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By Bob van der Zwaan, Hilke Rösler, Tom Kober, Tino Aboumahboub, Katherine Calvin, David Gernaat, Giacomo Marangoni and David McCollum

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

Abstract

We investigate 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. 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 GHG 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$.

Keywords: climate policies, low-carbon energy growth, technological innovation, mitigation costs

1. Introduction

In this paper we investigate the energy technology requirements for reaching a 2˚C global climate change target. The international research teams contributing to the LIMITS project analysed, amongst others, the needs to reach this ambitious aim for climate control from a global technology diffusion perspective. Their main tools – integrated assessment energy system models that serve studying the energy-economic implications of environmental protection – allow for researching the extent, direction and cost of technological change necessary to significantly abate emissions of greenhouse gases (GHGs). We inspect in this article how much technological innovation 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, and which others need to be expanded, and at what scale. We also assess what the direct implementation costs are of this technological transformation, and to what extent, and how, we need to invoke alternatives involving 'negative GHG emissions'. We hereby connect to a growing body of literature on energy system transformation pathways (GEA, 2012; IPCC, 2011) and feasibility aspects related to low radiative forcing levels (see e.g. van Vuuren *et al*., 2011). Our work also pertains directly to the UN's Sustainable Energy for All initiative (UN, 2012), as well as to the UNEP Emissions Gap Reports (2011, 2012), even while we here do not explicitly assess energy and development issues or study the near-term "emissions gap" (and its implications) that derives from a comparison between the GHG emission pathways that correspond to the relatively mild Copenhagen policy pledges and, respectively, future GHG emission paths that comply with the 2˚C target.

None of these questions can be answered with certainty, but integrated assessment models can take away some of the uncertainties, and the ensemble of their diverse outcomes is indicative for the nature of the technological change in the energy system our societies need to initiate. One of our main findings in this cross-model comparison exercise is that many different technology deployment pathways exist to reach ambitious climate change control. As we will see, uncertainty abounds regarding both type and extent of low-carbon technology deployment, as well as concerning individual technology costs. For example, in all energy transformation pathways CCS constitutes a significant part of the climate mitigation technology mix, but it applies, according to different models, to varying forms of primary energy (coal, gas and biomass) and types of energy carrier production (electricity, hydrogen and liquid fuels). In section 2 of this paper we briefly introduce the methodology used for this study, and list the models on which our research results are based. Section 3 reports our main findings in several subsections dedicated, respectively, to (1) global 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. We focus in this article mostly on CO_2 as contributor to climate change, since it accounts for about three quarters of all global GHG emissions, and zoom in on electricity generation and transportation, as approximately two thirds of all CO_2 emissions are produced in these two sectors (IEA-ETP, 2012).

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.

3. Results

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.

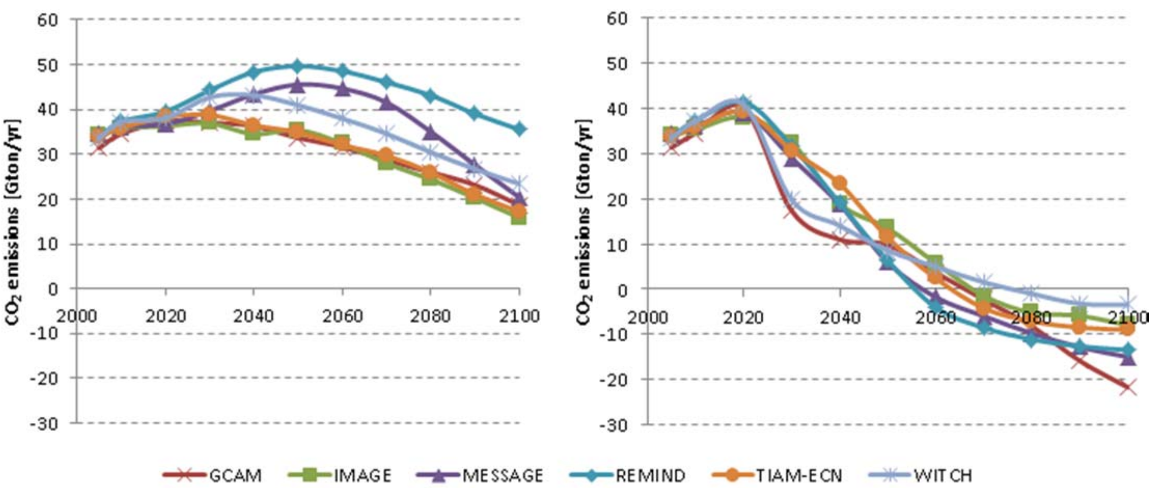


Figure 1. Global CO_2 emissions in scenarios StrPol (left) and RefPol-450 (right).

