Reforming Economies the energy supply sector is dominant. Also for N_2O the land-use sector is a dominant source , except for the OECD90 region in which the transport sector is also important. In the *Baseline* scenario in 2100, the share of CH_4 and N_2O in total emissions compared to 2005 levels decreases significantly in Asia and, to a lesser extend, also in Latin America and the Middle East and Africa. The share, however, increases in OECD90 and the Reforming Economy regions. This is mainly due to a large increase in CO_2 emissions in the developing regions. F-gas share are only small and only decrease slightly towards 2100.

In the *450* scenario, in 2100, the share of the non-CO_2 GHG emissions in total emissions (excluding the negative emissions from bio-energy combined with carbon capture and storage, bio-CCS) is much higher than in the *Baseline*, also compared to levels observed in 2005. The CO_2 emissions from energy production are reduced much more than the non-CO_2 emissions (and even go negative due to the use of bio-CCS), while for CH4 and N2O there are several sources that are hard to abate (see Section 3.1).

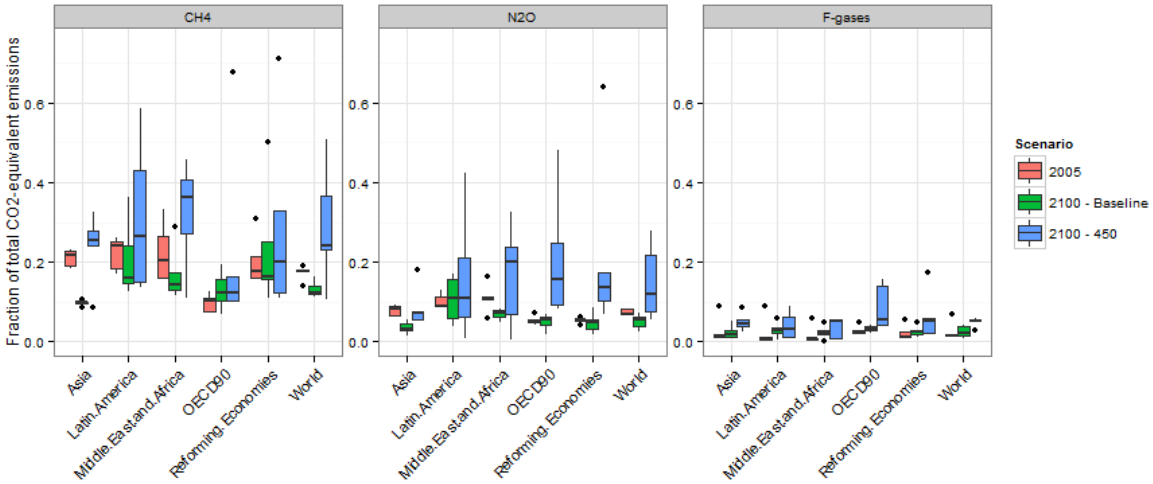

Figure 11: Regional shares of non-CO_2 emissions. For the 450 scenario bio-CCS is excluded from the total regional emissions.

4.3.6 Overall marginal abatement curves

Figure 12 shows the total non-CO_2 emission reduction (CH_4, N_2O and F-gas) in the harmonized scenarios from the AMPERE project (see methods) against the value of the carbon tax, giving an indication of the underlying MACs. Consistent with the earlier results, the figure shows that GCAM and MESSAGE show considerable less reductions for a given carbon price. This is in particular the case for methane and F-gas emissions. For N_2O, only GCAM shows relatively low reductions. The differences result from different assumptions on technological learning and maximal technical reduction feasibility (see Appendix C).

Overall, higher emission reduction levels are seen in the *450* scenario (MESSAGE 39%, GCAM 46%, WITCH 70%) compared to the diagnostic scenario (MESSAGE 31%, GCAM 46%, WITCH 69%), with the exception of the IMAGE model. This latter is related to the spread of carbon taxes in the LIMITS scenarios (relatively low for IMAGE).

