The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs

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This study gives a synthesis of a model comparison assessing the technological feasibility and economic consequences of achieving greenhouse gas concentration targets that are sufficiently low to keep the increase in global mean temperature below 2 degrees Celsius above pre-industrial levels. All five global energy-environment-economy models show that achieving low greenhouse gas concentration targets is technically feasible and economically viable. The ranking of the importance of individual technology options is robust across models. For the lowest stabilization target (400 ppm CO_2 eq), the use of bio-energy in combination with CCS plays a crucial role, and biomass potential dominates the cost of reaching this target. Without CCS or the considerable extension of renewables the 400 ppm CO_2 eq target is not achievable. Across the models, estimated aggregate costs up to 2100 are below 0.8% global GDP for 550 ppm CO_2 eq stabilization and below 2.5% for the 400 ppm CO_2 eq pathway.

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1. INTRODUCTION

The objective of the United Nations Framework Convention on Climate Change (UNFCCC) is “stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (UNFCCC 1992, Article 2). Reaching the target of climate stabilization at no more than 2°C above pre-industrial levels by the end of this century – which is how the European Union (EU) interprets Article 2 – is a historic challenge for humankind. To make it likely that this challenge will be met, greenhouse gas concentrations have to be limited to at least 450 ppm CO_2 equivalent (for a 50 % likelihood) or below. This presupposes a portfolio of mitigation options for very stringent emission reductions and requires taking action now.

The 2°C target must not only be technically feasible but also readily affordable economically if it is to be acceptable to stakeholders and decision-makers around the world. Obviously, this is a rather ambiguous criterion, as it depends among others on the assumed benefits of climate policy. To support climate policy making in this paper, we evaluate the technological feasibility of reaching these stabilization targets, explore the importance of individual technologies and estimate the associated economic costs. We do so using a multi-model approach, allowing comparison of results across different models as well as some assessment of model-related uncertainty.

Specifically, we try to answer two key questions:

(1) What are the technical and economic consequences of different targets that could be consistent with the 2˚C target? Specifically, we explore three different CO_2 stabilization scenarios (550, 450 and 400 ppm CO_2 eq). The probabilities for reaching a 2˚C target associated with these concentration levels increase from approximately 20% (550ppm), to 50% (450ppm), and 80% (400ppm CO_2 eq), based on the uncertainty in climate sensitivity (Hare and Meinshausen, 2006).

(2) What are some of the technological barriers or economic and political factors that are crucial for the intended emissions stabilization outcome? For example, what can still be achieved if some of the technology options fail or are ruled out? In this context, it should be noted that some of the technologies that may be indispensable for reaching very low emission paths – such as large-scale use of biomass, Carbon Capture and Storage (CCS), or nuclear power – may be saddled with high risks and adverse side effects.

In order to assess the two key questions, five global regionalized energy-environment-economy models (E3) are compared in a coordinated manner.[1] So far, only few energy-environment-economy models have assessed the attainability

1. The comparison has been performed as part of the ADAM project (Adaptation and mitigation strategies: supporting European climate policy), www.adamproject.eu.

of such low concentration levels but exploring low stabilization targets has become increasingly relevant in recent years. This growing interest in ambitious climate stabilization scenarios may well be attributable to a clearer realization of at least two factors. First, only recently has public appreciation of the need for low stabilization to limit the damage expected from continued increases in global mean temperature strengthened. It is now realized that global warming will have severe impacts (*e.g.,* Stern, 2007; Parry et al., 2007; Hansen et al*.,* 2007; Smith et al*.,* 2009) and that further temperature increases may trigger tipping points in the climate system (Lenton et al*.,* 2008). This has stimulated more interest in the corresponding scenarios and how to achieve them in the short-term. Second there was a technical reason why little had been done before. Inflexibilities in the energy systems, shortcomings in applications of mitigation technologies, and myopic investment behavior are among the reasons why low concentration pathways have so far been assessed and achieved by only a small number of models. In general, however, the space occupied by low-stabilization targets in both the politically and economically feasible regions has increased.