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/m² 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).

3.2 Primary energy

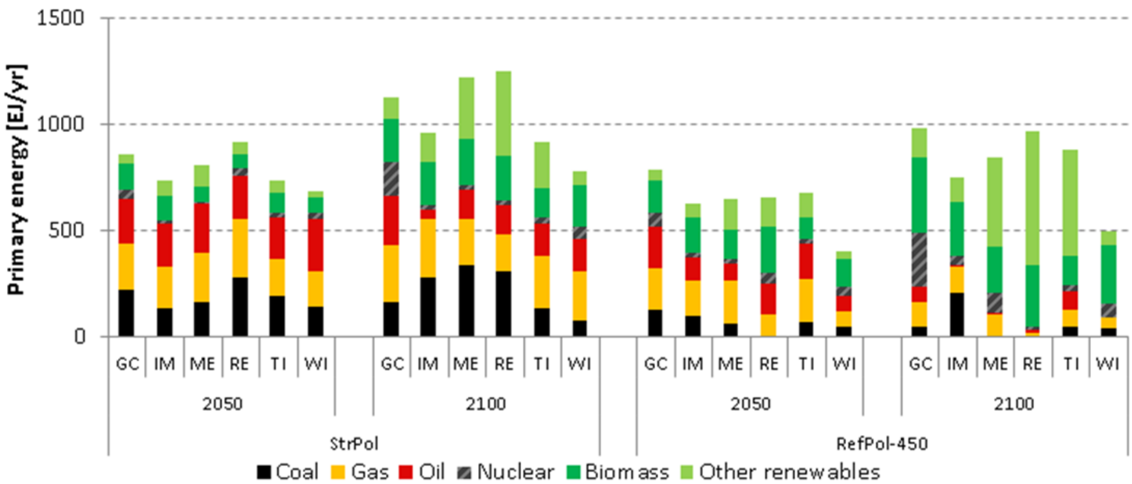


Figure 2. Global primary energy use in 2050 and 2100 in scenarios StrPol and RefPol-450.

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/m² 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.

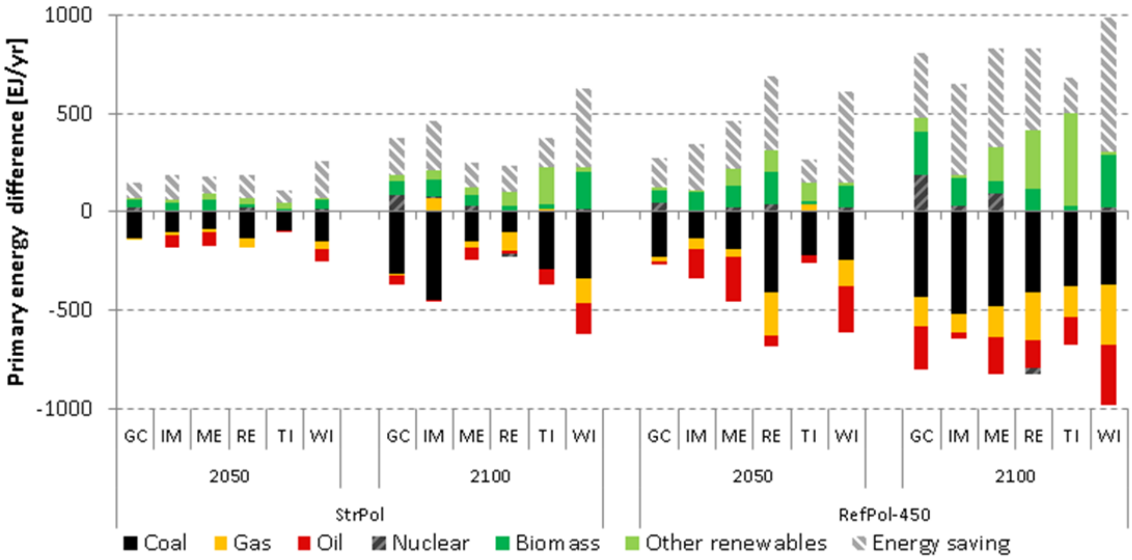
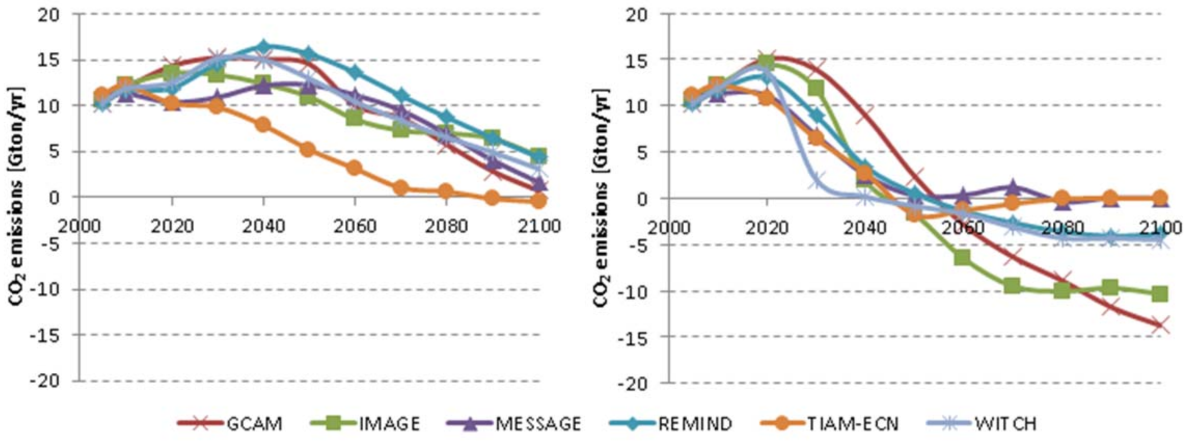


