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1 Introduction

The role of the work package (WP) M2 (“Mitigation at the global level”) is to assess important elements of global climate policies (and by default of the EU as a world region) using numerical modelling methods. More specifically, WP M2 aims at studying the economics of mitigation options for a post-Kyoto era of the EU in a global context, building on existing research findings that allow for the effects of induced technological change on costs and choice of options and for various policy portfolios.

In order to assess different combinations of mitigation options and their respective emission reduction potentials, a comparison of global regionalised energy-environment-economy (E3) models is performed (Regional Modelling Comparison Project, RMCP). These models are different in their constitutive framework, ranging from econometric simulation models to macro-economic optimal growth models and to energy system models or a combination of these, all with a regional disaggregation component. The overall objective of this model comparison is to explore the feasibility of different CO₂ stabilisation targets, to find robust results despite conceptual and theoretical model differences and to identify the key model features that lead to diverging model results.

For this model comparison, one common baseline pathway for GDP and population up to 2100, and common 2000 base year values for CO₂ emissions and primary energy consumption have been agreed upon to make the results more comparable. Various emission scenarios with different reduction targets and technology options are run. Besides the respective reference emission scenarios of 550ppm, 450ppm and 400ppm CO₂-equivalent, a set of scenarios is run, where certain technologies are fixed to the business-as-usual case in order to evaluate the option value of this technology, or where additional resources are available. Additionally, a set of policy scenarios is performed.

The model comparison is conducted in two steps: in a first step the models are compared in view of their mitigation strategies with a focus on technology options with a moderate stabilisation target of 550ppm CO₂-equivalent. Results from this first part are briefly summarised in section 1.1. A detailed analysis was given in Deliverable D-M2.4 (Report on model comparison).

In a second step of this model comparison energy-investment paths are investigated that are more likely to limit global warming to 2°C compared to pre-industrial values. This provides an analysis of a much more ambitious low stabilisation emission pathway to 400ppm CO₂-eq. Economic consequences and the implications of a low stabilisation target on the technology portfolio are the main focus of this paper.

1.1 Results from the first step of the model comparison

The most remarkable results concerning the model comparison of the 550ppm CO₂-eq scenario are that (i) all models can achieve the CO₂ stabilization target at moderate costs (ii) the models follow different strategies e.g. concerning the energy mix to achieve this target and (iii) the models themselves are flexible in their strategies.

Each of the models follows a different strategy to achieve the emission reductions, e.g. by increasing energy efficiency and reducing energy use, focusing on large amounts of renewables, or by placing the emphasis on a mix of CCS and renewables. By setting a restriction on a certain technology, the models show that the technology mix is highly adaptable in reaching the target without that very technology: in principle, every model can achieve the target even when technological change is fixed to baseline values (no induced change), or when the amount of renewables, nuclear or CCS are fixed to their baseline values. This adaptability is mirrored in the mitigation costs: the models report moderate GDP losses (gains in one model), but the option values for the different technologies are not very pronounced and are very different among the models.

Whereas in the business-as-usual scenario the energy mix is dominated by fossil energy, the energy mix in the mitigation scenario shows more flexibility. Each model has a different technology that turns out to be the most important one. In terms of policy, this means that it is not possible a priori to identify a dominant “must-have” energy technology. A mix of technology options is needed, which is very likely to be different for each country and over time, and the best strategy seems to be to support a broad portfolio of energy technologies. This result is consistent with the economic analysis.

1.2 Results from the model comparison on low stabilisation

In this second step a very ambitious emission pathway – here a concentration overshoot scenario towards 400ppm CO₂-eq stabilisation – is chosen. This pathway has usually required negative emissions by the end of this century and therefore poses a challenge to all models, though the pathway may also translate in a rapid and early decarbonisation of the global economy without necessarily achieving negative emissions by 2100. To be able to reach this target, some of the models were updated with new technology options, e.g. biomass in combination with CCS or the fast breeder option and others with new policy options, e.g. revenues from permit auctions being used to provide low-carbon technological incentives. The results from the first part of this model comparison are at this stage of the project therefore not fully comparable with results from the second part, e.g. concerning the absolute numbers for the mitigation costs. Nonetheless, the interpretation of the results, e.g. concerning the adaptability of the technology portfolio, remains the same.

Up to now, such low emission pathways have only been reported rarely and were not fully included in the IPCC AR4. Therefore, the most remarkable result from the analysis of the 400ppm CO₂-eq pathway is that all models show that this target is feasible in terms of limiting the emissions. Moreover, although the costs in most models may increase compared to the 550ppm scenario (however some models point towards a decrease), they are still moderate. Depending on the assumptions of availability of technologies and emissions from other greenhouse gases, overall losses are reported to be smaller than 1.7% GDP (by 2100?) compared to the business-as-usual case and with it in the lower to medium range compared to the values reported in the IPCC AR4. Despite the overall ability of the models to achieve the cap, some caveats concerning mitigation strategies and energy pathways are in order. It turns out that, in contrast to the results from the analysis of the 550ppm scenario, in the low stabilisation scenario there are indeed technology options that are essential to reach the target, namely CCS and expanded deployment of renewables. The assumptions about the potential of

biomass and CCS will determine the costs for mitigation, if not rapid and early action is taken. Nuclear power, without the option of fast breeders, however, plays only a minor role.

The detailed analysis of this low stabilization pathway and its economic and technology related implications are provided in this report. The report is structured as follows. In section 2 we will give an overview of the models participating in this comparison, in section 3 the baseline assumptions and the definition of the mitigation scenarios are presented. In section 4 we analyse the results in view of their mitigation costs, the strategies for CO₂ reduction and the energy mix with a comparison of the 550ppm, 450ppm and the 400ppm target in section 4.2 and an analysis of the technology option values in section 4.3. A conclusion is given in section 5.

2 Models

2.1 Model overview

For this model comparison we use the macro-econometric simulation model E3MG, the optimal growth models MERGE-ETL (abbreviated as MERGE in the following) and REMIND-R (abbreviated as REMIND in the following) and the energy system model POLES. All models but REMIND are described in the first deliverable of M2 in detail (Deliverable D-M2.1), with an excerpt of this deliverable concerning the model descriptions given in section 2.2. REMIND-R is a fairly extended version of REMIND-S that was used in the first part of the study.

E3MG, MERGE and REMIND are top-down macro economic models with bottom-up energy modelling components. POLES is a bottom-up energy system model. In Table 1 a brief classification of the models is given.

Model classification	Calculus	Model
Optimal growth model	Welfare maximisation	MERGE-ETL (Kypreos and Bahn, 2003 and Kypreos, 2005a) REMIND-R (Leimbach et al., 2008)
Energy system model	Cost minimisation	POLES (European Commission, 1996)
Econometric simulation model	Maximum fit to data	E3MG (Barker et al., 2006)

Table 1: Classification of the models participating in the model comparison.

The policy scenarios are analysed for the period from 2000 – 2100, where the optimisation models are run beyond 2100 to avoid end effects. Data are provided on a five year basis (10 year for E3MG after 2020).

The models provide different numbers of World regions. For this comparison exercise we agreed on seven World regions: China (CHN), Russia (RUS), Europe (EU27), India (IND), Japan (JPN), USA (USA), and the rest of the World (ROW). Additionally we investigate the aggregated WORLD region. For details see Appendix 7.1.

2.2 Model details

For a better understanding of the models, a short description of each model is given. Moreover, we give here an overview concerning the way induced technological change (ITC) is modeled in each model, as this is a central point for modeling mitigation. Some more specifications, e.g. the way other greenhouse gases (GHG) are treated, are given in Table 2.

2.2.1 E3MG

E3MG - Cambridge Centre for Climate Change Mitigation Research (4CMR, formerly Department of Applied Economics): an econometric simulation model of the global energy-environment-economy system, estimated on annual data 1971-2002 and projecting annually to 2020 and every 10 years to 2100. It is a non-equilibrium model with an open structure such that labour, foreign exchange and public financial markets are not necessarily closed. It is very disaggregated, with 20 world regions (including the 13 nation states with the highest CO₂ emissions in 2000), 12 energy carriers, 19 energy users, 28 energy technologies, 14 atmospheric emissions and 42 industrial sectors, with comparable detail for the rest of the economy. The methodology of the model can be described as Post Keynesian, following that of the European model E3ME developed by Cambridge Econometrics, except that at the global level some markets are closed, e.g. total exports equal total imports at a sectoral level allowing for imbalances in the data. It is designed to address the issues of energy security and climate stabilisation both in the medium and long terms, with particular emphasis on dynamics, uncertainty and the design and use of economic instruments, such as emission allowance trading schemes.

ITC

E3MG incorporates endogenous technological change in three ways: (i) Top-down macroeconomic effects: the sectoral energy and export demand equations include indicators of technological progress in the form of accumulated gross investment and Research and Development (R&D), (ii) bottom-up engineering effects: the energy technology submodel incorporates learning-by-doing through reductions in costs of investment in energy-generation technologies according to global-scale economies, and (iii) amplifying effects: the extra investment in new technologies, in relation to baseline investment induces further output and therefore investment, trade, income, consumption and output in the rest of the world economy through a Keynesian multiplier effect.

R&D is endogenously related to industrial gross investment, with an exogenous component determined by government funding policy. It affects aggregate energy demand and fuel mix. R&D is also part of gross investment which is a measure of technological progress impacting exports, imports, industrial hours worked, employment, industrial prices, export and import prices. All these are part of the macro-econometric model and the corresponding parameters (for energy and exports) are econometrically estimated. R&D is in turn influenced by extra investments in new technologies, which emerge from mitigation measures that induce change towards low-carbon technologies. Furthermore, R&D is amongst the policy instruments in the model promoting greenhouse gas abatement.

Out of the 28 energy technologies available in E3MG, 14 have learning included and are effectively used in the model. Learning is implemented in the energy technology bottom-up submodel through learning curves with varying learning rates. Learning curves are modelled through regional investment in energy generation technologies that depend on global scale economies. As investment is made in new technologies, learning takes place and the cost of these new technologies decreases so that they become competitive with the more

“established” technologies. The model is capable of explaining how low-carbon technologies are adopted as the real cost of carbon rises in the system, with learning-by-doing reducing capital costs as the scale of adoption increases.

A switch from one technology to another is modelled within the energy technology bottom-up submodel in E3MG. This allows for a treatment of substitution between energy technologies (for example between fossil and non-fossil fuel technologies), accounting for non-linearities (and threshold effects) resulting from investment in new technology, learning-by-doing, and innovation. The submodel is an annual dynamic technology model of energy supply based on the concept of a price effect on the elasticity of substitution between competing technologies. Although the submodel is not estimated by formal econometric techniques it does model in a simplified way the switch from carbon energy sources to non-carbon energy sources over time. For each type of energy demanded there is usually a technology or fuel of choice – a marker technology – against which the alternatives will have to compete. The total capital and operating costs of using this fuel per unit of output are used as a basis or numeraire for expressing the relative costs of the alternatives.

Emissions trading

The emissions trading scheme is implemented in E3MG globally only for the energy and energy-intensive sectors through permit auctioning. The emissions trading is assumed to start from 2011 and the revenues raised are recycled and spent within each of the corresponding region by reducing indirect taxes to ensure macroeconomic inflation stability. For the non-energy sectors carbon taxes are globally applied with the tax rate given by the ETS price, again assuming revenue recycling region-by-region. In the stringent policy scenarios some of these revenues are redirected to encouraging technological and behaviour change.

Climate model and other GHG

E3MG is a macro-econometric model and does not include a climate sub-model. Cumulative emissions corresponding to different stabilisation targets are taken from the inputs provided by the TIMER/IMAGE model. Other GHGs are for the time being still treated simplistically in E3MG. E3MG does not yet have implemented marginal abatement curves for other GHGs and these paths are not endogenised in the model; they are derived or imputed as a CO₂ equivalent to achieve certain targets. In other words, CO₂ is used only to interpret what CO₂-eq results would be like. However, work on having endogenous emission pathways for other GHGs is underway.

2.2.2 MERGE

MERGE-ETL - Paul Scherrer Institute: The Model for Evaluating Regional and Global Effects (MERGE) is an integrated assessment model (IAM) that comprises a disaggregation of the energy system in electric and non-electric sectors, a macro-economic production function and a simplified climate model. The world modelled in MERGE is divided into nine geopolitical regions. An ETA-MACRO model describes each of these nine regions. The ETA component is a “bottom-up” engineering model that describes the energy-supply sector of a given region, and captures price-dependent substitutions of energy forms and energy to

achieve specified CO₂ reduction targets. The MACRO component is a “top-down” Ramsey-type macroeconomic growth model that balances the non energy part of the economy of a given region using a nested constant-elasticity-of substitution (CES) production function. The MACRO model also captures autonomous (e.g., price-independent) effects and macroeconomic feedbacks between the energy sector and the rest of the economy, such as the impacts of higher energy prices (e.g., resulting from CO₂ control) on economic activities. MERGE also includes a simple climate (see below) and damage model which considers market (through production losses), and non-market damages (through losses in global welfare). Those derived non-market damages (i.e. disutility) are proportional to a quadratic temperature change function. Finally, MERGE allows the modelling of multi-gas climate-change mitigation strategies and the assessment of the impact of alternative policy instruments on stimulating technological change towards a low-carbon global energy system.