In the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), only three models containing 6 out of a total of 177 mitigation scenarios presented provide results for the lowest IPCC category of a radiative forcing of 2.5 – 3.0 W/m², corresponding to a 445-490ppm CO_2 eq level (Fisher et al., 2007). Since then, a few new studies on stabilization levels below 450 ppm CO_2 eq have been published, including work by van Vuuren et al. (2007) exploring 400ppm CO_2 eq, den Elzen and van Vuuren (2007) considering the effects of peaking in mitigation scenarios, and Azar et al. (2006) focusing on bioenergy with carbon capture. More recently, Rao et al. (2008) investigate the 400ppm CO_2 eq profile by van Vuuren et al. (2007) with the models MESSAGE and IMAGE/TIMER. Nordhaus (2007) reports results for a 1.5 °C target but at relatively high costs. Some model studies even report infeasibilities of low concentration levels (e.g. Tol, 2009). Van Vuuren et al. (2006c) point out that assumptions on technologies are crucial for achieving low stabilization targets and Rao et al. (2008) report infeasibilities of low stabilization targets under different baseline assumptions. As low stabilization will most probably depend on the available technologies implemented in the models, we focus in detail on this aspect. Moreover, feasibility depends on the early and full participation of all countries (e.g. Luderer et al. (2009), Clarke et al. (2009)). The challenge of increasing global participation is addressed in Knopf et al. (2010, this Issue).

Model comparison analysis can help identify a range of pathways to a low carbon economy and shed light on the robustness of the associated cost estimates and technology options. Edenhofer et al*.,* (2006) provide an overview of this literature. Recent examples that were included in the IPCC AR4 (Fisher et al., 2007) are comparisons by the Stanford University based Energy Modeling Forum (EMF), with EMF-21 focusing on multi-gas mitigation (Weyant et al*.,* 2006, van Vuuren et al., 2006b) and EMF-19 on technology and climate change policy (Weyant, 2004). The Innovation Modeling Comparison Project (IMCP) by Edenhofer et al. (2006) focused on endogenous technological change, and the Climate Change Science Program (CCSP) (Clarke et al., 2007) in the United States presented a comparison of three models. A number of such comparisons are already completed, for instance within the EMF on transition scenarios in the EMF-22 (Clarke et al., 2009), or a comparison on sectoral analysis of the energy system (Luderer et al., 2009, van Vuuren et al. 2009b).

Exploring the lower limit of stabilization and attaining robust information concerning the importance of individual technologies for low stabilization is the overarching challenge and focus of the model comparison in this paper. We are aware that pure model analysis is insufficient to address the full range of socio-economic, political and risk management issues potentially raised by the transition to low-carbon stabilization. Nevertheless, we concentrate here on the technical feasibility and economic viability and will not discuss the socio-economic or political feasibility of low stabilization scenarios. These issues are beyond the scope of this model comparison but are addressed in detail in Knopf et al. (2010, this Issue).

The paper is organized as follows: Section 2 presents the models used; Section 3 describes the baseline and the policy scenarios; Section 4 then applies the models and compares the economic and technical results for harmonized baselines with the mitigation scenarios. It discusses alternative ways to achieve low stabilization and explains how individual technology options can be valued. Section 5 offers conclusions.

2. MODELS

For this model comparison, we use the models MERGE-ETL (hereinafter MERGE, Kypreos and Bahn, 2003; Kypreos, 2005), REMIND-R (hereinafter REMIND, Leimbach et al., 2009), POLES (European Commission, 1996), IMAGE/TIMER (hereinafter TIMER, Bouwman et al., 2006, van Vuuren et al., 2006a) and E3MG (Barker et al., 2006; Barker et al., 2008). MERGE and REMIND are hybrid models with a top-down macro-economic model and a bottom-up energy system model. Both are optimal growth models where a social planner maximizes global welfare over a given period. POLES and TIMER are bottom-up energy system models with a high resolution of different technologies. The macroeconomic dynamics are exogenous to these models. The E3MG model is an econometric simulation hybrid model. Table 1 gives a classification of the models. As none of the models takes damages from climate change into account, the models are not run in a cost-benefit but rather cost-effective mode. The remainder of this section introduces the models and reflects on their advantages and limitations.

MERGE represents a modified version of MERGE5 described by Kypreos and Bahn (2003) and Manne and Richels (2004a; 2004b). Key features include a nine-region global disaggregation, a combined 'top-down' Ramsey-type economic and 'bottom-up' engineering modeling approach, a simple climate

Table 1. Classification of the Models Participating in the ADAM Model Comparison

Model	Model classification	Modeling approach	Objective Function
MERGE REMIND	Intertemporal general equilibrium model	Optimization with perfect foresight over whole period	Welfare maximization
POLES TIMER	Energy system model	Recursive dynamic	Cost minimization
E3MG	Econometric simulation model	Initial value problem; limited foresight	No objective function (demand driven)

model, and international trade. Regional technological learning with global spillovers and costly climate-change impacts enhance the regional links and interactions (Magné et al., 2010, this Issue). Technologies for electricity generation (including options for CCS), and secondary fuel production (synthetic fuels from coal and biomass, H_2 from a range of sources, including options for CCS) are explicitly included in MERGE. Technological learning is represented by two-factor learning curves for technology investment costs. A limitation in MERGE is that the model relies on perfect competition and information, production/utility function continuity, representative agents, etc. The low level of technology detail also permits only a generic representation of end-use energy efficiency as explicit end-use technologies are not represented.