Figure 3. Global primary energy change from Base to scenarios StrPol and RefPol-450.

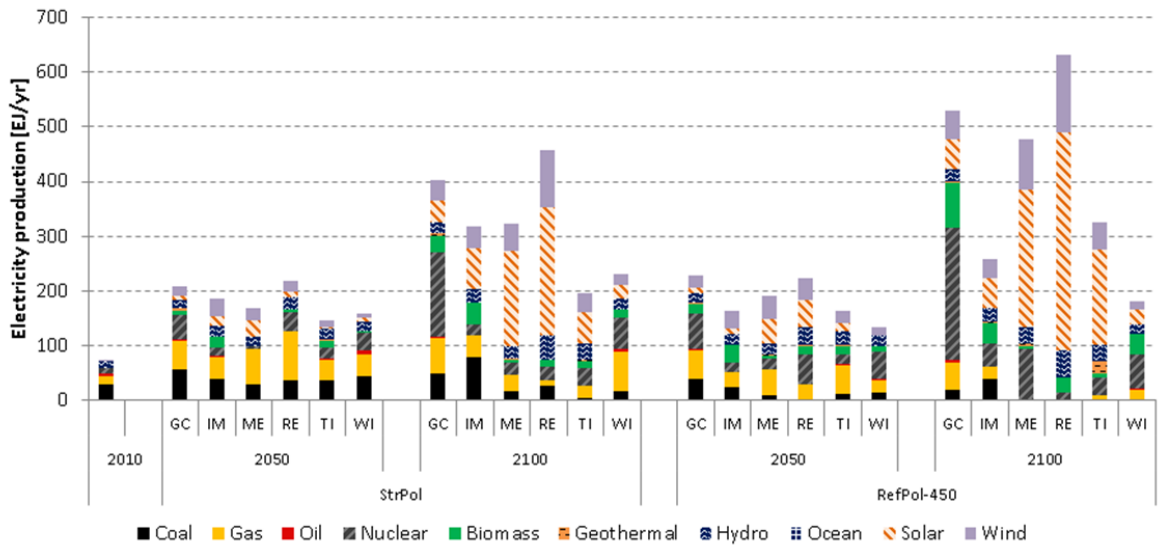
Besides differences, the models show some similar developments as well: for all models both the stringent climate policy and the 2.8 W/m^2 forcing target scenarios lead to a large reduction in the use of fossil fuels with respect to the baseline scenario, as can be seen in Figure 3. There is also clear 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).

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.