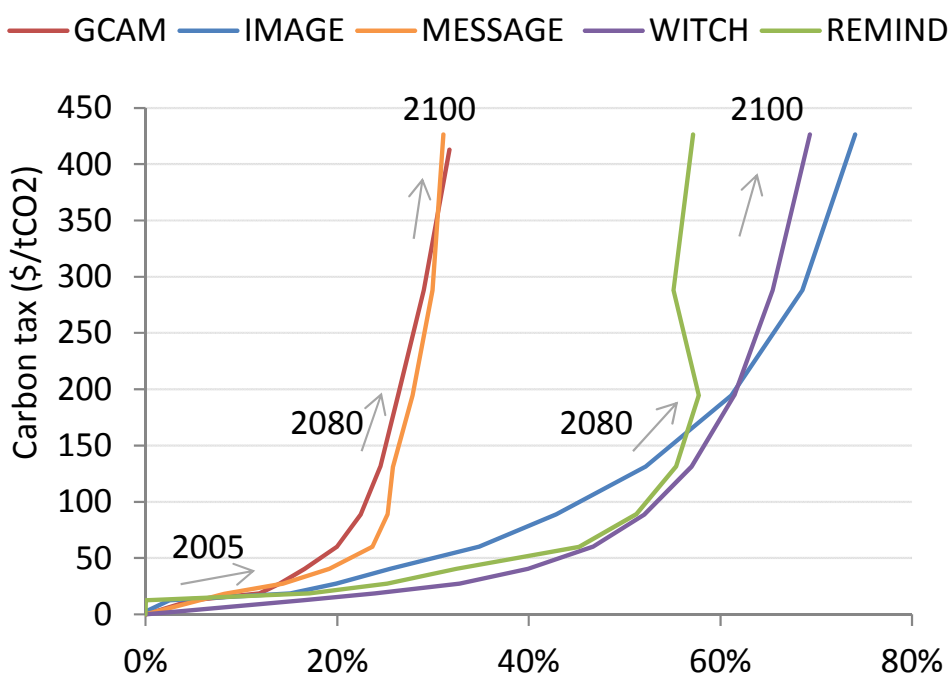

Figure 12: Increasing carbon tax (4% per year) versus non-CO_2 reduction compared to baseline. Data is taken from the diagnostic runs of the AMPERE project (Kriegler et al., in press)Kriegler et al., in press). Here, the carbon tax in 2005 is $0 per ton CO_2 increasing to $12.50 in 2010, reaching approximately $200 in 2080 and $426 in 2100.

4.3.7 Implications for climate change

In the previous sections, we have seen that in all integrated assessment models the reduction potential of non-CO_2 gases is significantly constrained compared to CO_2. At the same time, the results also show that there is quite some uncertainty in the reduction potential for non-CO_2 gases. A key question that emerges from this is the implication of these findings for the feasibility of stringent climate targets, such as the 2 degree C target.

In order to explore this, we have calculated the impact of the different non-CO_2 emission projections on temperature increase. We have made different combinations of the outcomes of the scenarios discussed in the previous sections (see Table 2). Because we focus on the impacts of non-CO_2 gas assumptions, we use IMAGE model results for CO_2 as default. Clearly, by combining the outcomes of different models and scenarios we create rather inconsistent sets of assumptions. However, these pathways can still provide good insights into the role of assumptions on the reduction potential for non-CO_2 gases for achieving low climate target.