ITC

All energy technologies include learning, with the exception of a few conventional power stations such as existing fossil-based or hydro power plant. We apply two-factor learning curves for the investment costs of each learning technology. Experience and R&D expenditures are thus endogenously accounted for in MERGE.

In both electric and non-energy sectors, technologies are generally considered to be perfect substitutes, i.e. all production levels are summed up to satisfy energy needs. The least cost technology supplies the demand, up to some maximum potential level, e.g. wind power capacity or biomass availability, and accounting for demand-side constraints (e.g., limitations to the direct use of coal in the residential sector). The changes in each production level are controlled according to bounds on expansion and decline rates (see Kypreos and Bahn, 2003).

Emissions trading

CO₂ permits are traded on an international market and give rise to a price of carbon, along with other traded commodities, i.e. the numeraire good, oil, gas, coal, biomass, the energy intensive sector good. Global trade constraints applied in each period ensure that international net trade of CO₂ permits (the difference between export and imports) is balanced.

Climate model and other GHG

MERGE includes a simple climate model which determines radiative forcing and global temperatures according to a function of the aggregate GHG emissions levels, atmospheric, ocean and terrestrial carbon stocks and absorption rates. MERGE also includes non-CO₂ emissions and marginal abatement cost curves from EMF 21 (de la Chesnaye and Weyant, 2006), facilitating the analysis of multi-gas climate change mitigation strategies.

2.2.3 REMIND

REMIND-R - Potsdam Institute for Climate Impact Research (PIK): a multi-region hybrid model which couples an economic growth model with a detailed energy system model and a simple climate model (that is switched off here). REMIND models the economic dynamics of each world region by adopting an endogenous growth framework. It calculates time paths of investment, consumption and trade decisions that are intertemporally optimal. The objective

is to maximize the social welfare of each region, defined as the present value of utility, which is a function of per capita consumption exhibiting diminishing marginal utility. The macroeconomic production function is a CES function of the production factors labour, capital and end use energy. To be able to calculate this end use energy, there is a nested tree with additional CES production functions. The end use energy of the upper production level is calculated as a production function which comprises the transportation energy and the stationary used energy.

The macroeconomic system and the energy system are linked by final energy, which is demanded by the aggregated production sector and which is supplied by the energy sector. In turn, the energy sector demands investments which are supplied by the macroeconomic sector. The energy sector comprises more than 50 technologies, each of which is characterized by its input and output, its capacity and specific investment, operation and fuel costs. Technological change has an exogenous formulation with increase in labour and energy productivity, and an endogenous formulation with learning by doing in a few energy technologies. REMIND extends this structure by essential elements of regional interactions due to trade in energy resources, an aggregated good and emission permits.

ITC

Induced technological change represents changes in the technological characteristics of the economic and energy system driven by exogenous policies (e.g. climate policies and trade policies). As part of endogenous technological, induced technological change is modeled in REMIND in several ways. First, production factors can be substituted by each other, in particular the production factor energy can be substituted by capital. Second, ITC is represented by the energy mix, which is driven by investments into energy technologies transforming primary energy into secondary energy and secondary energy into final energy. Finally, REMIND models learning-by-doing by means of learning curves, in particular for renewable energies. Investment costs of renewable energies decrease by 10%-20% for each doubling of cumulative installed capacity. There is no global learning, hence the different progress of regions in technological learning is taken into account.

Emissions trading

For each unit of fossil resources converted into secondary energy a permit is needed. Each region in REMIND is allocated an amount of emission permits for free, which corresponds to the regional emission cap and follows a given allocation rule. In scenarios with a global emissions cap, the sum of the regional emission permits equals the exogenously given global CO₂ budget of the energy sector. Emissions trading provides the opportunity to buy and sell the permits. At each time step the worldwide sum of the exports of emission permits equals the sum of imports. The emissions trade is part of the whole trading system. All exports and imports of a region are subject to an intertemporal trade balance which ensures that no deficits can be sustained in the long run. However, lending and borrowing of permits is possible temporarily.

Climate model and other GHG

The applied REMIND-R version integrates a simple climate model which is represented by a set of equations that restrict welfare optimization. The climate model considers the impact of greenhouse gases and sulphates on the level of global mean temperature. The radiative

forcing of both the non-CO₂ greenhouse gases and the CO₂ emissions from land use change is taken into account by exogenous scenarios. Marginal abatement cost curves are not yet included to calculate the costs of abatement in other GHG. For this model comparison, REMIND-R does not activate its climate module, but tries to meet the prescribed emission path.

2.2.4 POLES

POLES - ENERDATA/ LEPII-CNRS, Université Pierre Mendès France: works in a year-by-year recursive simulation and partial equilibrium framework from 2005 to 2100, with endogenous international energy prices and lagged adjustments of supply and demand by world region. Many parts of the global energy system are detailed in POLES, from the primary energy supply sector (oil and gas discovery module) to fairly detailed demand modules (industry, transport, services and dwellings). The transformation sector includes the production of power and electricity, for both of which the model also provides a detailed description of a large number of technologies (large-scale, new and renewables) in each of the 47 POLES countries or regions covering the world. Their regional development depends on different factors such as investment costs, efficiency, fuel prices and policy choices. The improvement in the technology performances and costs can be projected in two different ways: either using exogenous data from the TECHPOL database or through endogenous technical mechanisms through two-factor learning curves, which combine learning by doing and learning by searching processes.

In the framework of the ADAM project, the electricity module of POLES has been significantly revised and further developed. It now integrates most of the renewable technologies within the “competing grid mix” module. Additional technologies were added like electricity generation from biomass with carbon capture and sequestration, which acts as a “carbon hoover” by 2100. The biomass resource is now properly modelled through supply cost curves attached to technical potentials, while markets for solid biomass and for biofuels have been introduced.

The POLES model is not directly linked to a climate model.

ITC

The impact of induced technological change on mitigation costs strongly depends on the way technological change is introduced. Technological change is the complex result of: exogenous events (scientific discoveries), inducement factors (e.g. R&D investment, relative prices) and endogenous mechanisms (e.g. learning by doing). The two-factor learning curves (TFLC) in the POLES model are meant to provide a simplified but meaningful description of technological change. The incorporation in POLES of TFLC relationships for the main technologies and technology clusters enable POLES to perform R&D policy simulations in a dynamic environment where an increase in R&D effort produces improvements leading to higher technology adoption and hence to further improvements through experience gained in a virtuous learning circle. R&D spending is exogenous in the model. Some technical change has also been introduced in end-use technologies (vehicles and buildings) through a sensibility of their investment cost to the Carbon Value in the energy system.

Emissions trading

Emissions trading for each country is calculated as the difference between actual emissions and allocations. In each scenario POLES determines the Carbon Value for each individual carbon market.

Relative abatement and trading costs are then calculated through the production for each country of the Marginal Abatement Cost curves of the energy sector: these curves are confronted to the Carbon Value of the amount of permits traded. The POLES model is then able to determine abatement and trading costs for all countries.

Climate model and other GHG

The POLES model simulates the emissions of non-CO₂ gases for the energy and the industry sectors; emissions from land use and agriculture are not included though.

The gases considered are: CO₂, HFC and PFC from industrial processes, CH₄ from the energy sector, and N₂O and SF₆ from both sectors. Each gas is associated to abatement cost curves.

A comparative overview of the different mitigation options that are available in each model is given in Table 5 in Appendix 7.2. Some detailed information about special technologies is shown in Table 2.

	E3MG	MERGE	REMIND	POLES
CCS technologies	Generic CCS technology for coal and gas; not for biomass; No leakage assumed	Pre-combustion for IGCC and biomass gasification; post-combustion for pulverised coal and NGCC. For other technologies: biomass H ₂ and FT liquids, coal and gas H ₂ ; No leakage assumed; Storage potential is limited to 1450 GtCO ₂	natural gas combined cycle with capture; gas to hydrogen with capture; integrated coal gasification cc with capture; pulverised coal power plant with capture; pulverised coal power plant with oxyfuel capture; coal based fischer-tropsch with capture recycle; coal to hydrogen with capture; biomass based fischer-tropsch with capture recycle; biomass to hydrogen with capture; No leakage assumed	IGCC and biomass: pre-combustion Pulverized coal & gas combined cycle : post-combustion; No leakage assumed
Learning rates	Solar and wind: 30%	Learning by doing: Solar: 10% Wind: 5% Learning by searching: Solar: 10% Wind: 5%	Solar PV: 20% Wind: 10%	The learning evolves with the distance to "Floor costs". In the baseline: Solar: investment cost divided by 2 for thermodynamics, by 4 for PVs by 2050; Wind: For onshore cost decreases by 40% 2100 and for offshore cost is divided by 2 by 2100
Biomass use		In the 400ppm scenario biomass is used roughly 1/3 for electricity, 1/5 directly and the remainder for fuel production; no co-emissions from biomass use assumed	Mostly used for fuel production; no co-emissions from biomass use assumed	Two types of biomass: "energy crops" for 1st generation biofuels only and "wood-based biomass" used for both transport and other uses (direct use, electricity, H ₂); no co-emissions from biomass use assumed
Emission cap	Cumulated emissions by 2100	With climate module	Exogenous* stabilisation path	Exogenous stabilisation path
Treatment of other GHG	Exogenous path; no special abatement in other GHG	Exogenous emissions path for the baseline and MACs from EMF21	Exogenous path; no special abatement in other GHG	Other GHG are exogenous for energy+industry; abatement with MACs; land-use emissions are exogenous

Table 2 : Overview over specific model features. MAC: marginal abatement cost curves.

***REMIND has a climate module that is not used in these experiments.**

3 Baseline and mitigation scenarios

3.1 Baseline scenario

As a reference (baseline) scenario we assume that climate policy has no decisive influence on the economy and on the social sphere. In order to achieve a minimal consensus about the business as usual path, all models agreed upon GDP projections (Deliverable D-S.1), which were tried to fit as closely as possible. Moreover, projections for population (based on data from UN, 2003) and CO₂ emissions from land use (from POLES and IMAGE (Alcamo et al., 1994)) are used as exogenous inputs. Additionally, the primary energy consumption at the starting point in the year 2000 was agreed on. Baseline projections for GDP, population and CO₂ emissions for the different regions are given in Figure 1.

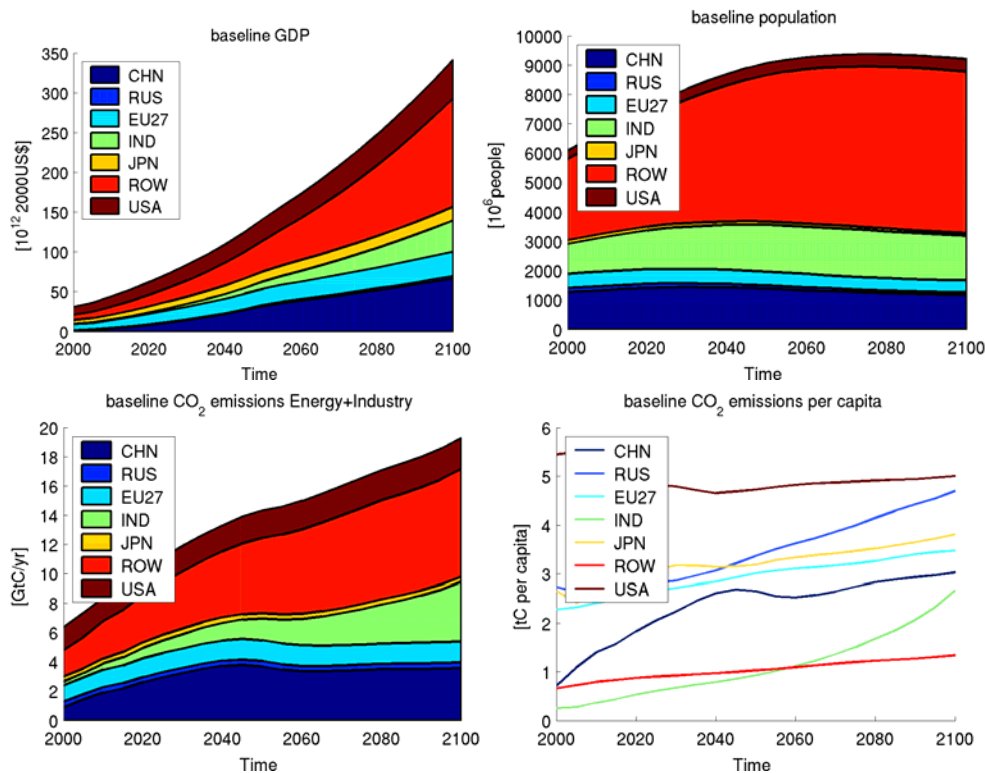


Figure 1: Reference baseline projections for GDP (in market exchange rates, MER), population, CO₂ emissions and CO₂ emissions per capita for the different regions (from POLES).

In Figure 2 the baseline results for GDP, population, energy related CO₂ emissions and total energy use are given. All models tried to fit as best as possible the GDP baseline and the CO₂ emissions with the intention to harmonize the models to exclude baseline effects. For GDP and population the values are in very good agreement, for CO₂ emissions and primary energy use the models show a very similar path until 2070 and report some major differences thereafter.

The low CO₂ emission pathway for REMIND, e.g., is caused by the assumption of an expensive price path for fossils so that a switch away from coal to renewables can already be seen in the baseline. Assuming cheap coal (but still expensive oil and gas), the CO₂ emissions would increase up to about 19 GtC/yr in the year 2100.