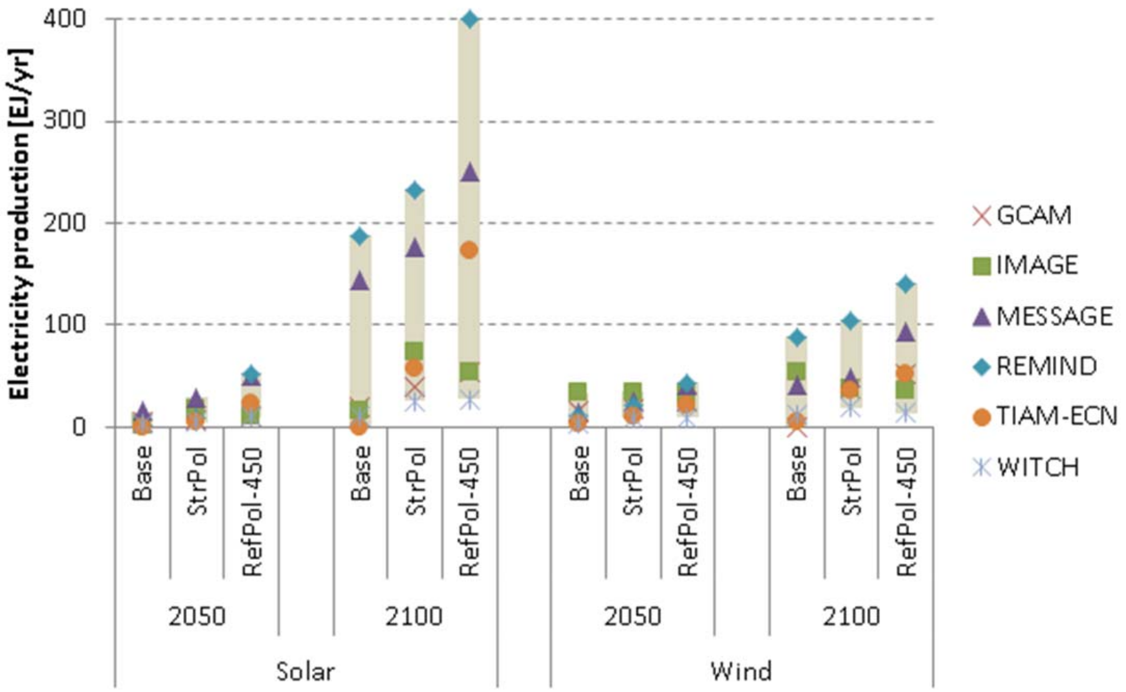


Figure 5. Electricity production from solar and wind energy in 2050 and 2100 in scenarios Base, StrPol and RefPol-450.

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).

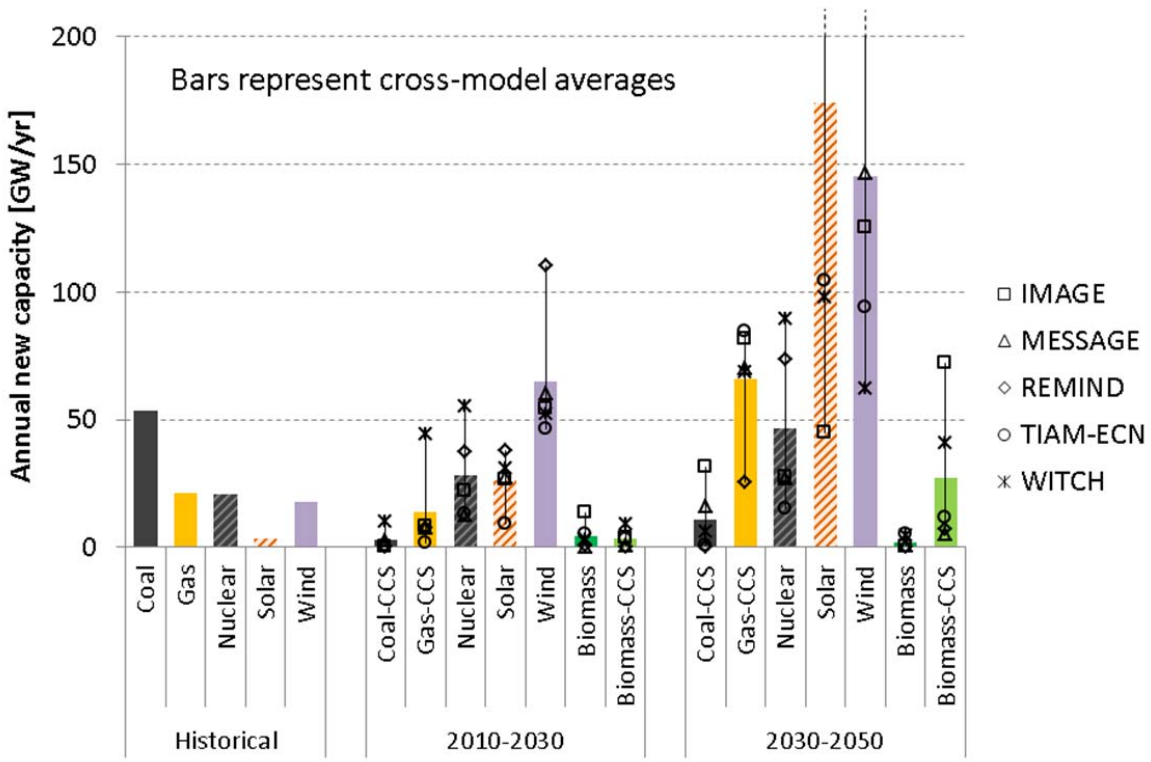


Figure 6. Average annual capacity additions (history and short to medium term future) for various fossil-based and low-carbon energy technologies in the RefPol-450 scenario.