The global multi-region model ***REMIND*** represents an intertemporal optimizing energy-economy-environment model which maximizes global welfare subject to equilibrium conditions on different markets. REMIND is a hybrid model which couples an economic growth model with a detailed energy system model and a simple climate model via a hard-link. The main advantage of REMIND is a high technological resolution of the energy system with more than 50 conversion technologies and intertemporal trade relations between the 11 world regions. Trade is modeled for coal, gas, oil, uranium, and the residual composite good as well as for emission permits. Macroeconomic output is determined by a nested CES production function of labor, capital and several end-use types of energy. The switch between energy technologies is a crucial element of endogenous technological change in REMIND. This is supplemented by learning-curve effects that impact the investment costs of wind and solar technologies. While providing a first-best solution based on the perfect foresight assumption, a drawback in REMIND is that it ignores market imperfections and treats technological change as exogenous in the macroeconomic sector.

The ***POLES*** model is a global sectoral model of the world energy system. It has been developed in the framework of a hierarchical structure of interconnected sub-models at the international, regional and national levels. This partial-equilibrium model is solved year-by-year through recursive simulation. It makes provision for international energy prices that are endogenous and for lagged adjustments of supply and demand by world region. The model provides

Table 2. Overview Over Specific Model Assumptions Within the Energy System

	MERGE	REMIND	POLES	TIMER	E3MG
CCS technologies	Many possibilities for CCS with coal, gas, biomass Total storage capacity: 400 GtC	Many possibilities for CCS with coal, gas, biomass Unlimited storage capacity	Many possibilities for CCS with coal, gas, biomass Unlimited storage capacity	Many possibilities for CCS with coal, gas, biomass (CCS+biomass only allowed in 400ppm scenario); Total storage capacity: 1500 GtC.	Generic CCS for coal and gas; no CCS+biomass Unlimited storage capacity
Coal	Electricity, Heat, CtL, CtG, solids	Electricity, Heat, CtL, CtG, solids	Electricity, CtL, solids, heat	Electricity, Heat, solids	Electricity (technology explicitly modeled); Heat (partially modeled), CtL and CtG (at demand side)
Renewables	Learning-by-doing and learning by searching: Solar: 10% Wind: 5%	Learning rates: PV: 20% Wind: 10%	Learning-by-doing and learning by searching, learning rate evolves with the distance to floor costs. PV: 20% in 2010, 4% in 2050; large scale solar : 30% in 2010, 3% in 2050; wind: 14% in 2010, 5% in 2050	Learning rates: PV: 35% in 2000, 9% in 2100 Wind: 28% in 2000, 8% in 2100	Learning rates Solar and wind: 30%
Biomass use	Various options for biomass use (BtL, BtG, CHP, Biodiesel, …). Mostly used for electricity production;	Various options for biomass use (BtL, BtG, CHP, Biodiesel, …) and options to combine biomass+CCS; In the baseline: mostly used for fuel production mitigation scenario: mostly used for H2 production; no possibility for electricity production from biomass	Biomass is mostly used for CHP and direct use. 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).	Various options for biomass use (BtL, BtG, Biodiesel, …). Biomass mostly used for BtL and electricity generation. Energy crops: maize, sugarcane and woody. Woody either solid fuel or 2nd generation liquid fuel.	explicitly modeled as an electricity generation technology (crops and waste, CHP); combustable waste as energy carrier for heat generation in the residential sector; Biofuels not modeled.

Table 2. Overview Over Specific Model Assumptions Within the Energy System (continued)

Hydrogen	H_2 from: nuclear, solar thermal H_2+CCS possible with coal, gas, biomass	H_2+CCS from: coal, gas, biomass	H_2 from: solar thermal, nuclear H_2+CCS possible with coal, gas, biomass	H_2 from: solar thermal H_2+CCS possible with coal, oil, gas, biomass	H_2 from coal and gas No possibility for H_2+CCS
others			Great detail in modeling the demand side (e.g. vehicles, buildings, rail). Econometric functions for consumption patterns.	Hydrogen cars	Great detail in modeling the demand side (e.g. plug-in vehicles); Revenue recycling from permit auctioning

PV refers to photo voltaic, CtL: coal to liquid, CtG: coal to gas, BtL: biomass to liquid, BtG: biomass to gas, CHP: combined heat and power, H2: Hydrogen.

comprehensive energy balances for 47 countries and regions, among them the members of the OECD and key developing countries. 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 latter feature is an important advantage of the POLES model. A limitation of the model is that it uses only currently used or fully documented prospective technologies. However, by 2100, future advances in fundamental science may trigger the development of completely new technological concepts.