The assumptions about the prices for fossil energy are quite different among the models (see Figure 3) and determine the energy mix and the CO₂ emissions in the baseline (see section 4.2.3). In MERGE and REMIND the price is endogenous in the model and depends on the assumption of the respective fossil resource potential², while in POLES it depends on market fundamentals (namely the differential dynamics of supply and demand and the relative amount of spare capacities).

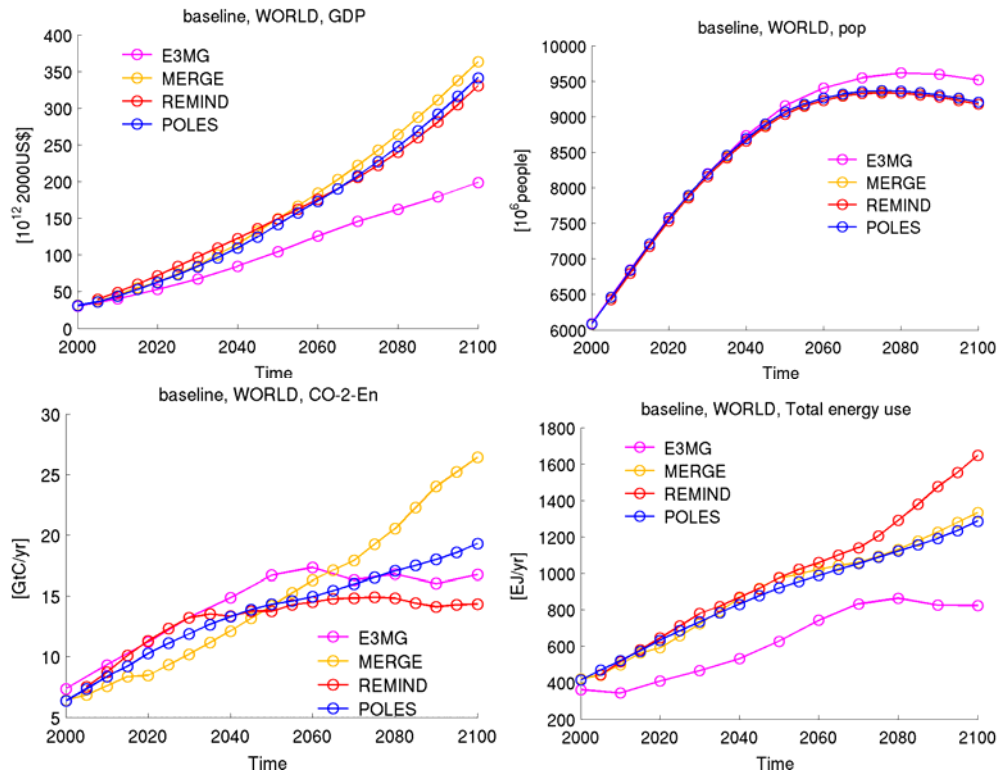


Figure 2: Baseline results for the WORLD region. Globally aggregated values for GDP, population, CO₂ emissions from energy (CO-2-En), and total primary energy use. E3MG does not assume long-term convergence in GDP between the regions. For the differing population data for E3MG see Appendix 7.1.

The different costs for fossil energy result, for example, in disparate paths for renewable energies in the baseline (cf. Figure 4): partly due to the high oil and coal prices, REMIND and E3MG report a high amount of renewables already in the baseline. However, renewable energy use is assumed to be much greater in the baseline in REMIND relative to E3MG, particularly towards the end of this century. This boils down to the different approaches to modelling economy-energy systemic interactions. REMIND projections are based on supply-side assumptions including perfect foresight and perfect competition, whereas E3MG bases

² In these models the global social planner perspective (with perfect foresight) does not consider how market power or failure to anticipate market developments may affect prices and the allocation of rents. Instead, it considers only the optimal allocation of global resources, with prices representing the marginal cost of production. This, of course, means that the oil price in MERGE and REMIND is not comparable with today's spot market price.

its projection on historical behaviour (e.g. the large amount of hydropower already being used in China and the large amounts of wind power being already proposed in the USA). The influence of the price assumptions is further investigated in section 4.2.3.

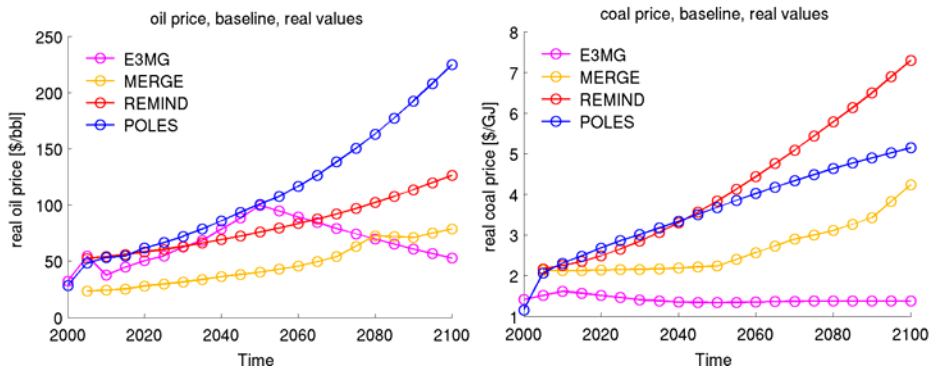


Figure 3: Oil and coal prices in the baseline scenario for the different models (in real values). Note that in MERGE, REMIND and POLES the costs are endogenous to the model; for MERGE and REMIND shadow prices are given based on resource extraction costs, for POLES it depends on market fundamentals. In E3MG real oil price is an input into the model that follows POLES price path up to 2050 after which a decline is assumed. For E3MG, the coal price is an average of hard coal and other coal (for USA).

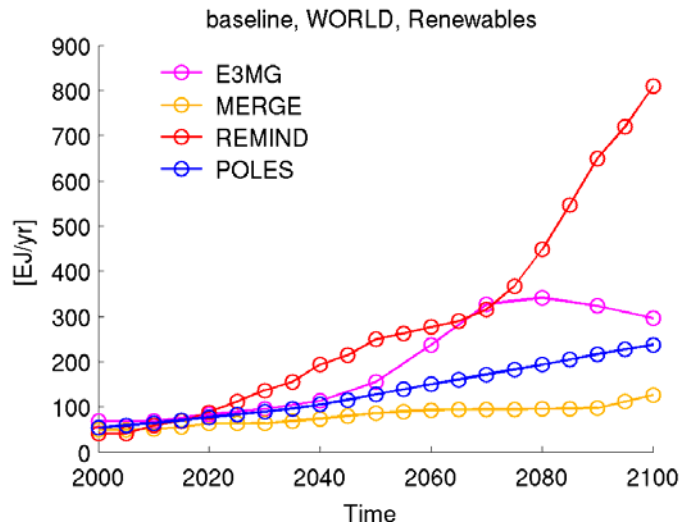


Figure 4: Development of renewable energy in the baseline scenario.

3.2 Mitigation scenarios: long-term stabilisation target

In this study we investigate a range of stabilisation targets that have different probabilities to reach the 2° goal. We chose targets which range from “unlikely” to “medium likelihood” and through to “likely” (according to the IPCC terminology) to limit global warming by 2° (see Figure 5): we investigate a 550ppm, a 450ppm and a 400ppm CO₂ equivalent scenario (see Figure 6). The emission data for CO₂ emissions from energy and industry, from land-use and data for other GHGs for all three scenarios are provided by the IMAGE/TIMER model (van Vuuren 2007). The 550ppm scenario (Deliverable D-S.1) shows an increasing concentration pathway beyond 2100. The 450ppm scenario (IMAGE 2.9, van Vuuren et al., 2006, 2007) peaks at over 3 W/m² and declines to a radiative forcing level of 2.9 W/m² in 2100. The 400ppm scenario (IMAGE 2.6, van Vuuren et al., 2006, 2007) has radiative forcing that peaks rapidly near 3 W/m² and declines to a radiative forcing of 2.6 W/m² in 2100. In Figure 7 the concentration pathway for CO₂-only is given.

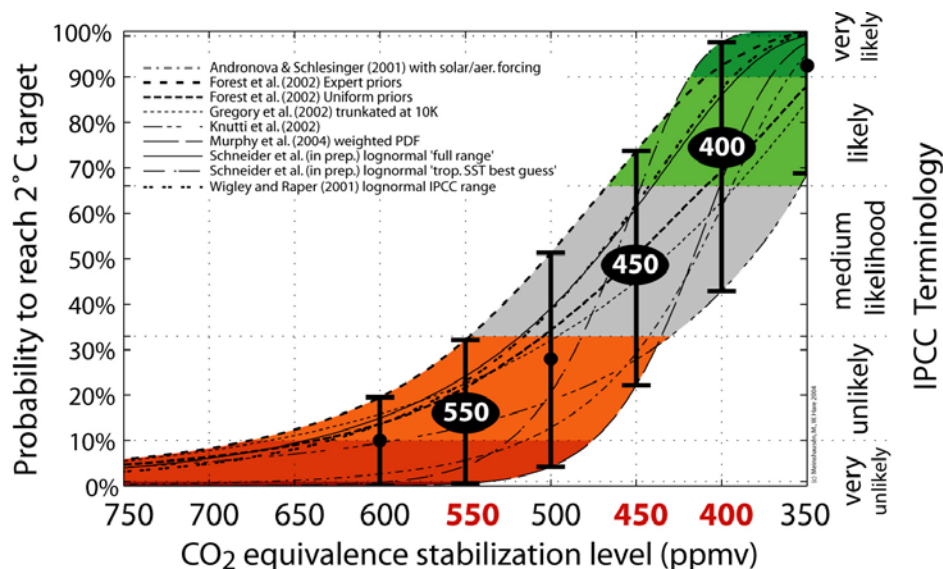


Figure 5: Probability to reach the 2° target. Source: Meinshausen and Hare (2004).

As outlined above, some of the models were updated with new technology options to be able to reach the negative emissions prescribed by the 400ppm scenario. On this account, the 550ppm scenario was done again with the upgraded models and results are reported here as well to be able to compare the implications of the 550ppm with the 400ppm scenario.

In all models but MERGE, which is run with a climate module, the emission cap for CO₂ emissions from energy and industry from these scenarios is taken as the binding cap. In E3MG the cumulated emissions are taken as a binding limit. In POLES the other GHGs from energy and industry are calculated endogenously, while land-use GHGs are taken from the IMAGE model. In REMIND the other GHGs are prescribed exogenously and the CO₂ equivalent emission pathway is therefore consistent with the data given by IMAGE.

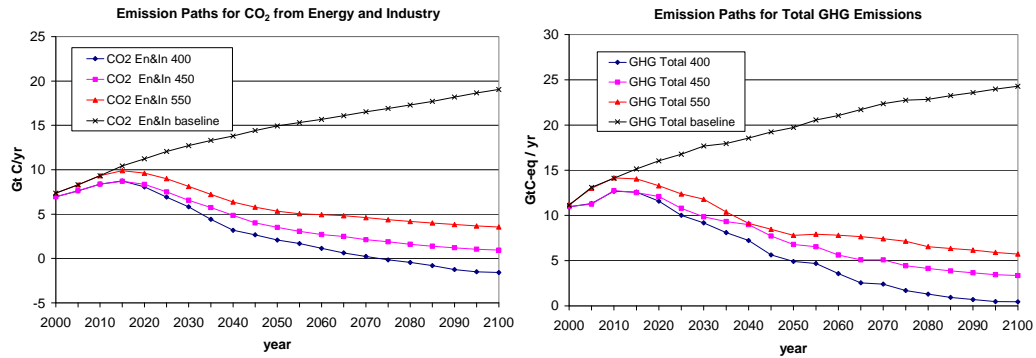


Figure 6: Emission pathways for the baseline and for 550, 450 and 400ppm CO₂-equivalent using the TIMER-IMAGE model. Left: CO₂ Emissions from Energy and Industry, right: CO₂-eq emissions from all sectors including land-use emissions and emissions of other GHG.

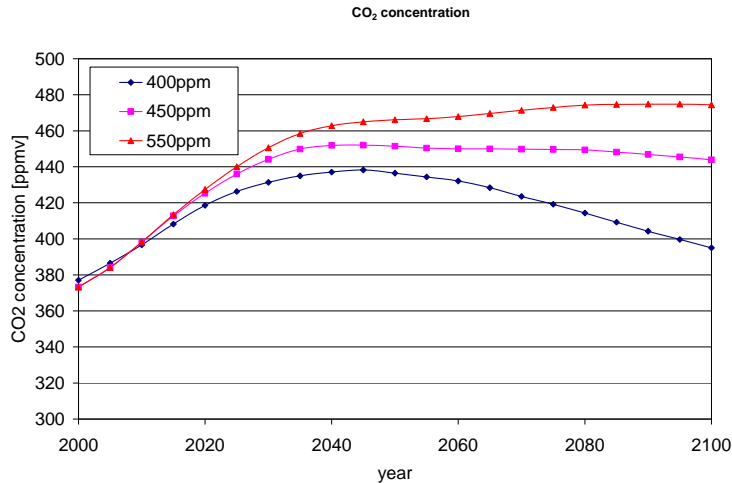


Figure 7: CO₂ concentration pathway (CO₂-only) for 550, 450 and 400ppm CO₂.