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.

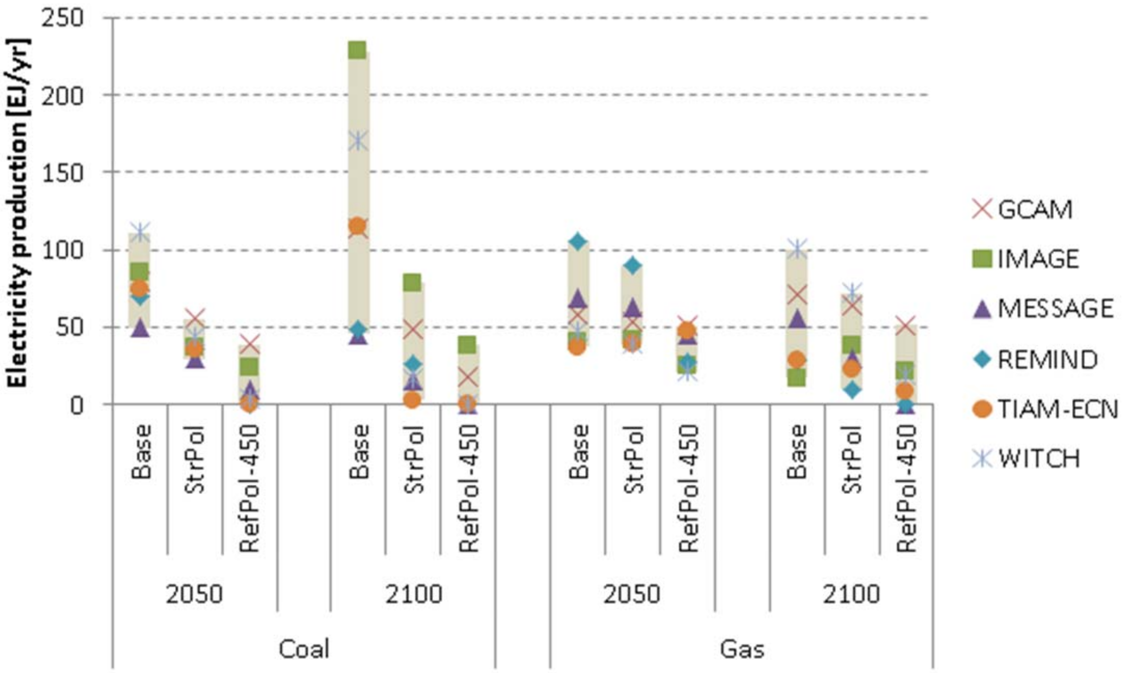


Figure 7. Electricity production from coal and gas plants in 2050 and 2100 in scenarios Base, StrPol and RefPol-450.

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).

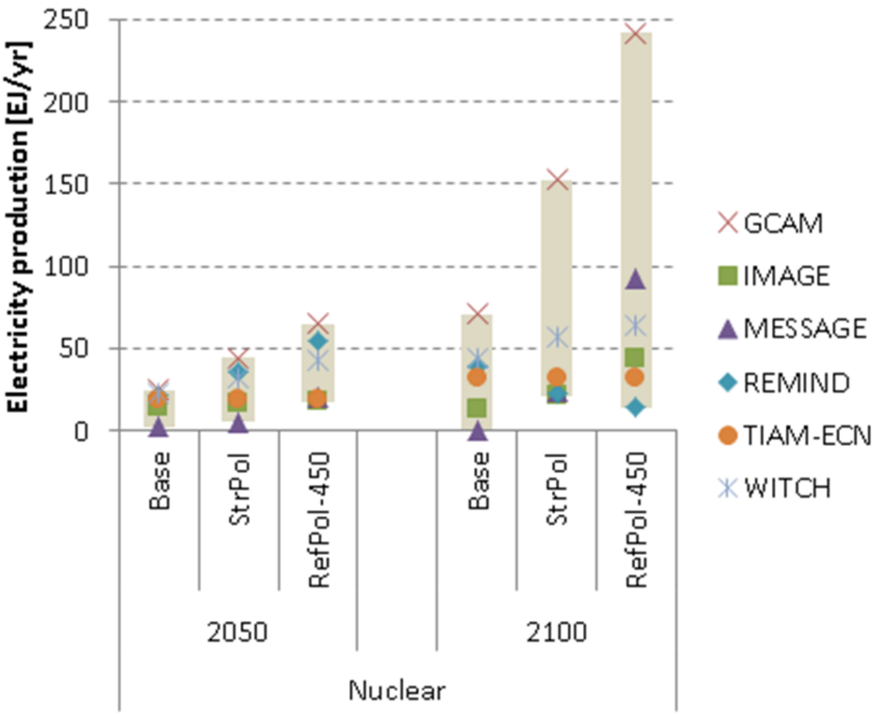


Figure 8. Nuclear power production in 2050 and 2100 in scenarios Base, StrPol and RefPol-450.