Table 2: Pathway definitions used for climate experiments

Pathway	CO_2	Non-CO_2
IMAGE-base	IMAGE baseline	IMAGE baseline
IMAGE-base/450-IMAGE	IMAGE baseline	IMAGE 450
IMAGE-450/450-X (x-name model)	IMAGE 450	450 from the different models
IMAGE-450/Base-IMAGE	IMAGE 450	IMAGE baseline
IMAGE-450/zero	IMAGE 450	Zero non-CO_2 emissions
IMAGE-NoNeg450/base-IMAGE	IMAGE 450 restricting emissions to go negative	IMAGE Baseline
IMAGE-NoNeg450/450-IMAGE	IMAGE 450 restricting emissions to go negative	IMAGE 450

We assess the impact of the non-CO_2 emission reductions by comparing the temperature differences between the *IMAGE-Base* and the *IMAGE-base/450* pathway. This comparison shows a 0.8C° reduction in 2100 temperature (from 3.7 C° to 2.9 C°).

The impact of the uncertainty in emission reduction potential of the different models can be assessed by comparing the temperature differences between the pathways that combine the CO_2 emissions from the *IMAGE-450* scenario with the non-CO_2 emissions from the *450* scenarios of the various models. Figure 13 shows a range of 1.9 to slightly below 1.6° in 2100 (thus around 0.3°C difference). Three models (IMAGE, TIAM-ECN and WITCH) show an early peak (1.7-1.8 C°) around 2070 followed by a decline to 1.6-1.7 C° in 2100, while the other models (GCAM, MESSAGE and REMIND) show a later and higher temperature peak (1.8-1.9 C°) around 2085 followed a slower decline to 1.8-1.9 C° in 2100. The differences across the models might be important for conclusions on the feasibility of the 2°C target given the 0.3° C range.

Finally, we compare the temperature outcomes between the normal *IMAGE-450* scenario with the *IMAGE-450/zero* pathway that immediately reduces non-CO_2 emissions to zero in 2010. This shows the potential impact of completely phasing out of non-CO_2 emissions (if it would be possible to increase reduction potential by e.g. new technologies or lifestyle changes). Assuming an immediate phase-out of non-CO_2 GHG the 2100 temperature decreases by 0.8 C° compared to the *IMAGE-450* scenario, resulting in an increase of the global mean temperature of only 1°C compared to pre-industrial levels. Thus, further reductions of non-CO_2 GHG increase the likelihood of reaching the 2°C target and reduce the requirement of steep long-term CO_2 emission reductions from the energy system.