3.3 Mitigation scenarios: definition of scenarios

The main focus of this part of the model comparison is to provide an assessment of the technological and economic feasibility of very low stabilisation scenarios in view of the EU Commission's 2° target. To assess this question, the three above introduced stabilisation scenarios are run to compare and evaluate the implications of a decreasing emission target. To appraise the specific implications of the low stabilisation target of 400ppm on the technology portfolio, a set of technology scenarios is set up. In each of these scenarios one possible technological mitigation option is limited to its use in the baseline and is not allowed to extend due to mitigation, or a limited potential of certain technologies/resources is assumed. This is done to assess the importance of this particular option and the costs of doing without this option.

It is important to note that the realisation of these scenarios is not performed as a cost-benefit analysis. The focus of this analysis is on the appraisal (in the modelling context) of different mitigation options to reach a certain stabilisation target. The models do not include costs of adaptation or saved costs due to avoided damages. Note also that a full appraisal of the options would include considerations of safety and risk, energy security and public acceptability, and hence the results for scenarios where mitigation options are switched off should be mostly viewed as a modelling exercise to evaluate the option values of that very technology and not as a policy recommendation.

Scenario name	Description
baseline	Business-as-usual (reference) scenario
550ppm	Emission cap according to the 550ppm scenario
450ppm	Emission cap according to the 450ppm scenario
400ppm	Emission cap according to the 400ppm scenario; biomass potential: 200 EJ/yr; unlimited CCS potential*
400ppm:	
- biomax	Biomass potential is limited to 400 EJ/yr
- biomin	Biomass potential is limited to 100 EJ/yr
- ccsm	CCS potential is limited to half of the amount that is used in the 400ppm scenario
- nonuke	Amount of nuclear energy is fixed to baseline values
- norenew	Amount of renewable energy is fixed to baseline values
- noccs	Amount of CCS is fixed to baseline values (to zero)
- fbr	Inclusion of the fast-breeder option (only for MERGE)
- nuke fix baseyear	Amount of nuclear energy is fixed to values in the baseyear
- no electric cars	scenario without electric plug-in vehicles (only for E3MG)
- no extra incentives	without extra incentives through revenue recycling to support low carbon technologies (only for E3MG); carbon prices fixed to values of the 400ppm scenario

Table 3: Definition of scenarios. Additional scenarios, besides the standard scenarios run by all models, are marked with light grey. *In MERGE the CCS storage potential is limited to 1450 GtCO₂ (~400 GtC).

4 Results of the model comparison

4.1 Achievement of the stabilisation target

As outlined above, the models follow different approaches how the cap on CO₂ emissions is introduced (see Table 2). In MERGE, a climate module limits the radiative forcing to the desired target, in E3MG the cumulated CO₂ emissions by 2100 are taken as the upper limit and in REMIND and POLES the CO₂ cap is prescribed in each timestep from the reference mitigation scenarios.

The first remarkable result is that all models can achieve the ambitious concentration cap of 400ppm. This is an important result as so far only a few models have reported the ability to reach such a low stabilisation pathway (e.g. van Vuuren, 2006, 2007, Fisher et al., 2007).

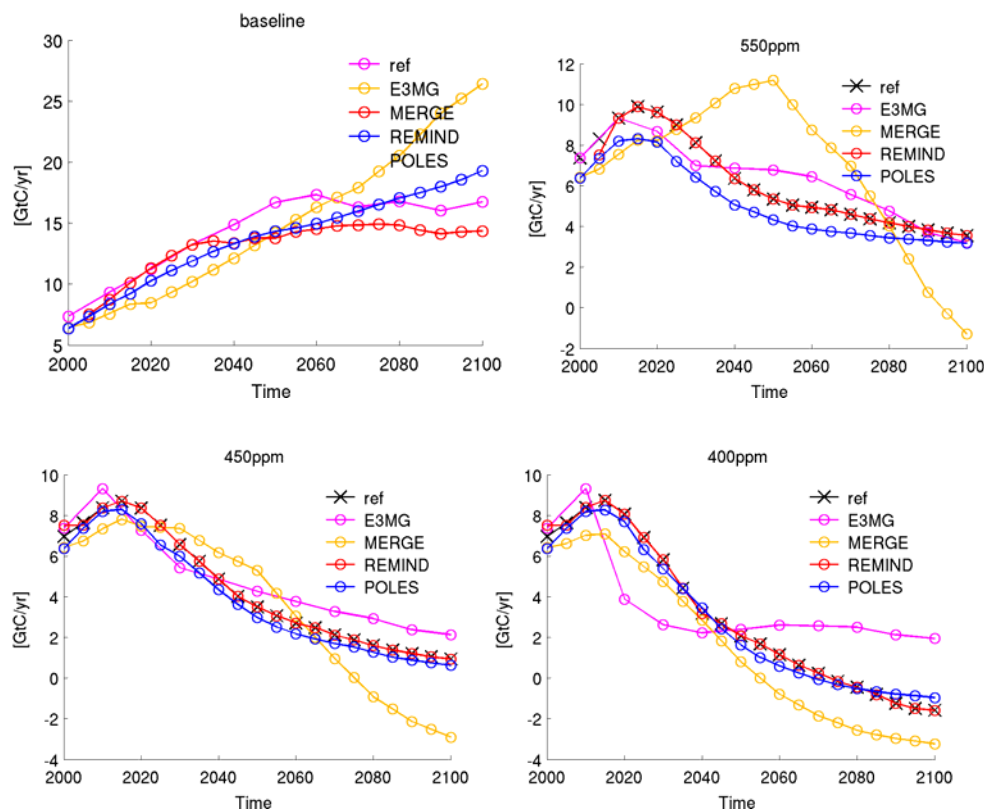


Figure 8: Emission pathway for the baseline scenario and for the 550ppm, 450ppm and 400ppm scenario. The reference path is added as well (black crosses, same curve as REMIND).

An overview, in which scenarios the target can be met is given in Table 4. With respect to the other technology scenarios where one option is limited to the baseline or a limited potential is assumed, it is an important finding that except E3MG none of the other models can achieve the target when either the CCS option is not available (noccs) or when renewables are fixed to baseline (norenew). This is mainly due to the fact that the required negative emissions by the end of the century cannot be achieved without both CCS and large recourse to biomass use. E3MG can only reach the target by rapid and very early action on the demand-side as can be seen in Figure 8 for the 400ppm scenario.

With a lower CCS potential the target can be achieved by all models (ccsmin), whereas for a reduced biomass potential (biomin) POLES does not reach the target. Nuclear power does not act as a key technology to achieve the 400ppm target beyond its contribution in the baseline, amongst others because depletion of uranium resources occurs before most of the mitigation is required. All models achieve the cap without an increase in nuclear power compared to the baseline (nonuke).

To achieve the target, MERGE exploits additional abatement options for CO₂ emissions since abatement options for the other GHGs, e.g. for N₂O, are limited and/or expensive. Due to its flexibility based on the climate module, MERGE can postpone the CO₂ reduction compared to the reference path (e.g. for the 550ppm scenario, see Figure 8).

	E3MG	MERGE	REMIND	POLES
550ppm	+	+	+	+
450ppm	+	+	+	+
400ppm	+	+	+	+
- biomax		+	+	+
- biomin		+	+	-
- ccsmin		+	+	
- nonuke	+	+	+	+
- norenew	+*	-	-	-
- noccs	**	-	-	-
- fbr		+		
- nuke fix baseyear		+	+	
- no electric cars	-			
- no extra incentives	-			

Table 4: Overview over the different scenarios run by the models. A green plus (+) means that the stabilisation target has been met, a red minus (-) means that the stabilisation target has not been achieved. Some scenarios are specific for each model, so results are reported only for one model (cars, revenue, fbr). For the description of the scenarios see Table 3. Non-standard scenarios are marked with light grey. *In the norenew scenario, E3MG is fixing renewables associated only with electricity generation (not with heat). **In the noccs scenario of E3MG, some errors were spotted, so results are not reported here but will be included in the final report.

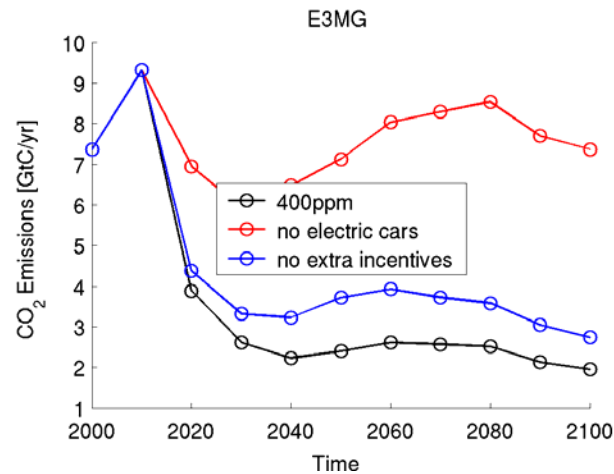


Figure 9: Emission pathway for the 400ppm scenario in E3MG (black) and two scenarios that do not achieve the target (red and blue). The black curve gives the reference 400ppm emission path for E3MG. The other curves show the influence of switching off the option of plug-in vehicles (red) and of no extra incentives through revenue recycling (blue). For the definition of the scenarios, see Table 3.

E3MG is the only model that can achieve the cap without the use of CCS or with renewables (in the electricity sector) fixed to baseline (cf. Table 4) due to the different emission path with early action. On the other hand, especially the option of the adoption of plug-in vehicles is a crucial option without which the target cannot be met (see Figure 9). Moreover, the recycling of revenues from carbon permit auctioning and carbon taxes turns out to be an important model feature in E3MG, as confirmed by many studies in the literature (Barker et al, 2007: 642). Further detailed explanations with regard to the set-up of the 400ppm CO₂-equivalent stabilisation scenario in E3MG that entails extra incentives for the promotion of low carbon technologies and the acceleration of induced technological change are provided in Barker et al. (2008). The formulation of the “no extra incentives” scenario in E3MG can thus be deduced from switching off these extra options.

4.2 Comparison of the 550, 450 and 400ppm scenario

Our own studies within the first step of this model comparison revealed that a 550ppm scenario is economically and technically feasible and, most important, that the models are flexible in their strategies, even if one technology option fails. We will now analyse whether these results are still valid for lower stabilisation targets (i.e. the 400ppm scenario) and whether significant differences in mitigation costs, strategies or the energy mix can be discovered between the three stabilisation scenarios.

4.2.1 Mitigation costs

The mitigation costs³, as cumulated losses/gains of GDP relative to baseline values⁴, are given in Figure 10 for the three reference mitigation scenarios. In Figure 11 the time path for the

³ In the following we will use the phrase “mitigation costs” simultaneously for both, losses and gains due to mitigation.

⁴ Unless otherwise stated, we use a discount rate of 5% here.

mitigation costs as yearly losses are shown. The models report different kind of costs. For the energy system model POLES, e.g. abatement costs are provided, as GDP is prescribed exogenously. For a detailed discussion about the different cost concepts we refer to Edenhofer et al. (2006).

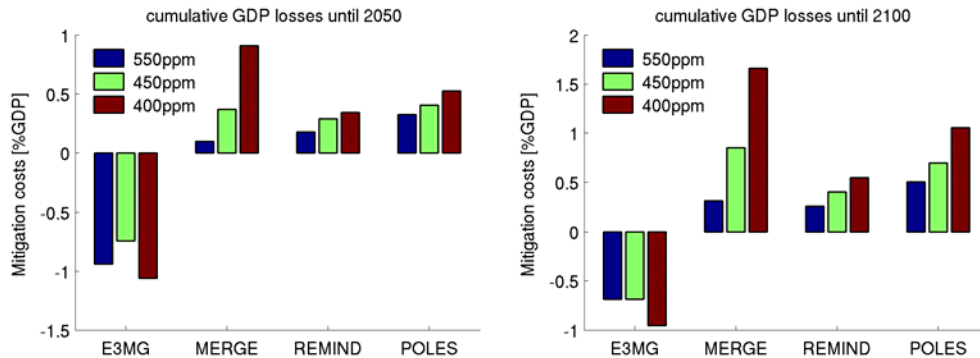


Figure 10: Mitigation costs as cumulative GDP losses relative to baseline in %GDP for the 550ppm, 450ppm and the 400ppm scenario for 2050 (left) and 2100 (right). POLES reports the increase of abatement costs relative to baseline in %GDP.