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.

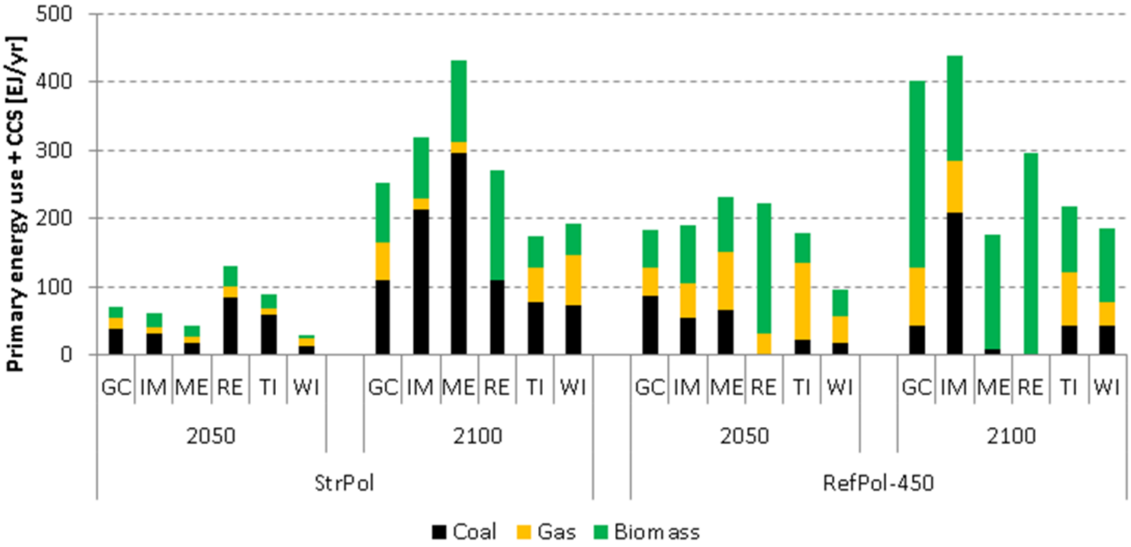
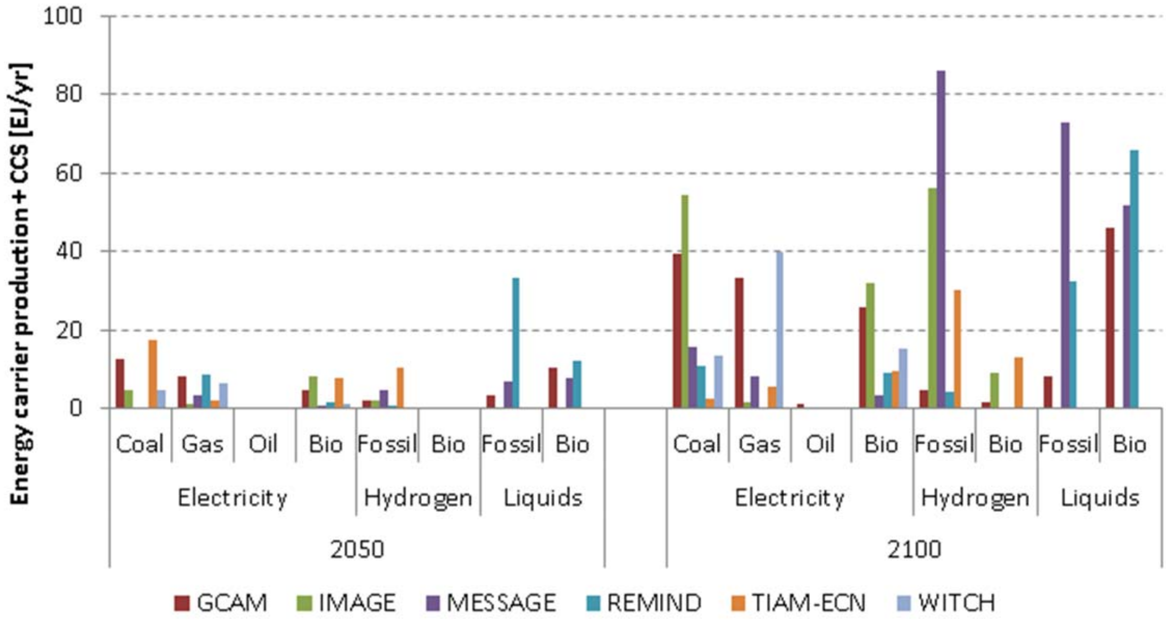
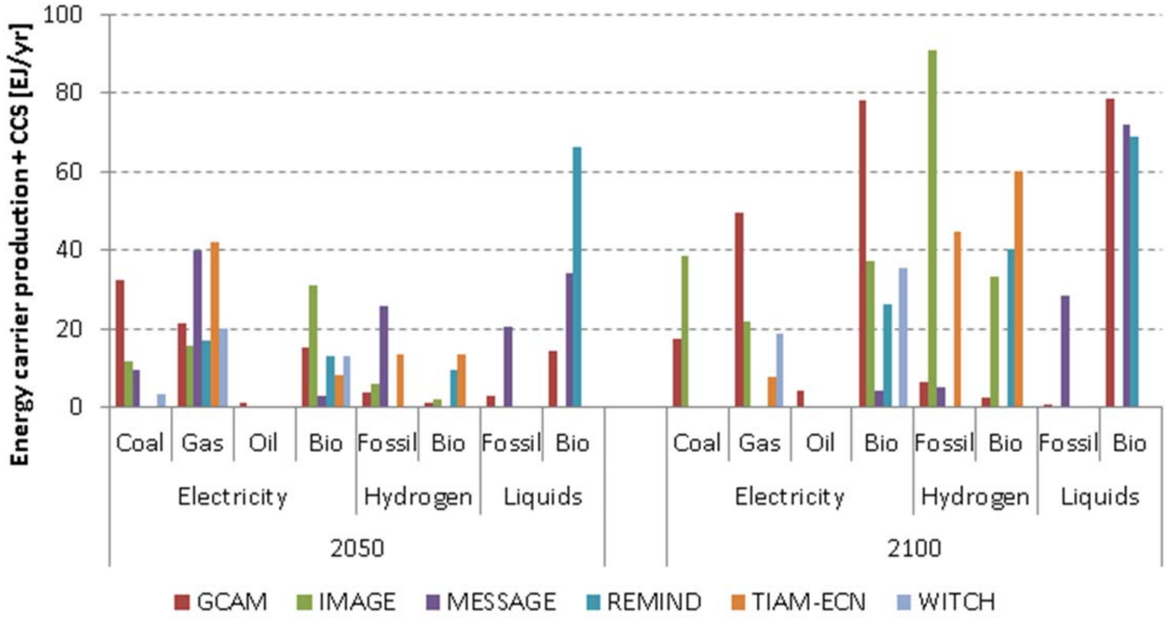