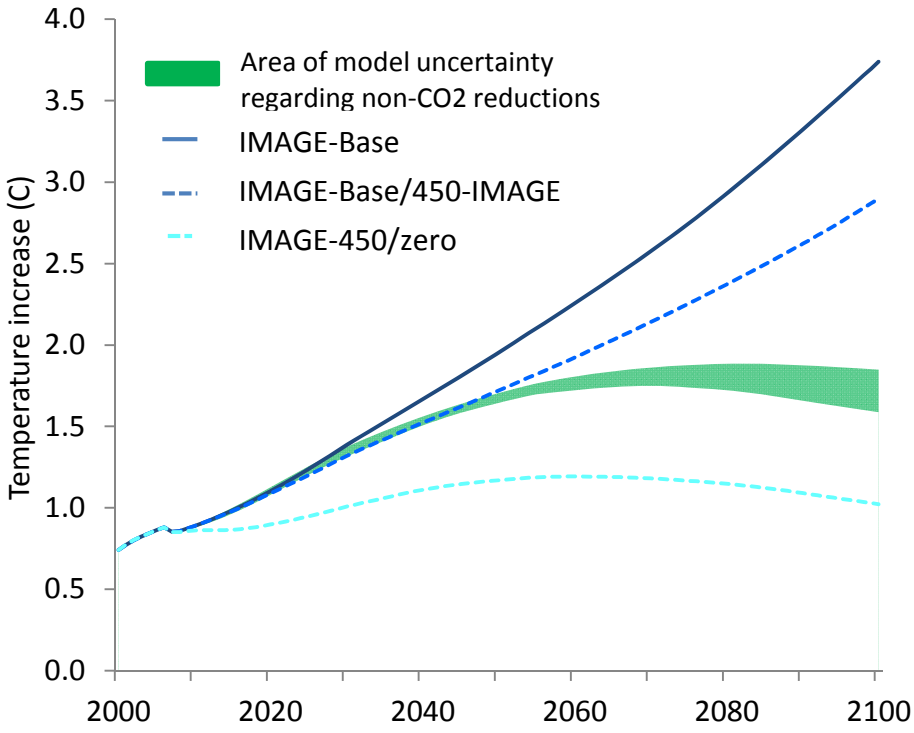

Figure 13: Temperature increase (based on MAGICC) for different non-CO_2 emission levels for the period 2000-2100 (see table 3 for scenario definitions). The green area indicates the model uncertainty regarding non-CO_2 reductions.

It should be noted that the temperature development towards the end of the century (and later) is determined by both the remaining non-CO_2 emissions and level of the negative CO_2 emissions (via bio-CCS). In order to illustrate this further, we compare the impact of the negative CO_2 emission on the global temperature increase with that of the non-CO_2 emission reductions (Figure 14). Comparing the normal IMAGE *450* scenario with a scenario that excludes negative CO_2 emissions (IMAGE-NoNeg450/450-IMAGE) result in a difference of temperature of 0.2 C°. Interestingly, the impact of not considering non-CO_2 emission reductions in climate mitigation (IMAGE-450/Base-IMAGE) (0.4 C°) is stronger than the impact of excluding negative emissions (0.2 C°).

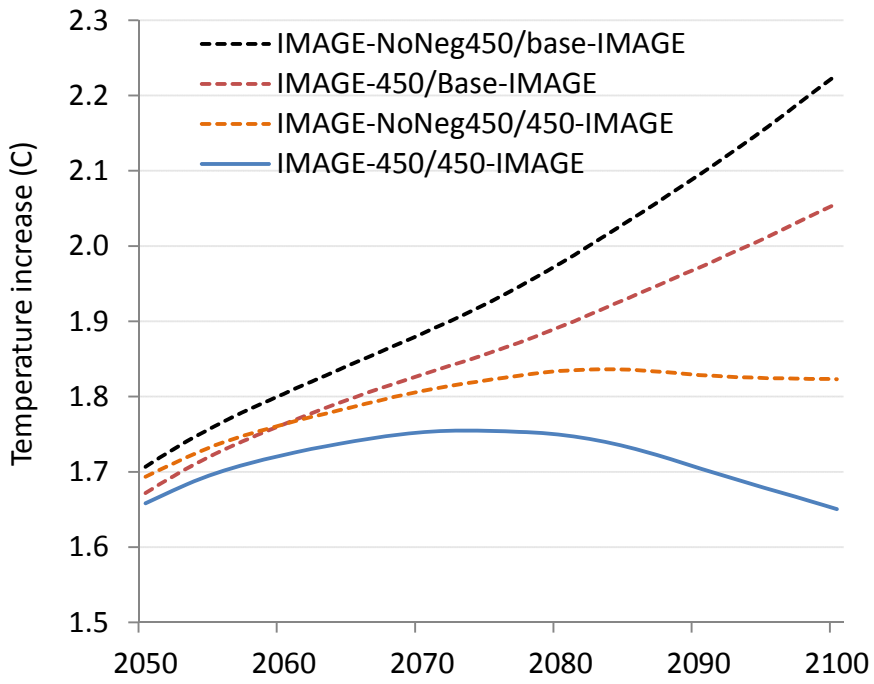

Figure 14: Temperature increase for three experiments (IMAGE-450/Base, IMAGE-NoNeg450/Base and the IMAGE-NoNeg450/450) compared to the normal IMAGE-450/450-IMAGE scenario.