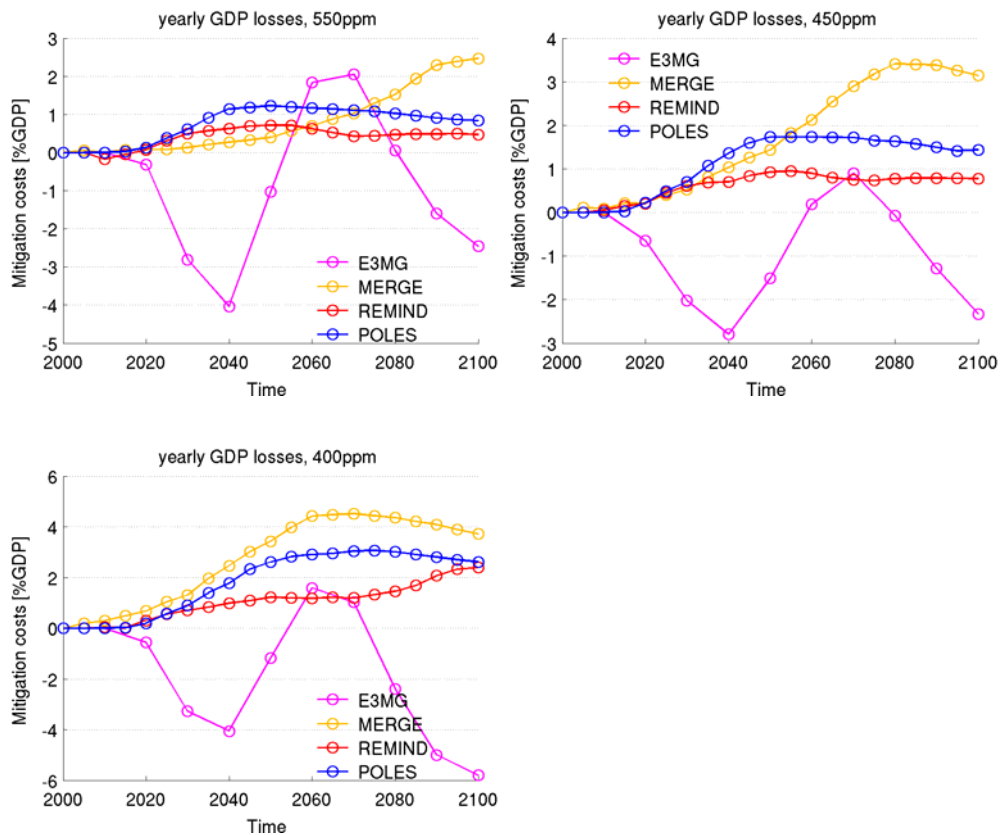


Figure 11: Mitigation costs as yearly losses of GDP relative to the baseline in %GDP for the 550ppm, 450ppm and the 400ppm scenario. POLES reports abatement costs relative to baseline in %GDP.

All models except E3MG show overall losses of GDP for all scenarios. For the other three models, the costs for all stabilisation targets are very moderate with losses below 1.7% GDP until 2100 for the most stringent scenario (see Figure 10). The yearly losses are moderate until 2050 but increase in all three models during the transition phase of the energy system and stabilise or even decline thereafter. The increase is seen especially for MERGE in case of the 450ppm and the 400ppm scenario (see Figure 11).

Compared to the other models, REMIND reports very low costs what is due to the fact that on the one hand the price path for fossil energy is assumed to be high, so that renewable energy sources are already used to a large extent in the baseline (see section 4.2.3). Moreover, abatement is not valued for other GHG, as e.g. in MERGE and POLES, which leads to slightly lower costs⁵. As POLES includes only the costs for the transformation of the energy system but no macro-economic costs, one would assume that costs in POLES are lower compared to REMIND and MERGE. However, POLES reports relatively high costs for abatement, as there is no feed-back effect of lower GDP on the energy demand and therefore on emissions. A smooth increase in costs with lower stabilisation level is observed when going from 450ppm to 400ppm (see Figure 12). MERGE reports the highest costs for the 400ppm scenario and the steepest increase with lower stabilisation targets. Overall, the costs are at the lower end of the results reported in the IPCC AR4 (Fisher et al., 2007, Fig. 3.25, p. 205).

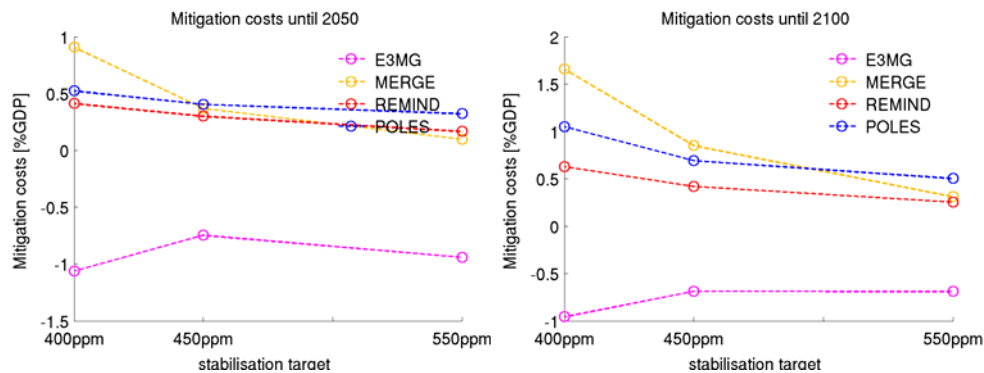


Figure 12: Mitigation costs as cumulative GDP losses relative to baseline in dependence on the stabilisation target. Left: cumulative GDP losses until 2050, right: cumulative GDP losses until 2100.

E3MG reports overall gains (see Figure 10) due to the extra investments generated from induced technological change, economies of scale and specialisation of low-carbon technologies stimulating the transfer of labour from traditional to modern sectors and overall demand. Moreover, revenue recycling and removal of distorting taxation by mitigation policy is an important feature of E3MG and results in gains due to mitigation. The mitigation benefits (and costs) reported by E3MG depend on the year of the projection (Figure 11). The wave of early investment in plug-in vehicles, energy efficiency options in buildings and low-GHG energy supplies leads to acceleration of GDP growth to 2040 (negative costs), but GDP

⁵ First experiments with the inclusion of abatement in other GHG with MACs have shown that the global GDP losses increase not noticeably; consumption losses increase by 0.2 percentage points globally.

then falls below base for two decades (positive costs) before rising again towards the end of the century as the first generation investments are replaced. The characteristics of this Kondratieff wave are dependent on the policy portfolios in each scenario.

The price for CO₂ is rising over time in most models, where the costs for the 400ppm scenario are more than five times as high as in the 550ppm scenario (Figure 13). On the other hand, by the end of the century fossil energy will only be used to a limited amount, so the price becomes less important. Moreover, the price prevents fossils from re-entering the energy system.

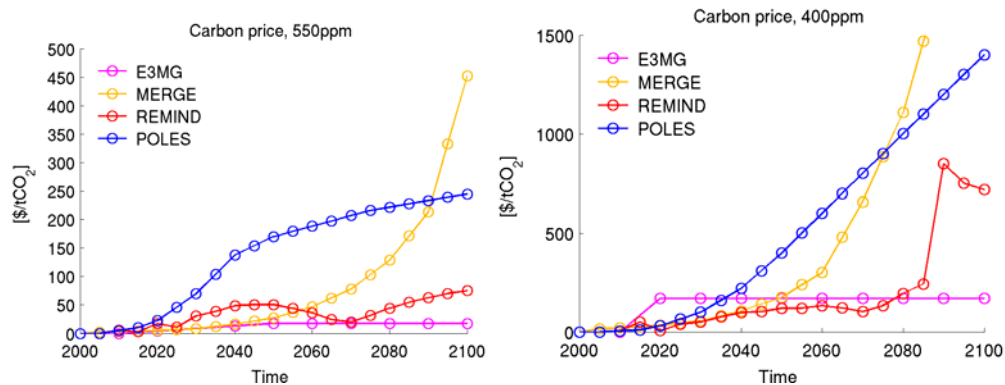


Figure 13: Carbon price for 550ppm and for 400ppm. The carbon price in MERGE increases up to 3000 \$/tCO₂ in 2100.

4.2.2 Emission reduction: strategies

We concentrate here on the reduction of CO₂ from energy and refer in the following only to these CO₂ reductions. Emissions from land-use change are prescribed exogenously in the models. Abatement in other GHG is reported only by MERGE and POLES but will not be analysed here. The CO₂ reductions that are needed to meet the target are shown in Figure 14. This reduction is quite consistent among the models as all models agreed on the same baseline. REMIND has lower reductions due to lower CO₂ emissions in the baseline (cf. section 3.1), MERGE has to reduce more CO₂ due to the higher amount of other GHG (cf. section 4.1).

For reducing CO₂ emissions there are three major options to achieve the mitigation target. According to Kaya's identity, CO₂ reductions can be attributed either to reductions in carbon intensity CI (defined as CO₂ emissions per primary energy), or to reductions in energy intensity EI (defined as primary energy per GDP) or limited growth of GDP – always as reductions relative to baseline. A decomposition analysis allows quantifying the contributions of these different options.

In order to further analyse the reduction of the carbon intensity, we extend the Kaya identity by a further classification of the carbon intensity CI into CI fossil, CI nuclear and CI renew (see Appendix 7.3 for a derivation). CI fossil, CI nuclear and CI renew describe the relative change of fossil, nuclear and renewable energy and their influence on the change in CO₂ emissions that then can be attributed to the carbon intensity.

The extended Kaya analysis of the mitigation options is given in Figure 15. It can clearly be seen that the reduction of the carbon intensity is in nearly all cases the most important strategy and becomes more and more important the stricter the stabilisation target is. Within the reduction of CI, the reduction of CI in the fossil sector has the largest influence on the emission reduction mainly due to a switch away from coal to gas or the use of CCS.

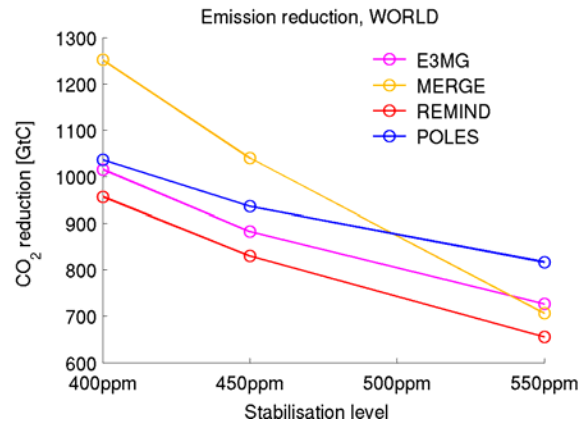


Figure 14: Cumulated CO₂ emission reduction from energy and industry in relation to the stabilisation target.

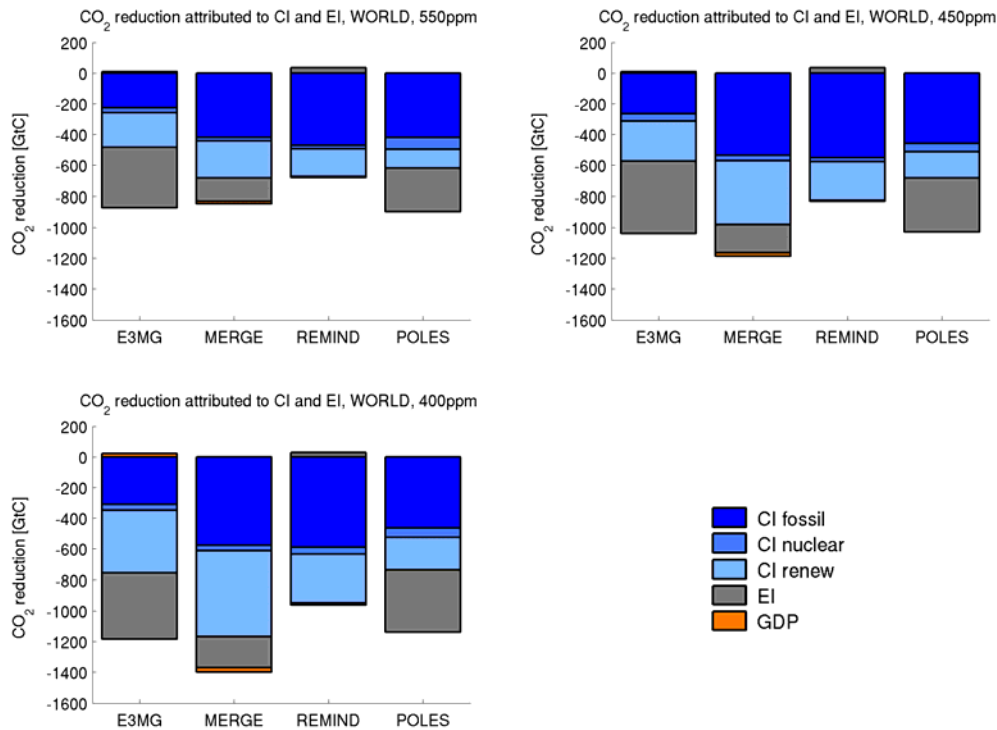


Figure 15: Cumulative CO₂ reduction attributed to reductions in carbon intensity CI (blue colours), energy intensity EI (grey) and GDP (orange). The carbon intensity CI is extended further into the change of the primary energy mix related to fossil energy (CI fossil), to nuclear energy (CI nuclear), and to renewable energy (CI renew). Reductions are always given relative to baseline. Positive values describe an increase compared to the baseline.

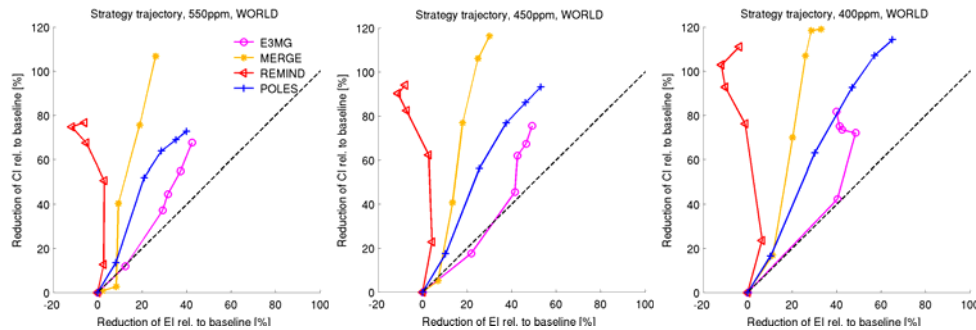


Figure 16: Global Strategy trajectories related to energy intensity reduction and carbon intensity reduction for 550ppm, 450ppm and 400ppm. Trajectories start at the origin, markers are given every 20 years. The dashed line marks the line, where CI and EI are equally reduced.