Within the Integrated Model to Assess the Global Environment (IMAGE), the global energy system model ***TIMER*** describes the investment in, and the use of, different types of energy options within a simulation framework. The value of these options is affected by technology development (learning-by-doing) and resource depletion. The TIMER model describes long-term trends in the world energy system. It encompasses long-term energy demand, resource depletion and technology development affecting various energy sources, cost-based substitution in production, and the development of climate policy. The substitution across different energy carriers is described on the basis of multinomial logit equations. IMAGE computes land-use changes and emissions from land use, natural ecosystems and agricultural production systems. The model also takes account of the exchange of carbon dioxide between terrestrial ecosystems and the atmosphere. The IMAGE model is particularly strong in the detailed description of energy technologies and of geographically explicit land use. The integration of land and energy use in one model is itself noteworthy. A drawback of the model is that economic development is treated as an exogenous driver. Hence changes in the energy sector and in land use are decoupled from changes in GDP.

E3MG is a macro-econometric non-equilibrium hybrid simulation model of the global E3 system, estimated on annual data 1971-2002. It is used for annual projections to 2030 and in 10-year intervals thereafter to 2100. E3MG is based upon a New Economics view of long-term dynamics (Barker, 2008), drawing as well on Post Keynesian features taking a historical approach of cumulative causation and demand-led growth, and incorporating technological progress in gross investment enhanced by research and development (R&D) expenditures. It is a non-equilibrium model implying that labor, foreign exchange and financial markets do not necessarily clear but have deficits or surpluses in open economies depending on the year and region. A bottom-up energy-technology simulation has been incorporated allowing for the explicit modeling of 28 energy technologies. This allows for the modelling of a two-way feedback between the economy, energy demand/supply and anthropogenic emissions. One of the model's limitations is that parameters estimated from a recent time series of 32-years may not be time-invariant over coming decades.

Low stabilization crucially depends on assumptions about available technologies. This is evident from Azar et al. (2006), Rao et al. (2008) and van Vuuren et al. (2007). Table 2 provides an overview of specific model features concerning assumptions on low carbon technologies. In all of the models no leakage for CCS storages is assumed, but most assume a limited capture rate. Some models apply a limit on the CCS storage capacity. The IPCC (Metz et al., 2005) estimates a technical potential of at least 545 GtC of storage capacity in geological formations up to a much higher potential when including saline formations. All models assume a biomass potential of 200 EJ/yr as a reference, compared to typical estimates in the order of 0-150 EJ/yr for residues and about 100-200 EJ/yr for bio-energy crops (cf. van Vuuren et al., 2010, this Issue). TIMER assumes a slightly higher biomass use compared to the other models, in the 400ppm scenario, e.g., 290 EJ/yr used at its maximum, but at the same time TIMER assumes a larger amount of traditional biomass compared to all other models. The models do not account for co-emissions from biomass use such as those resulting from fertilizer application.

All models apply assumptions about learning-by-doing, especially for renewable energy sources (cf. Table 2). Nordhaus (2009) points out that learning coefficients tend to be overestimated and that in optimization models a bias towards technologies with high learning rates is manifested. This effect is not accounted for in the models. Moreover, R&D investments in the energy system, as applied in the models, may crowd out investments in other sectors of the economy (Popp and Newell, 2008). This effect is also not considered here and it is assumed that measures for energy R&D do not shift R&D investment from other sectors, but rather increase the total R&D expenditure.