4.4 Conclusion

In this report we have assessed the sectoral mitigation effort of non-CO_2 emission sources (CH_4, N_2O and F-gases) in a scenario aiming for long-term stabilization of the global mean temperature of 2^{O}C compared to pre-industrial levels. To cover some of the uncertainty we have used a model comparison approach that includes results for six different integrated assessment models. The questions we look into are: (1) What is the role of the remaining non-CO_2 emissions in deep mitigation scenarios?; and (2) How do mitigation strategies compare across models for the reduction of non-CO_2 emissions at a sectoral level? The following conclusions can been drawn:

In scenarios with deep mitigation targets, non-CO_2 emissions could become a lion's share of total greenhouse gas emissions. In deep mitigation scenarios CO_2 emissions tend to be reduced to negative numbers, by using bio-energy in combination with CCS. At the same time, reductions of non-CO_2 gases are assumed to be constrained, particularly in the land-use sectors. This implies that in all models looked at, non-CO_2 emissions become increasingly important over time in terms of the remaining share in total emissions and that they are compensated by strong reductions of CO_2 emissions from the energy system.

In general, strong emission reductions can be achieved in the energy supply sector but much less in the land-use sectors. The energy supply sector shows a consistent reduction potential of CH_4 across models for the *450* scenario of 87-99% compared to *Baseline* scenario in 2100. This reduction is driven by both end-of-pipe mitigation assumptions, such as gas flaring and CH_4 recovery, and reduced fossil fuel use. On the contrary, the livestock sector shows both less overall reduction potential and considerable differences between the models, resulting in a wider range of 9-43% reduction for CH_4 in 2100 and 26-45% for N_2O.

At the levels of sectors considerable differences can be noted across the models.
There are considerable differences between the models. For example, reductions from the livestock sector range for CH_4 emission from 9 to 43% and for N_2O from 26 to 45%. These differences can add up significantly, for example CH_4 emission reductions from the waste sector shows a reduction of 10% by 2100 in the MESSAGE model and up to 90% in the IMAGE model, which is approximately 3 Gt CO_2-eq/yr difference. The same holds for CH_4 emission reductions from the livestock sector, where MESSAGE shows a reduction of 9% by 2100 and the other models 39-43%, resulting in a difference of approximately 2 Gt CO_2-eq/yr. Differences between model results with respect to the non-CO_2 emission projection and reductions are especially high for the F-gases, where the lowest and highest projections differ a factor 6.

Assumptions on abatement potential and costs for non-CO_2 greenhouse gases are critically important in reaching low temperature targets
Overall, the non-CO_2 emission reductions for the 450 scenario differ between 46% and 72% compared to *Baseline* in 2100 across the different models. Around 0.3^{o}C can be attributed to this uncertainty for non CO_2 mitigation potential. Furthermore, assuming an immediate phase-out of non-CO_2 emissions would reduce climate change by 0.8 C°. Obviously, this is not possible according to current estimates of technology and lifestyle patterns, but the experiments emphasize the importance of better exploring the potential for further non-CO_2 emission reductions in all sectors.

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References

Bates, J. (2001). Economic Evaluation of Emission Reductions of Nitrous Oxides and Methane in Agriculture in the EU [: Bottom-up Analysis, European Commission.

Bosetti, V., C. Carraro, et al. (2006). "A world induced technical change hybrid model." The Energy Journal 27: 13-38.

Bosetti, V., M. Tavoni, et al. (2009). The 2008 WITCH model: new model features and baseline, Nota di lavoro//Fondazione Eni Enrico Mattei: Sustainable development.

Brink, C. (2003). Modelling cost-effectiveness of interrelated emission reduction strategies: the case of agriculture in Europe, Wageningen Univ.

Calvin, K. V. e. a. (2011). GCAM wiki Documentation. Wikipedia.

Clemens, J. and H.-J. Ahlgrimm (2001). "Greenhouse gases from animal husbandry: mitigation options." Nutrient Cycling in Agroecosystems 60(1-3): 287-300.

DeAngelo, B. J., C. Francisco, et al. (2006). "Methane and nitrous oxide mitigation in agriculture." The Energy Journal(Special Issue# 3): 89-108.

Granier, C., B. Bessagnet, et al. (2011). "Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980–2010 period." Climatic Change 109(1-2): 163-190.