The more stringent the target, the more CI is reduced by the adoption of renewables by all models. Whereas CI reduction from fossil energy remains more or less the same throughout all scenarios, reduction of carbon intensity due to the use of renewables is increasing substantially. Reduction of CI referring to increasing nuclear power is negligible.

The reduction of energy intensity plays only a minor role as a mitigation option (except for E3MG), which is due to the fact that e.g. MERGE and REMIND do not model end-use energy efficiency technologies in the same detail as supply side technologies. Moreover, energy intensity is already reduced substantially in the baseline, what is in line with historic observations (e.g. Nakicenovic et al., 2000, Fig. 3-13 or Fischer et al, 2007, Fig. 3.6). Increasing the reduction of energy intensity with a more stringent target is only an option used by POLES and partly by E3MG. A recent study notes that end-use efficiencies are supposed to deliver about 60% of the CO₂ abatement and require about 80% of the investments compared to those of the supply-side energy sector in estimates for the G8 50% scenario (IEA, 2008, p. 64 and p. 243).

The timing of the mitigation options (see Figure 16) shows that MERGE and POLES follow the same strategy over the whole time period. For E3MG, the reduction of EI and CI is equally important until the mid of the century and then the reduction of CI becomes more important. In REMIND there is nearly no reduction in energy intensity relative to the baseline, but actually an increase due to the fact that renewable energy is used extensively by the end of the century, so energy efficiency plays no role for mitigation.

4.2.3 Energy mix

The energy mix and the development of the energy demand are very different among the models already in the baseline (see Figure 3). This is partly due to different assumptions of the fossil price paths. Despite the very similar mitigation costs among the models (cf. Figure 10), the energy mix in the baseline and in the mitigation scenarios is very different between the models. Each model follows here an own strategy: either reduction of energy use (MERGE, E3MG, POLES), a massive extension of renewables (REMIND) or the reduction of fossil energy by an increasing energy efficiency (E3MG). This means that in contrast to the mitigation costs, the energy mix is not a very robust feature among the models, but depends heavily on the model assumptions about the available technologies, learning rates or resource prices.

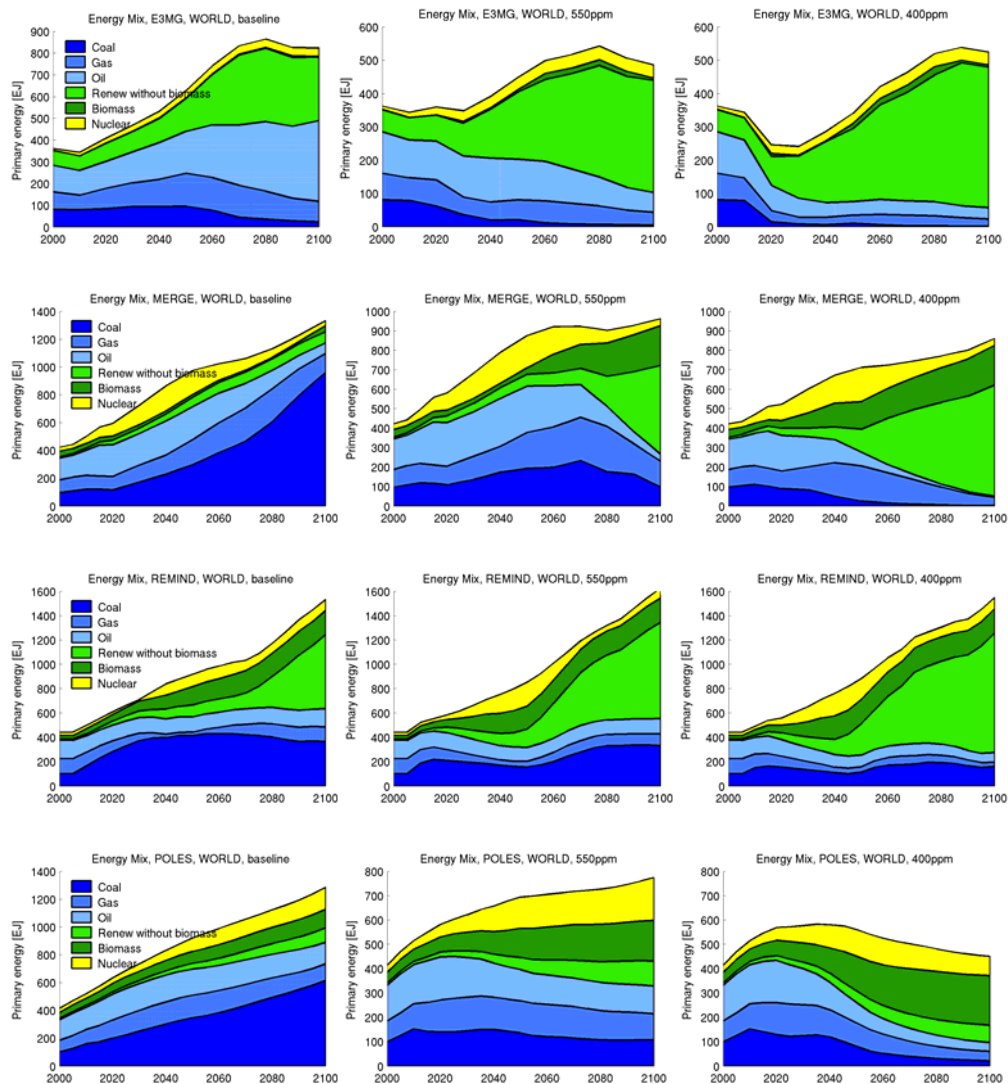


Figure 17: Energy mix for baseline, 550ppm and 400ppm (from left to right) for the different models (from top to bottom: E3MG, MERGE, REMIND, POLES).

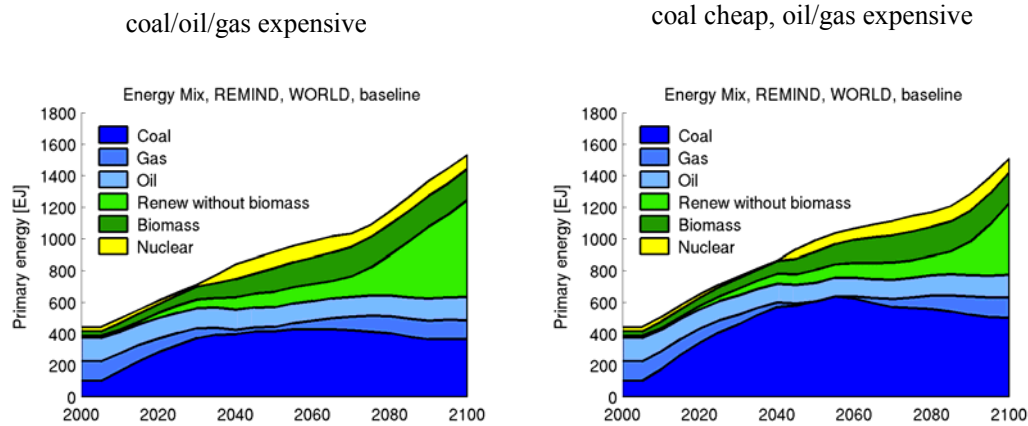


Figure 18: Energy mix for REMIND for the baseline for different price assumptions. Left: coal/oil/gas are assumed to be expensive (as in Figure 3, this is the default for REMIND within this comparison), right: coal cheap, oil/gas expensive.

In Figure 18 it can be seen that the assumption on the price for fossil energy has a large impact on the energy mix in the baseline: with cheaper coal, coal is used much more and the amount of renewables starts to increase later in the baseline case. This has also implications for the CO₂ emissions: with cheaper coal the emissions stabilise at about 19 GtC/yr instead of 14 GtC/yr (see Figure 2). For the policy scenario, however, the price path for fossils has no decisive influence on the energy mix.

The transformation of the energy system happens in most models just in the second half of the century and with it relatively late (see Figure 19). Only in the 400ppm scenario the transition has to start earlier. Comparing the different stabilisation levels, the major switch can be observed by going from the 450ppm to the 400ppm target (besides the general switch from baseline to 550ppm). The 550ppm and the 450ppm scenario, however, show a very similar fraction of the different energy carriers in the energy mix.

Two further findings are important to note. Firstly, nuclear energy seems to be important as an “interim-energy”, as the fraction of nuclear power increases in most models until 2050, but decreases subsequently until 2100 due partly to depletion of uranium resources. In the energy mix in the year 2100 nuclear energy has only a significant share in the POLES model. Secondly, the stricter the target, the more is the energy mix dominated by renewables and biomass. Apart from POLES, it is a consistent finding that the energy mix in the year 2100 (the fractions, not in absolute numbers) is very similar among the models.

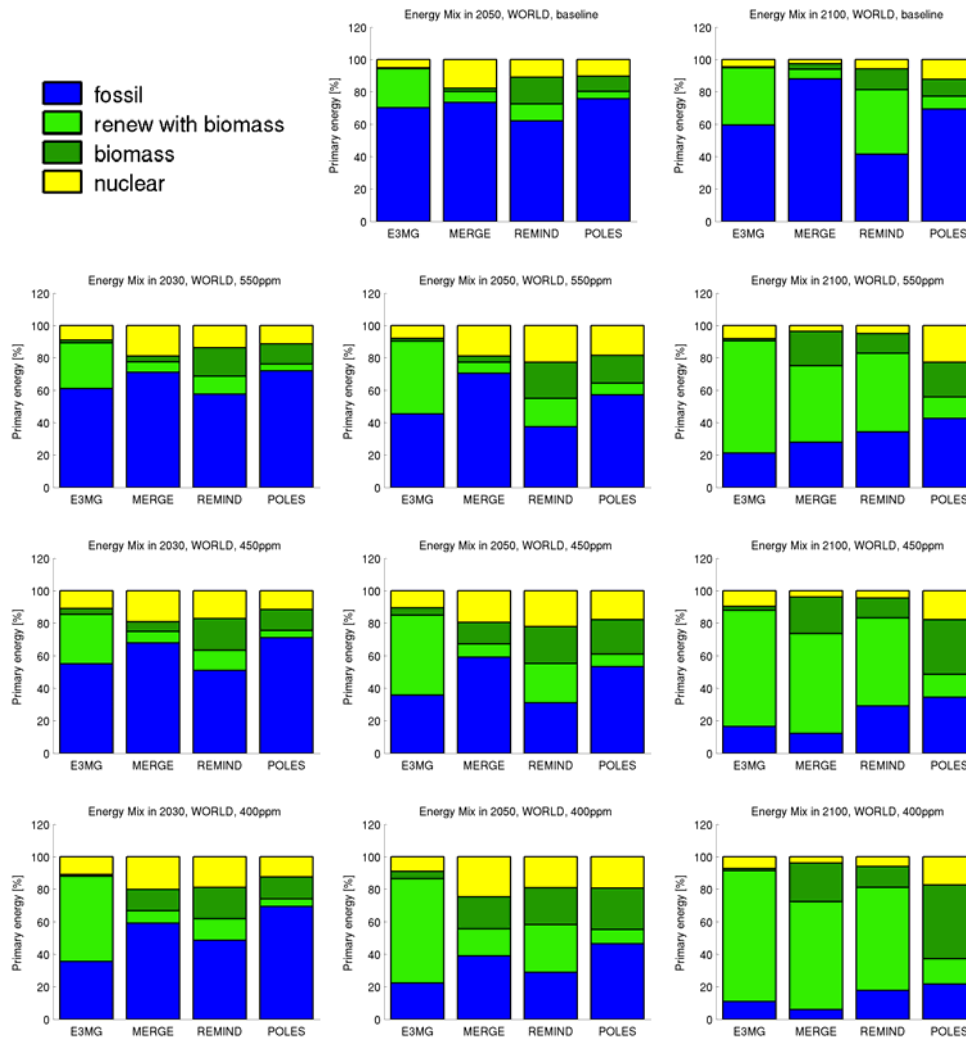


Figure 19: Primary energy mix in percent for 2030, 2050 and 2100 (from left to right) for baseline, 550ppm, 450ppm and 400ppm (from top to bottom).

4.3 Technology scenarios: the role of biomass, CCS and nuclear

4.3.1 Mitigation costs: option values

As has been pointed out in section 4.1, the achievement of the stabilisation target is not possible without the CCS option or with renewables fixed to baseline, but can be achieved when nuclear is fixed to baseline. To further explore the role of biomass and CCS we run some additional scenarios where the biomass potential is fixed at 100 EJ/yr and 400 EJ/yr, respectively, compared to the standard biomass potential of 200 EJ/yr in all models. The CCS potential is not limited in the models (except in MERGE), so an artificial constraint is set that limits the CCS potential to half of the potential that is used in the reference 400ppm scenario (cf. Table 3).