3. SCENARIOS AND METHODS

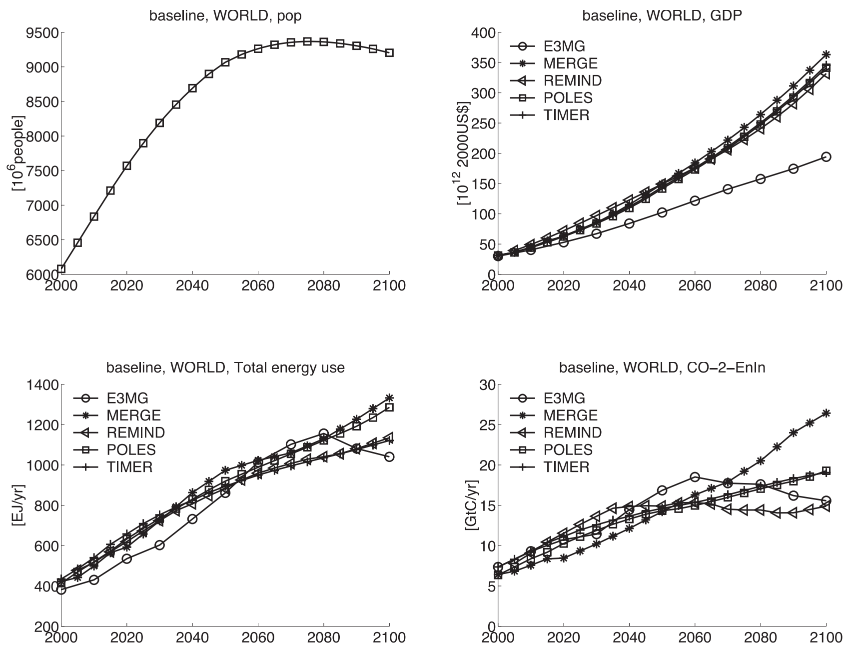
3.1 Baseline Scenario

As far as possible, the building blocks for the baseline without climate policy were harmonized for comparability across the different models particularly with regard to population projections and economic growth. For this, we use the ADAM reference scenario as our baseline. The underlying assumptions are detailed in van Vuuren et al. (2009a).[2] The effect of climate policy will be evaluated against this baseline scenario, where we assume that climate policy has no decisive influence on the economy and the social sphere.

Due to the very different modeling assumptions, full harmonization of all variables between all models is not possible. As Figure 1 shows, all models use the same exogenous projections for global and regional population (based on data from the United Nations, 2003, see Figure 1). The economic profile is a medium growth scenario, but with high growth rates for India and China (see van Vuuren et al., 2009a). Models with exogenous GDP profile (POLES and TIMER) directly

2. The base year for our analysis is 2000. As the project started in 2006, no full data set was available for 2005 (and in fact, most models are only recalibrated every few years). We are aware of the fact that today (i.e. 2009), some recent trends, e.g. the development of the oil price and the financial and economic crisis, are at odds with our short-term projections. We firmly believe, however, that taking these factors into account do not alter the overall conclusions drawn from our analysis.

Figure 1. Baseline Results for the WORLD Region



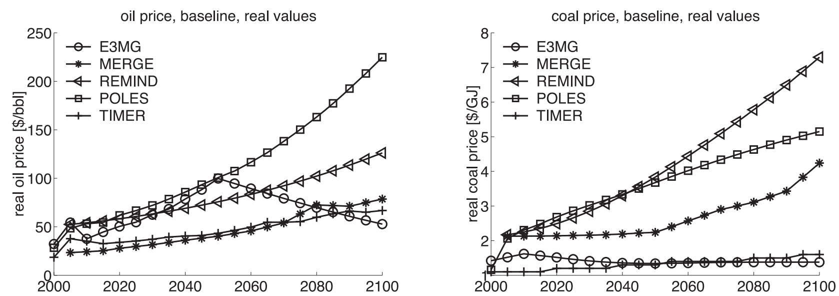
Projected values aggregated at the global level are reported for population, GDP, total primary energy use, and CO_2 emissions from energy and industry (CO-2-EnIn). E3MG reports the same GDP growth rates but lower GDP values as it does not assume long-term convergence in GDP between the regions, with GDP values being reported in constant market prices and not in purchasing power parity (PPP) terms.

use this projection as an input on the global as well as on the regional level.[3] All other models except E3MG stay close to it in Figure 1.

Though they share regional and global GDP baseline functions and use the same starting values in the year 2000 for energy consumption and CO_2 emissions, the models differ in their projections of such emissions. This can be explained by large differences in fossil-based energy prices between the models (see Figure 2) affecting the energy mix and the CO_2 emissions in the baseline. In MERGE for instance, CO_2 emissions increase much more than in other models. This is due to low fossil fuel prices encouraging continued use of coal, gas and oil. Conversely, the low CO_2 emission pathway for REMIND arises from assuming a high cost path for fossil fuels. Hence a switch away from coal to renewables is already captured to some degree in the baseline. E3MG projects some penetration

3. Due to the different regionalization in the models POLES and TIMER, the global value for GDP differs slightly.

Figure 2. Oil and Coal Prices in the Baseline Scenario (In Real Values)



In MERGE, REMIND and POLES the costs are endogenous to the model; for MERGE and REMIND shadow prices are given. They reflect resource extraction costs and are not comparable with today's spot market price. In POLES, the price depends on market fundamentals, namely the differential dynamics of supply and demand and the relative amounts of spare capacities. In E3MG, not the price but historical trends determine the model's emissions. In E3MG, the real oil price is an input into the model that follows the POLES price path up to 2050 after which a decline is assumed equal to 2% a year. For E3MG, the average of hard coal and other coal (for USA) is shown as the coal price.

of renewables in the baseline in the long-run, hence the slight decrease in annual CO_2 emissions from 2060 onwards.