Graus, W., M. Harmelink, et al. (2004). "Marginal GHG-abatement curves for agriculture." Ecofys, Utrecht, the Netherlands.

Heijnes, H. (1999). Reduction of the emissions of HFC's, PFC's and SF6 in the European Union, European Commission.

Hendriks, C. and D. de Jager (2001). "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis." A final report to European Commission.

Hendriks, C., D. De Jager, et al. (1998). "Emission reduction potential and costs for methane and nitrous oxide in the EU-15." Utrecht, Ecofys.

Höglund-Isaksson, L. (2012). "Global anthropogenic methane emissions 2005–2030: technical mitigation potentials and costs." Atmospheric Chemistry and Physics 12(19): 9079-9096.

IPCC (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. D. Q. S. Solomon, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.). Cambridge, United Kingdom and New York, NY, USA.

Irving, W. N. and M. Branscombe (2002). emissions from HCFC-22 production, Background Studys IPCC Expert Meetings on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. IPCC National Greenhouse Gas Inventories Programme, TSU, Hayama, Kanagawa, Japan: 271–283.

Klein Goldewijk, K., J. G. J. Olivier, et al. (2005). Greenhouse Gas Emissions in The Netherlands 1990–2003, National Inventory Report 2005, National Institute for Public Health and the Environment, Bilthoven, The Netherlands.

Kober, T., B. C. van der Zwaan, et al. (2013). "Emission Certificate Trade and Costs under Regional Burden-Sharing Regimes for a 2 C Climate Change Control Target." Climate Change Economics.

Kriegler, E., N. Petermann, et al. (in press). "Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy." Technological Forecasting and Social Change(Climate stabilization).

Kriegler, E., Tavoni, M., Aboumahboub, T., Luderer, G., Demaere, G., Krey, V., Riahi, K., Rosler, H. (2013). "Can we still meet 2 °C with global climate action ? The LIMITS study on implications of Durban Action Platform scenarios." Climate Change Economics(282846).

Kriegler, E., J. P. Weyant, et al. (2013). "The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies." Climatic Change: 1-15.

Lucas, P. L., D. P. van Vuuren, et al. (2007). "Long-term reduction potential of non-CO2 greenhouse gases." Environmental Science & Policy 10(2): 85-103.

Luderer., G., M. Leimbach, et al. (2011). Description of the ReMIND-R model.

Meinshausen, M., S. C. B. Raper, et al. (2011). "Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration." Atmos. Chem. Phys. 11(4): 1417-1456.

MNP (2006). Integrated modelling of global environmental change. An overview of IMAGE 2.4. T. K. a. K. K. G. A.F. Bouwman. Bilthoven, The Netherlands, Netherlands Environmental Assessment Agency (MNP).

Mosier, A., J. Duxbury, et al. (1998). "Assessing and mitigating N2O emissions from agricultural soils." Climatic Change 40(1): 7-38.

OECD (2012). OECD Environmental Outlook to 2050: The Consequences of Inaction, OECD.

Riahi, K., A. Grübler, et al. (2007). "Scenarios of long-term socio-economic and environmental development under climate stabilization." Technological Forecasting and Social Change 74(7): 887-935.

Riahi, K., E. Kriegler, et al. (2013). "Locked into copenhagen pledges—implications of short-term emission targets for the cost and feasibility of long-term climate goals." Technological Forecasting and Social Change.

Riemer, P. W. (1999). The Abatement of Methane Emissions, IEA Greenhouse Gas R&D Programme.

Rösler, H., B. van der Zwaan, et al. (2014). "Electricity versus hydrogen for passenger cars under stringent climate change control." Sustainable Energy Technologies and Assessments 5: 106-118.

Schaefer, D. O., D. Godwin, et al. (2006). "Estimating future emissions and potential reductions of HFCs, PFCs, and SF6." The Energy Journal(Special Issue# 3): 63-88.