Figure 9. Primary energy use in combination with CCS in scenarios StrPol and RefPol-450.

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).

3.5 Technology costs of reaching 2˚C

Since other articles in this special issue 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 paper'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.

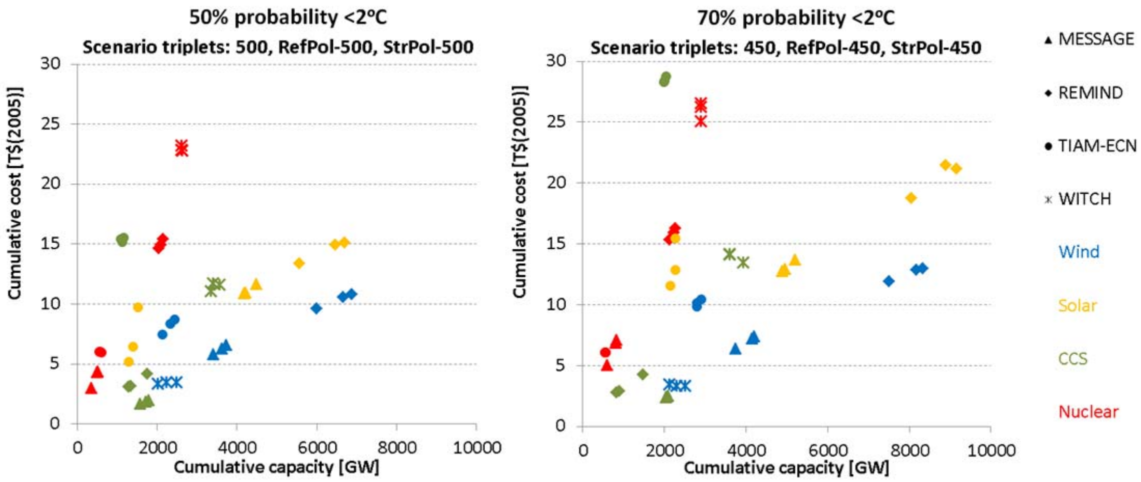


Figure 11. Cumulative cost versus capacity until 2050 for four low-carbon power supply options in scenarios 500, RefPol-500 and StrPol-500, respectively, scenarios 450, RefPol-450 and StrPol-450.