It turns out that the biomass potential included in the model determines the level of the mitigation costs. In MERGE and REMIND the costs are more than doubled with a restriction of the biomass potential. On the contrary, a higher biomass potential decreases the costs to nearly a half compared to the reference 400ppm scenario (for MERGE and REMIND). The same tendency is seen for POLES but the impact on the abatement costs is not so pronounced. Limiting the CCS potential (ccsmin) also has a large influence on the costs. In MERGE the costs (i.e., GDP losses) increase by one percentage point. In POLES the costs increase by half a percentage point when doing completely without CCS (noccs), but the stabilisation target can then not be reached. In REMIND the global costs do not change with a limited CCS potential.

The nuclear option, however, seems to be less important: the costs when nuclear is fixed to baseline increase only very moderately for REMIND and not at all for MERGE and POLES. This is partly because nuclear energy is already attractive in the baseline scenario but actually less attractive in the mitigation case for some models (POLES and MERGE, see Figure 21). An additional experiment with MERGE and REMIND, where nuclear power is fixed to the value in the base year and no increase in nuclear power is allowed, results in an increase in costs of 0.5 percentage points for MERGE and of only 0.2 percentage point in REMIND. MERGE also explores the option of implementing a fast breeder with which the costs can be decreased only moderately by 0.25 percentage points (not shown here).

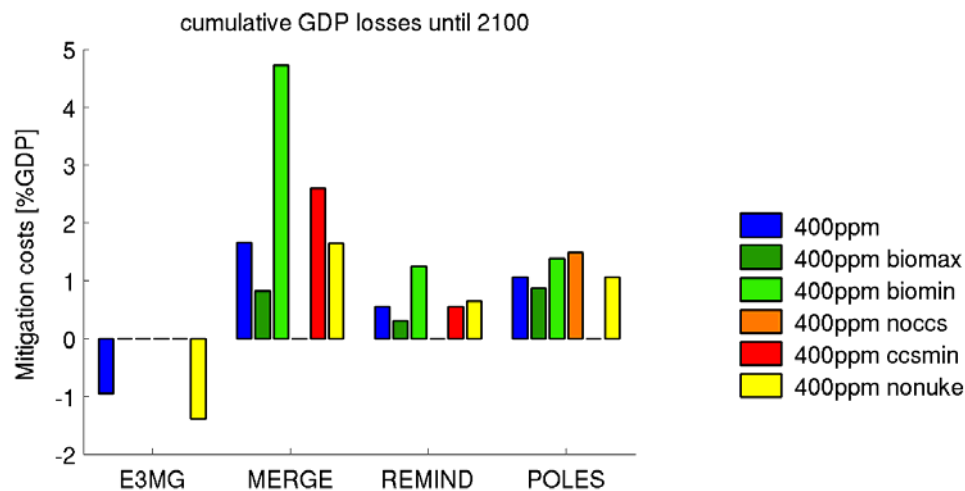


Figure 20: Mitigation costs as cumulative GDP losses until 2100 relative to baseline; POLES reports the increase of abatement costs relative to baseline in %GDP. Shown are the option values for different technologies for the 400ppm scenario. The biomax scenario refers to a biomass potential of 400 EJ, the biomin to a one with 100 EJ, compared to 200 EJ in the 400ppm reference scenario. In the ccsmin scenario the CCS potential is fixed to half of the potential that is used in the 400ppm reference scenario. In the noccs (nonuke) scenario, CCS (nuclear energy) is fixed to baseline values. Note that POLES does not stay below the cap for the noccs and the biomin scenario. See also Table 3 and Table 4.

It is important to note that MERGE, REMIND and POLES report a very similar structure in the assessment of the mitigation costs concerning the technology options and that the option values are a robust result among the three models. E3MG follows a different concept for these scenarios that is explained below. The conclusion is that the assumed biomass potential is

determining the mitigation costs and that secondly the CCS availability is important, whereas nuclear energy only plays a minor role concerning the effect on mitigation costs. This is consistent with the observation that negative net CO₂ emissions are required, and the only way to achieve this is with biomass combined with CCS.

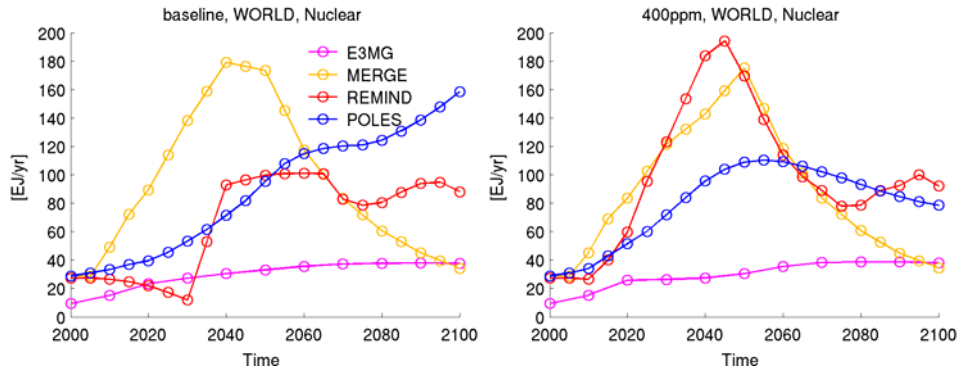


Figure 21: Nuclear energy in the baseline (left) and in the 400ppm scenario (right).

E3MG reports higher gains when fixing renewables or nuclear energy to its baseline values. The reason lies in the modelling framework of E3MG: E3MG is an "open" model in the sense that imbalances in employment, public borrowing and the balance of payments are not automatically resolved. The modelling properties come from the assumption that economies employ resources sufficient to meet investment demands and these extra investments create the extra supply required for higher growth. The results show that there is a substantial increase in global output relative to the baseline of above 10% by 2100 as the investments in low-carbon technologies necessary to achieve the stabilisation target are being distributed over the remaining mitigation options, which require more investment to achieve the demanded reduction in emissions. The required carbon price is very similar between most of the scenarios because much of the extra 400ppm CO₂-eq mitigation effort is coming from demand-side options with recycling of revenues and regulation. It is important to note though that these scenarios are simple model exercises within this special modelling framework of E3MG and should not be considered as realistic scenarios.

4.3.2 Implications of biomass use

The biomass potential not only plays an important role for the mitigation costs but also changes the energy mix substantially. It is important to note that so far only the technical potential has been varied in the model. A probable conflict with food production, co-emissions etc. are so far not investigated here. Conflicts with other types of land use, in particular food production and biodiversity protection, as well as the question whether this potential can be sustainably harvested have not been investigated so far. Furthermore, zero emissions are attributed to bioenergy use, thus neglecting emissions from direct and indirect land-use changes and the biomass production process itself. Certain types of land-use change (e.g. converting wetlands or tropical forests) will lead to increased greenhouse gas emissions rather than emission reductions. Neglecting these emissions will not only hide possible additional climate damage, but also yield an overoptimistic assessment of the economic

potential of biomass in scenarios including carbon pricing. To complete the analysis of biomass use, some of these issues will therefore be assessed by the biomass task force within the ADAM work package M2.

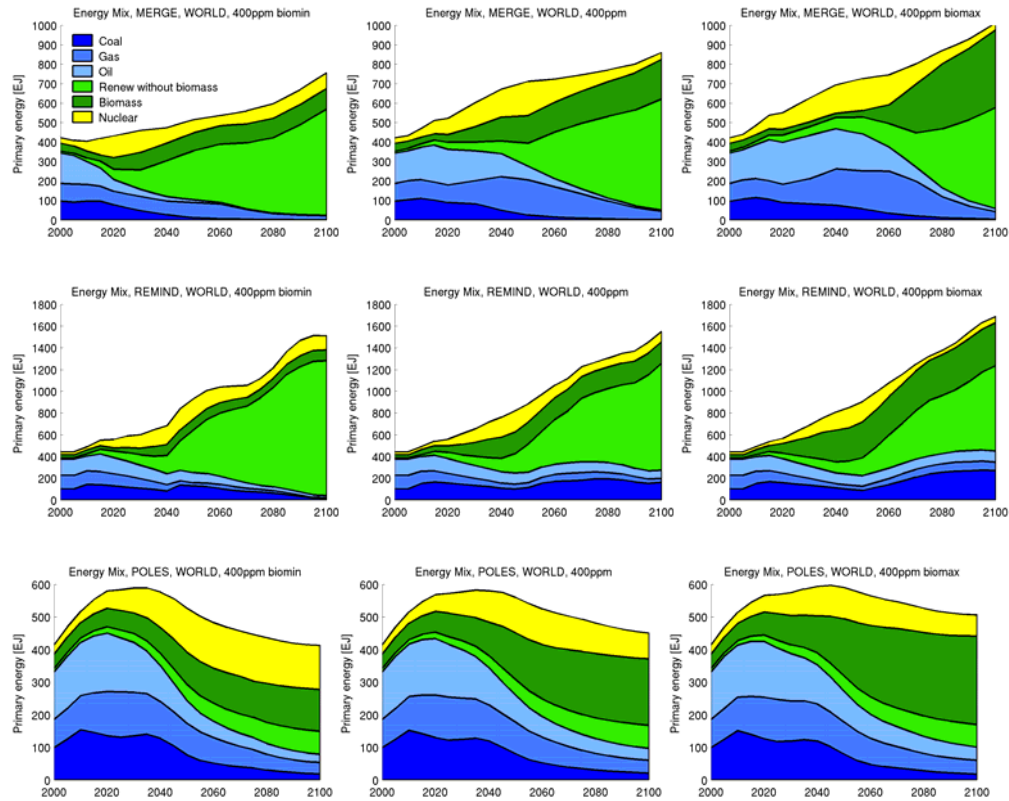


Figure 22: Energy mix for increasing biomass potential (from left to right: 100 EJ, 200 EJ, 400 EJ) for the models MERGE, REMIND and POLES (from top to down). POLES does not reach the target for the biomin scenario.

It turns out that biomass is competing with other renewable energy sources (for MERGE and REMIND). When increasing the biomass potential, an increasing amount of biomass is used, whereas the amount of other renewable sources decline (Figure 22). Moreover, the transformation of the energy system is postponed at a later date in MERGE, as here the huge amount of biomass is anticipated to be available at later times. On the other hand, a restriction on the biomass potential increases the innovation pace of the other renewables.

The reason for this is that with increasing biomass potential a renaissance of gas and oil (MERGE) or coal (REMIND) takes place, as a high biomass potential allows more negative emissions. In REMIND, these negative emissions allow then for an increasing use of coal in combination with CCS, as this is less costly compared to nuclear energy or other renewables. With a lower biomass potential this is not possible since the residual emissions remaining after CCS are still sufficient to make the use of coal unattractive. In MERGE, the high availability of biomass and the flexibility of the climate module enable the required emission reductions to be postponed to later in the century, so that until then more fossil energy can be used (see emission pathway of MERGE in Figure 23). With a lower biomass potential, the emission reduction has to start much earlier, which increases the mitigation costs.

With a reduced biomass potential, the models decrease the energy use (MERGE), increase the amount of other renewables (REMIND) and/or increase the use of nuclear power (POLES). However, in POLES the target cannot be met with a limited biomass potential mostly due to the capture ratio used for biomass plants (only a maximum of 70% of CO₂ emissions can be captured and then stored). In REMIND an additional experiment shows that below the limit of 70 EJ/yr biomass the emission path cannot be reached.

To sum up, the biomass potential has a strong effect not only on the costs, but also on the energy mix and the timing of the mitigation options. Again, it has to be pointed out that one has to be very careful in interpreting these results. In particular, the biomass potential should not be viewed as a purely technical parameter, since there are likely to be significant interactions between biomass availability and food production, land-use change and the emissions of other GHGs, none of which is the focus of this analysis here. Consistent scenarios that include the above mentioned caveats are under development.

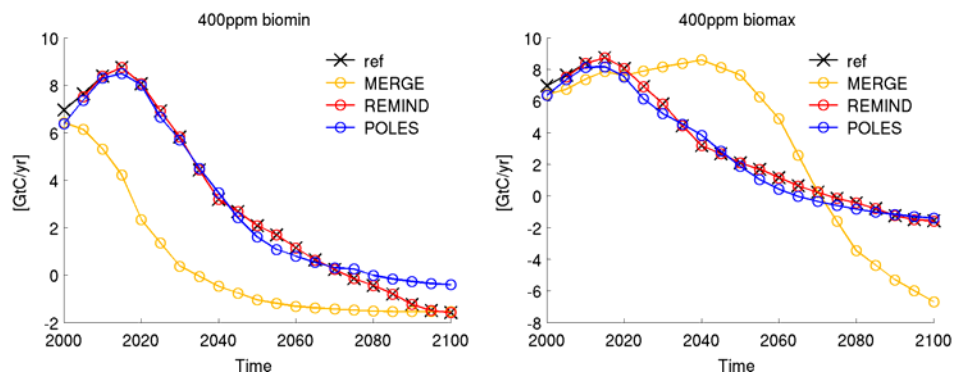


Figure 23: CO₂ emission pathway for the scenarios with a biomass potential of 100 EJ/yr (biomin) and of 400 EJ/yr (biomax). POLES does not reach the target for the biomin scenario.