Schwarz, W. and A. Leisewitz (1999). "Emissions and reduction potentials of hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride in Germany." Report for the German Federal Environmental Agency (Umweltbundesamt, UBA, Berlin).

Shindell, D., J. C. Kuylenstierna, et al. (2012). "Simultaneously mitigating near-term climate change and improving human health and food security." Science 335(6065): 183-189.

UNFCCC (2005). Kyoto Protocol to the United Nations Framework Convention on Climate Change.

UNFCCC (2009). Report of the Conference of the Parties on its fifteenth session, held in Copenhagen from 7 to 19 December 2009.

US-EPA, U. (1999). "Methane Emissions 1990–2020: Inventories, Projections, and Opportunities for Reductions." Washington DC, USA.

van der Zwaan, B., I. Keppo, et al. (2013). "How to decarbonize the transport sector?" Energy Policy 61: 562-573.

van Vuuren, D. P. (2007). "Energy systems and climate policy-long-term scenarios for an uncertain future."

van Vuuren, D. P., M. G. Den Elzen, et al. (2007). "Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs." Climatic Change 81(2): 119-159.

van Vuuren, D. P. and K. Riahi (2011). "The relationship between short-term emissions and long-term concentration targets." Climatic Change 104(3-4): 793-801.

van Vuuren, D. P., J. Weyant, et al. (2006). "Multi-gas scenarios to stabilize radiative forcing." Energy Economics 28(1): 102-120.

Velders, G. J., S. O. Andersen, et al. (2007). "The importance of the Montreal Protocol in protecting climate." Proceedings of the National Academy of Sciences 104(12): 4814-4819.

Wartmann, S. and J. Harnisch (2005). "Reductions of SF6 emissions from high and medium voltage electrical equipment in Europe." Environmental Sciences 2(2-3): 273-281.

Weyant, J. P., F. C. de la Chesnaye, et al. (2006). "Overview of EMF-21: multigas mitigation and climate policy." Energy Journal 27(1): 1-32.

Annex I - overview table of capacity saturation, duration, and max growth speed

Table ANNEX I -1 - overview table of capacity saturation, duration, and max growth speed. Margins depicted are a result of 5 global energy-environment models.

		K (GW)		dT (yrs)		Tm	
Scenario	**Variable**	**min**	**Max**	**min**	**max**	**min**	**max**
Base	Biomass|w/o CCS	845	845	84	84	2051	2051
Base	Coal|w/o CCS	7748	31320	102	130	2044	2086
Base	Gas|w/o CCS	8059	32889	67	116	2041	2084
Base	Nuclear	471	9407	28	127	1985	2092
Base	Wind	6978	9088	75	116	2082	2087
RefPol	Biomass|w/ CCS	300	1042	54	61	2080	2092
RefPol	Biomass|w/o CCS	3430	3430	61	61	2058	2058
RefPol	Coal|w/ CCS	68	2586	40	68	2077	2094
RefPol	Coal|w/o CCS	4523	10308	80	130	2023	2060
RefPol	Gas|w/ CCS	359	359	27	27	2074	2074
RefPol	Gas|w/o CCS	9536	28756	65	96	2040	2076
RefPol	Nuclear	2636	10664	98	130	2051	2085
RefPol	Solar	16125	72242	46	55	2074	2093
RefPol	Wind	12738	12738	86	86	2081	2081
450	Biomass|w/ CCS	351	5551	24	72	2038	2074
450	Biomass|w/o CCS	385	385	91	91	2056	2056
450	Coal|w/ CCS	451	451	30	30	2046	2046
450	Coal|w/o CCS	1840	2704	57	68	1992	2003
450	Gas|w/ CCS	1400	7721	15	80	2028	2075
450	Gas|w/o CCS	2254	3529	51	56	2015	2019
450	Nuclear	4119	11600	101	149	2073	2080
450	Solar	14096	39538	58	75	2077	2087
450	Wind	7849	23829	77	85	2068	2080