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).

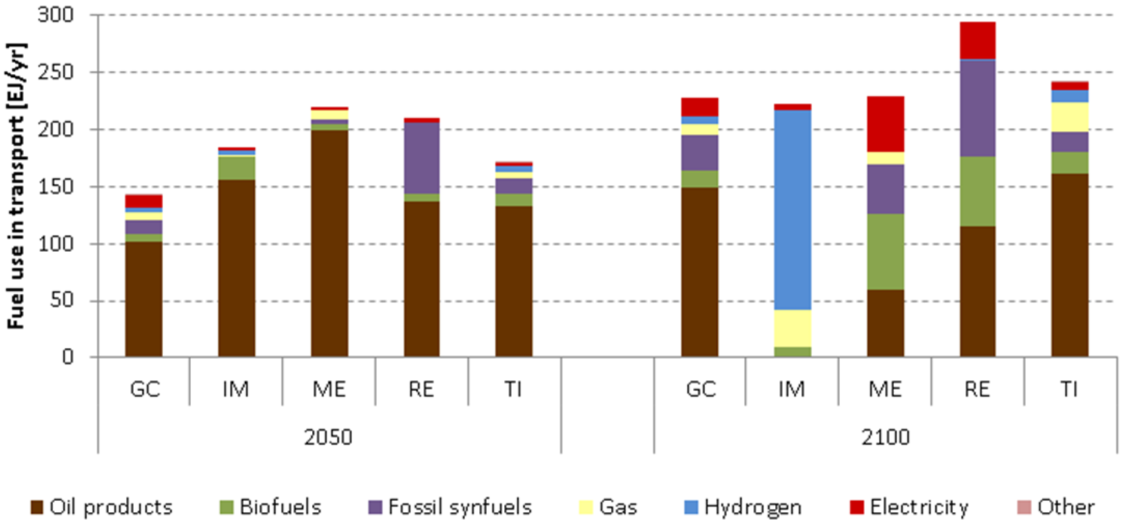


Figure 12. Fuel use in the transport sector in the Base scenario in 2050 and 2100.

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.

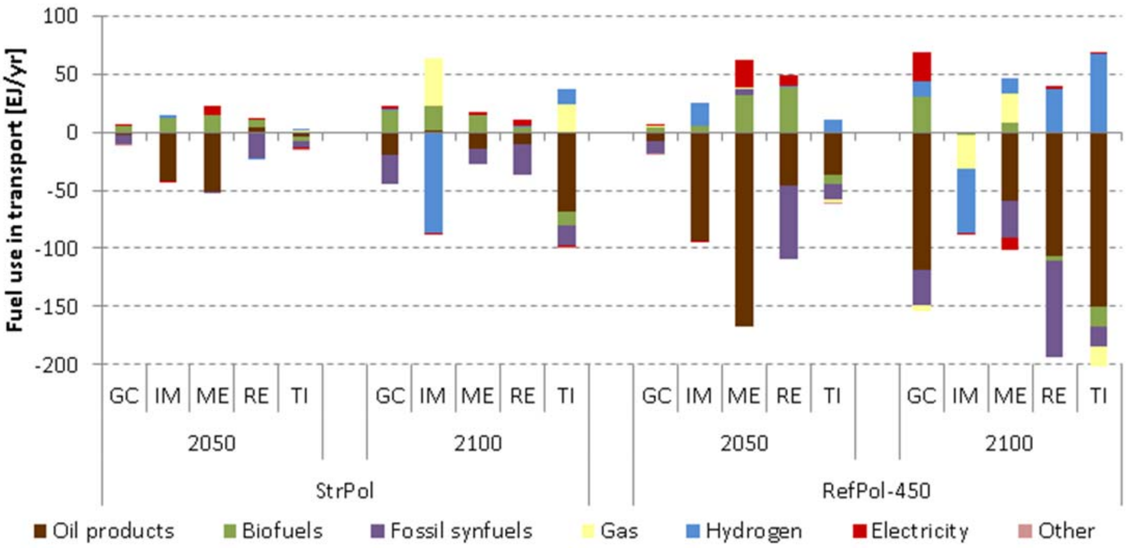


Figure 13. Difference in fuel use for transportation with respect to Base in StrPol and RefPol-450.

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 paper 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 paper 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.

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