All scenarios are analyzed for the period 2000-2100. The models provide regional and country classifications. This exercise distinguishes seven regions which together cover the global aggregate, WORLD: China (CHN), Russia (RUS), Europe (EU27), India (IND), Japan (JPN), the United States (USA), and Rest of World (ROW). E3MG reports on a EU25 region which is EU27 excluding Romania and Bulgaria. MERGE reports on EU15 and lumps Eastern Europe together with Russia (EERU) in its regional classification.

3.2 Mitigation Scenario: Long-term Mitigation Targets

In this synthesis, we report on a range of mitigation targets that have different probabilities of achieving the 2°C target. We investigate a 550ppm, 450ppm and 400ppm CO_2 equivalent concentration pathway (see Figure 3), referred to as "550ppm", "450ppm" and "400ppm" in the following. This corresponds to a range that goes from "unlikely" across "medium-likelihood" to "likely", as defined by the IPCC in Solomon et al. (2007), with respect to limiting global mean warming to less than 2°C. The 550ppm scenario (den Elzen and van Vuuren, 2007) shows concentrations that are increasing past 2100. The 450ppm scenario (den Elzen and van Vuuren, 2007), also labeled IMAGE-2.9 scenario, reaches its maximum by 2045 and declines slowly thereafter. The 400ppm scenario (IMAGE 2.6, van Vuuren et al., 2007) also reaches its maximum by 2045 but then declines more rapidly. The latter two achieve the stabilization level by 2150.

Table 3. Constraints Concerning the Stabilization Target and the Treatment of Other GHGs and Land-use Emissions

Model	Constraint	Other GHG	Land-use emissions
E3MG	Cumulative CO_2 emissions in 2100	Exogenous (IMAGE/TIMER)	Exogenous (IMAGE/TIMER)
MERGE	Radiative forcing in 2100 (own climate module)	Abatement via MACs	Exogenous (IMAGE/TIMER)
REMIND	En&In CO_2 emissions	Exogenous (IMAGE/TIMER)	Exogenous (IMAGE/TIMER)
POLES	En&In CO_2 emissions	Abatement via MACs	Exogenous (IMAGE/TIMER)
TIMER	Total greenhouse gas emissions in CO_2 eq., including all the Kyoto gases and also land use emissions	Abatement via MACs	Endogenous

En&In emissions refer to the energy and industry related CO_2 emissions. Marginal abatement cost curves (MACs) are applied by using the EMF-21 data (Weyant et al., 2006).

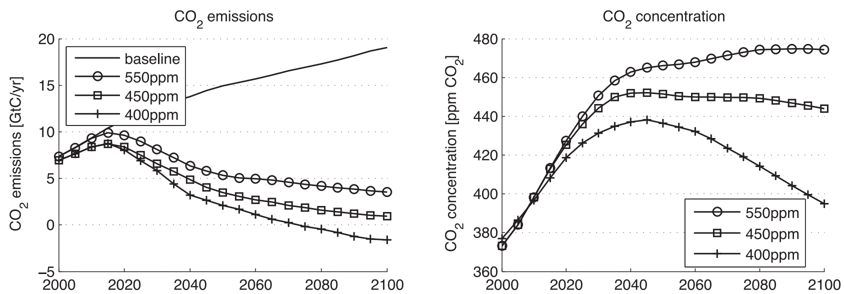
The data for these three scenarios for the CO_2 emissions from the energy and industry sector, the land-use emissions, and the emissions from other greenhouse gases (GHGs) are provided by the IMAGE/TIMER model (van Vuuren et al. 2007). The models apply different constraints to reach the targets (see Table 3). The target is binding from 2010 onward. In cases where the exogenous IMAGE/TIMER path is applied – e.g. as for land-use emissions in REMIND – the CO_2 eq emission pathway is consistent with the data given by IMAGE/TIMER.

4. LOW STABILIZATION: MODELING RESULTS

4.1 Storylines of the Future Energy Mix

This section contrasts the mechanisms and interactions involved in the baseline with those relied upon for meeting the stabilization targets of 550 and 400 ppm CO_2 eq. Although some consistency is achieved through shared data on population, GDP, total energy use and CO_2 emissions (see Figure 1), the models reveal very different strategies for meeting future energy demands and favor different energy carriers and technologies (see Figure 4). Different assumptions driving the models, for instance concerning the prices of fossil fuels or about learning rates and the emergence of breakthrough technologies, span a range of possible pathways to the future. This is a major advantage of this model comparison as it allows the underlying assumptions that lead to different trajectories of the future energy mix to be identified in the baseline as well as in the mitigation scenarios. The baseline itself is therefore important to analyze and understand before one can fully appreciate the added costs and technological challenges of climate change mitigation.