4.3.3 Implications of CCS

The amount of abatement attributable to CCS compared to total CO₂ emission reductions is depicted in Figure 24 and Figure 25. With a more stringent target, the use of CCS increases only slightly for MERGE and REMIND, whereas for POLES the amount of CCS stays constant. The same behaviour can be seen with increasing biomass potential, where the actual use of CCS is only increased noticeably for REMIND. Overall, the amount of CO₂ that is captured with CCS is very similar in MERGE and POLES, whereas REMIND reports a bit higher CCS use in some scenarios. In POLES and REMIND, the CCS potential is unlimited, implying that after a certain point the marginal costs for CCS become uncompetitive compared to other abatement options so a certain amount of CCS is used, regardless of the stabilization target. In REMIND the biomass potential has a decisive influence on the use of CCS as with larger biomass use combined with CCS more negative emissions can be achieved that allow then again the use of coal in combination with CCS.

In the case of MERGE, that has a limited CCS potential (~ 400 GtC) already in the standard mitigation scenarios, this potential is almost fully utilized in the 450 ppm case, meaning there

is very limited potential to capture additional carbon under more stringent targets. Regardless, stabilizing GHG emissions without or with limited CCS greatly increase the costs and reduces the scope for negative emissions.

MERGE has done an additional run to explore the limit of which stabilisation target can still be reached without CCS. MERGE reports here an emission path that stabilizes at roughly 450ppm CO₂-eq in the long-term that is possible without CCS at substantially increased costs of about 4% GDP losses until 2100.

E3MG does not bring CCS in (unless it is forced in) due to its high costs relative to other low carbon technologies. There is always a fuel penalty that applies to CCS (particularly for coal and gas), which will not be able to bring down costs as fast as for other low carbon technologies (e.g. renewables).

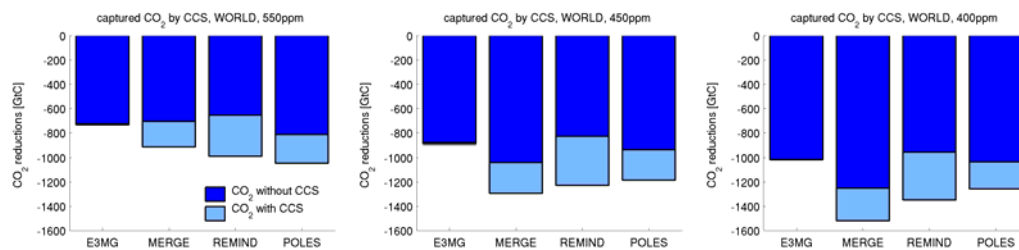


Figure 24: Amount of CO₂ captured by CCS compared to the total CO₂ reductions for decreasing stabilisation target (from left to right).

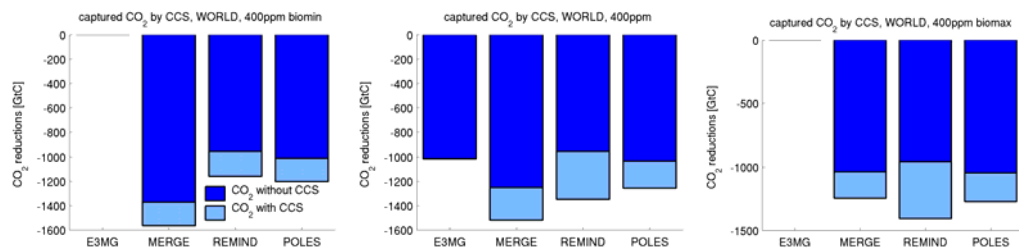


Figure 25: Amount of CO₂ captured by CCS compared to the total CO₂ reductions for increasing biomass potential (from left to right). E3MG uses only a very limited amount of CCS that can hardly be depicted here.

5 Conclusions

In this report we have conducted a model comparison of four energy-environment-economy models in view of their mitigation strategies and costs. We have analysed three different stabilisation scenarios ranging from 550ppm to 450ppm to 400ppm CO₂-eq (with a focus on the latter) in comparison to a business-as-usual scenario where no political action is taken to mitigate climate change. The 550ppm scenario was studied in detail in the previously reported first step of this model comparison (see Deliverable D-M2.4). In the present study we investigated in detail the technological feasibility and implications of a low stabilisation scenario of 400ppm CO₂ and compared this scenario with the other stabilisation targets in terms of mitigation costs, reduction strategies and the energy mix. The focus was on the option values of different technologies and limited potential of certain technologies/resources, e.g. biomass or the storage potential of carbon capture and storage (CCS).

Although the models compared in this exercise are quite different in their basic modelling approach and their assumptions about the availability of certain technologies, a robust conclusion among the models for some of the results can be drawn: Firstly, the major finding is that all models can represent such a low stabilisation target. This is an important result since so far only a few models have reported results for a stabilisation level at or below 400ppm CO₂-eq. Secondly, the costs for stabilising concentrations at such a low level are moderate in all models, ranging from cumulative GDP gains of about 1% up to 1.7% GDP losses by 2100 relative to the baseline. The uncertainties and costs increase the lower the stabilisation target is, but the costs for all scenarios reported here are in the lower to medium range compared to the values given in the IPCC AR4.

On the other hand, in contrast to the conclusion drawn from the investigation of the 550ppm scenario, where the models show a high flexibility in the different technologies and can in any case substitute one technology with another, in the 400ppm scenario this technological flexibility is to some extent lost. Biomass and CCS on the one hand and energy efficiencies and other demand-side regulatory measures on the other hand, play a very important part in reaching this low stabilisation level.

Concerning the technology options, the models MERGE-ETL, REMIND-R and POLES show a very similar picture whereas E3MG reports differing results. In the former models, the use of biomass and CCS are the most important technology options, without which this low stabilisation pathway is not possible at all. Moreover, the assumed biomass potential determines to a large extent the mitigation costs, in addition to having a decisive influence on the energy mix. The most critical point is that the use of biomass seems to compete with the other renewable sources: the more biomass that is available (and used), the lower is the amount of other renewables needed in the energy mix. In other words: by setting a restriction on biomass use, the innovation rate in the other renewables is accelerated, although the overall costs increase.

Analysing the implications of the biomass potential, it is important to keep in mind that with greater biomass use, potential conflicts with food production, poverty alleviation goals, forest resources and additional emissions associated with large-scale energy crop production have to be considered. This point is under investigation by the M2 biomass taskforce.

In two of the three models the CCS potential has a large influence on the mitigation costs as well. On the other hand, despite the unbounded CCS potential in REMIND-R and POLES, only around 200 to 400 Gt carbon is captured over the century.

Nuclear power was not seen to play an important additional role in mitigation scenarios compared to the baseline in any of the models. This is partly because nuclear energy is already attractive in the baseline scenario. In some models, nuclear power even becomes less attractive than in the baseline. Only when the biomass potential is assumed to be low, nuclear power becomes a more important option. Fixing nuclear energy to baseline values, the costs increase not at all or only moderately. In fact, nuclear power is used as an “interim-technology” until 2050 but decreases afterwards partly as a result of depletion of uranium resource (represented in some models). When abstaining from an expansion of nuclear power above the level in the baseline, this interim demand is substituted by coal-based generation coupled with CCS or by reduced energy use. But even with fixing nuclear energy at today’s level the mitigation target is still achievable at slightly higher costs. With the option of fast breeder reactors, which overcome resource depletion challenges of nuclear energy, the costs decrease slightly, while the fraction of nuclear power on electricity increases substantially.

E3MG reports differing results concerning the mitigation costs and the importance of some of the technologies. The reason lies in the different model set-up of E3MG, which aims to depict a more realistic world in the sense that full employment of resources is not assumed, and imbalances in employment, public borrowing and the balance of payments are not automatically resolved. Therefore, E3MG reports gains from mitigation due to the extra investments generated from energy efficiency policies, induced technological change, economies of scale and specialisation of low-carbon technologies stimulating the transfer of labour from traditional to modern sectors and overall demand.

In E3MG the use of biomass and CCS are not important options. On the other hand, here the early introduction of electric plug-in vehicles has a major impact on the emission path. Moreover, the recycling of revenues from carbon permit auctioning and carbon taxes turns out to be an important model feature in E3MG. This approach leads to a wave of early no-regrets investments from energy efficiency policies (electric vehicles and low-carbon buildings) that stimulate the global economy and raise global GDP above baseline at least until mid-century.

In summary, the models illustrate ways in which this low stabilisation target of 400ppm CO₂-eq for atmospheric GHG concentrations can be achieved at moderate cost. As a caveat, a substantial dependence on some of the technologies is observed in this low stabilisation scenario.

5.1 Outlook

In this study we have mainly investigated the technical feasibility of the 400ppm scenario. Additionally it is important to investigate the political feasibility of this scenario, e.g. the impact when one or more regions join the global reduction efforts at a later time.

Moreover, although the models report regional results, we have analysed at first the impact of low stabilization on global costs and energy system development. In a next step, the regional implications will be investigated further, also with a focus on the role of Europe.

Moreover, as outlined before, the implications of a high or a low biomass potential on food production and land-use change should also be assessed.

These aspects will be the focus of the final report on low stabilisation. For this last report we will also provide a synthesised analysis of the 550ppm, 450ppm and 400ppm scenario.

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7 Appendix

7.1 Definition of regions

CHN:	China
IND:	India
JPN:	Japan
EU27:	Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom
RUS:	Russia
USA:	United States
ROW:	Rest of the world is the residual obtained from subtracting the above six regions from the aggregate.

Note that E3MG reports a EU25 instead of the EU27 region (i.e. without Romania and Bulgaria).

MERGE reports EU15 (instead of EU27) and a region Eastern Europe with Russia (EERU) instead of Russia

Population inputs for E3MG are identical to those of the agreed baseline data across the entire period up to 2100. However, because of rounding errors increasing across time arising from E3MG reporting only every ten years, the population projections in the long-term marginally differ from the initially agreed population baseline.

7.2 List of mitigation options

	Mitigation options available from the models	E3MG	MERGE-ETL	REMIND-R	POLES
Policy	Emission allowance scheme (e.g. EU)	x	x	x	x
	Kyoto regime	x	x	x	x
	Direct or indirect taxes: energy, carbon, employment, etc.	x	x		x
	Recycling of carbon tax and part of the permit revenues in the form of lower indirect taxes	x			
	Credits or subsidies on investment costs of low energy or low emissions equipments	x	x		x
	Feed-in tariffs to stimulate renewable sources of energy	x			x
	Adoption of common low-carbon technologies between countries (e.g. via energy efficiency standards)	x	x	x	x
	International agreements leading to reductions in costs brought about by adoption of common standards and reduction of market barriers	x	x		
Technology, Market and Others Model Features	International emissions (permits) trading scheme	x	x	x	x
	International energy or capital trade, and/or foreign direct investments	x	x	x	x
	R&D investment in low-carbon technologies	x	x		x
	Induced technological change	x	x	x	x
	Energy efficiency improvements	x	x ¹	x ¹	x
	Renewable energies: hydro, wind, solar, etc.	x	x	x	x
	Carbon capture and Sequestration (CCS)	x	x	x	x
	Nuclear energy	x	x	x	x
	Synthetic fuels		x		x

Table 5: Overview over the different mitigation options that are available in each model. ¹Energy efficiency improvements are exogenously in MERGE and REMIND.

7.3 Extension of the Kaya identity

The basic rationale of the Kaya identity that CO₂ emissions F can be composed of the factors population P , affluence A , energy intensity e and carbon intensity c . Affluence is given in GDP per capita being derived by dividing GDP by population (POP). Energy intensity is defined as primary energy supply (PE) divided by GDP. Carbon intensity is then defined as CO₂ emissions divided by primary energy PE . Thus, the CO₂ emissions can formally be expressed as follows:

$$CO_2 = POP \cdot \left(\frac{GDP}{POP} \right) \cdot \left(\frac{PE}{GDP} \right) \cdot \left(\frac{CO_2}{PE} \right), \text{ or}$$

$$F = P \cdot A \cdot e \cdot c$$

A change in CO₂ emissions can be expressed as a change in the four factors by a linearisation:

$$\Delta F \approx A \cdot e \cdot c \cdot \Delta P + P \cdot e \cdot c \cdot \Delta A + P \cdot A \cdot c \cdot \Delta e + P \cdot A \cdot e \cdot \Delta c$$

In our setting, P is constant, so ΔP is zero. In order to get more detailed information about the influence of single primary energy carriers, the Kaya identity can be expanded. To get a broader understanding of the drivers of CO₂ emissions, the carbon intensity c is analysed more closely. As the carbon intensity c depends on the single primary energy carriers, it can be written as the weighted sum of the carbon intensities c_i of the respective primary energy carriers:

$$c = \sum_i \left(\frac{CO_{2,i}}{PE_i} \right) \cdot \left(\frac{PE_i}{PE} \right) = \sum_i c_i \cdot q_i$$

Therefore, the Kaya identity can be extended by a factor q_i being the relation of a specific primary energy carrier PE_i to the overall supplied primary energy PE :

$$F = P \cdot A \cdot e \sum_i c_i \cdot q_i .$$

It is obvious that only emission-intensive primary energy carriers can be covered. Trends for emission-free primary energy carriers, such as nuclear energy, hydro or renewable energy cannot be pictured as in the case $c_i = CO_2/PE_i = 0$. Therefore c_i needs to be weighted by a constant value, for example the average carbon intensity \bar{c} . With this zero-extension, the change in CO₂ emissions (ΔF) is the sum of the effects can thus be expressed as pictured in Figure 15.