Figure 3. IMAGE/TIMER Emission Pathways for CO_2 Emissions From Energy and Industry (left) and CO_2–only Concentration Pathways (right)



4.1.1 The Baselines for Each Model

In a scenario without climate policy, fossil fuels continue to dominate the energy system throughout the century in all models (see Figure 4, left column). MERGE and TIMER rely mostly on coal; renewables are not important. Also in the POLES model, only a little decarbonization occurs. The energy mix in the REMIND baseline however, is characterized by strong decarbonization through the use of biomass and the introduction of renewable energy sources.[4] In E3MG, renewables increase significantly in the baseline.

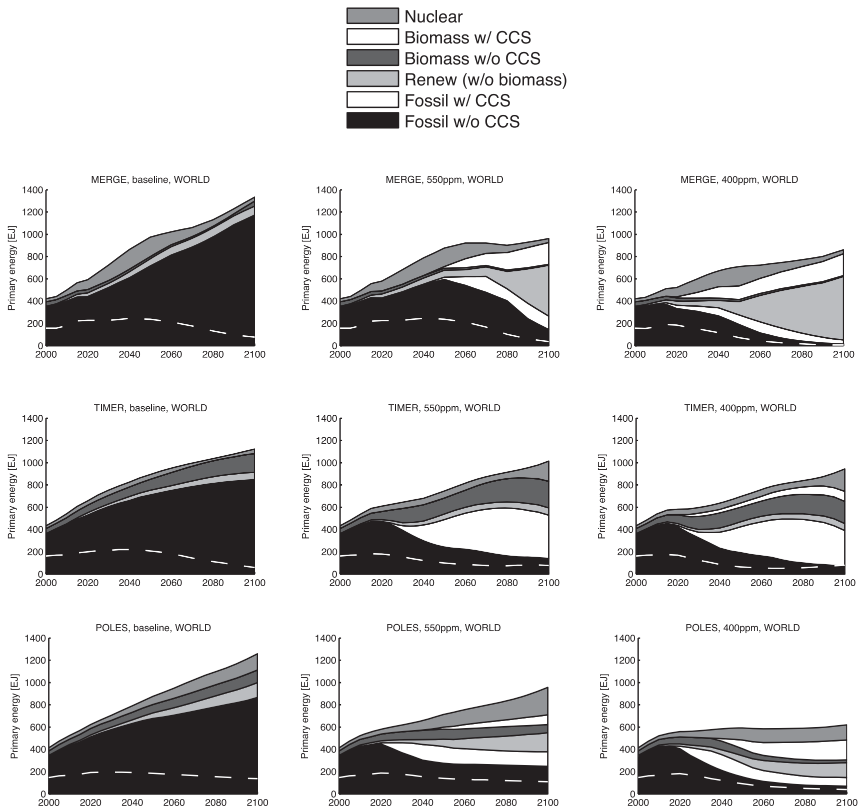
The models tell the following stories in their baselines:

In the ***MERGE*** baseline, the price of coal is low relative to natural gas and oil which are largely exhausted in the course of this century. This leads to high levels of coal use and hence more exploitation of electricity generation from coal and of coal-to-liquids fuel production. Both technologies benefit from technological learning. Nuclear power is an important technology in the baseline scenario, particularly towards the middle of the century. This is again driven by the relatively low costs of generation. However, in a baseline in which only light water reactors and limited uranium resources are assumed to be available, scarcity of these resources becomes a key constraint on any longer-term role for nuclear energy. Wind power technology shows moderate improvements in cost arising from learning. Most other renewable energy sources remain uncompetitive in the baseline scenario.

In the ***TIMER*** baseline, fossil fuels remain the dominant energy carriers throughout the century, with the share of oil decreasing due to rising oil prices. The choice of energy carriers in TIMER is determined by cost and by their suitability for use in the various sectors. Costs increase as resources are used

4. Here and in what follows, renewables include solar, wind, and hydro-electric power. Biomass is reported separately.

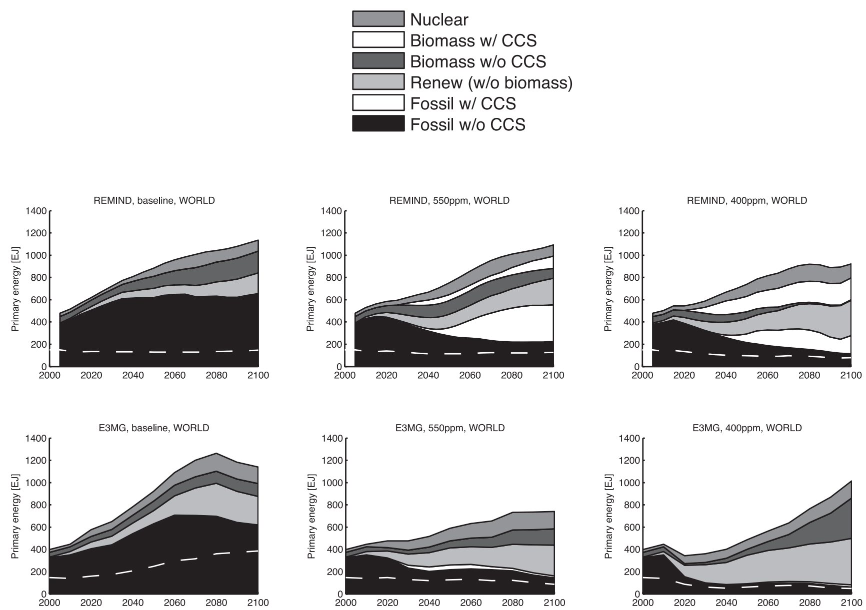
Figure 4. Primary Energy Mix for the Baseline, the 550ppm and the 400ppm Scenario (from left to right) for the Models MERGE, TIMER and POLES (Part 1)



up, but decrease due to learning-by-doing. The demand for "modern" biofuels for both electricity and liquid-fuel production increases gradually as the costs of oil and natural gas rise. In addition, technological improvements in production also make these biofuels more competitive. Wind energy use increases steadily, although it remains a minor part of global energy use, while solar energy remains too expensive for large-scale use.

In ***POLES***, capital and operating costs and relative prices jointly determine technological choices and the energy mix. POLES contains endogenous learning curves with a threshold that depends on technology floor costs (minimum engineering cost). The energy mix changes only slightly over time in the baseline scenario due to inertia in capital-intensive energy production and distribution systems. Renewables develop in the POLES model even in the baseline scenario because of their cost efficiency in the long term. Wind energy is capped by its technical potential in relation to land availability (basically natural

Figure 4. Primary Energy Mix for the Baseline, the 550ppm and the 400ppm Scenario (from left to right) for the Models REMIND and E3MG (Part 2)



The use of oil is indicated below the dotted line. Note that biomass is listed separately and not as part of renewables which only include energy from solar, wind, and hydro-electric power. For determining the share of renewables in the supply of energy, we apply the direct use concept. In E3MG, biomass includes combustible waste (about 80% of the total biomass use) such as primary solid biomass used for heating in the residential sector in developing countries.

plains areas differentiated by wind speed classes with an excluding factor linked to the population density). For decentralized production, solar PV is constrained by the available surface space of buildings. The theoretical potential of solar thermodynamic power plants is linked to the size of sunny desert regions, but this vast potential is not usable for export because of the unavailability of transcontinental electricity grids and H_2 transmission lines.

REMIND takes renewables, in particular biomass, into the baseline. The biomass and renewables option becomes competitive because of increasing fossil fuel prices arising from scarcity in the second half of the century (see Figure 2). Biomass is a general-purpose energy carrier; it can be converted into all secondary energy carriers. Biomass-to-liquid is available at comparable prices to those of coal-to-liquid but using biomass helps to conserve coal for conversion into other secondary energy carriers, such as electricity, and for later use. REMIND considers changes in the relative prices of energy carriers, driven by uneven rates of technological advance in the different sectors, as the main factor that can change the energy mix. For instance, conversion coefficients of technologies using fossil fuels tend to improve gradually over time while marginal costs of investing in wind and solar PV may be lowered dramatically through innovations resulting from learning-by-doing.

In ***E3MG***, the baseline incorporates some decarbonization of the global economy as the historical trend of falling carbon intensity is projected into the future. This trend combined with endogenous technological change leads to a significant replacement of fossil fuels, particularly coal, with low-carbon energy sources after 2050 following investment cycles particularly in renewables. Combined with some energy efficiency improvements, this results in a slight reduction in annual CO_2 emissions from 2060 onwards, although it is far from achieving any significant reductions.

The comparison of the baselines shows that despite a number of similar assumptions, e.g., about population and GDP development, each model is different in its vision of the future. This indeed is a major advantage of a model comparison exercise as these models are then able to cover a wide range of possible futures.

4.1.2 Storylines of a Decarbonized World

The first major result of the analysis of the mitigation pathways is that each of the models can achieve the three stabilization targets, even in the case of the 400ppm CO_2 eq stringent mitigation scenario. This is a very important result because, as noted in the Introduction (Section 1), not many modeling results have been reported for such low emissions-stabilization targets. However, some of the models in our analysis had to be equipped with a wider portfolio of low-carbon technologies, such as CCS and biomass in combination with CCS, to enhance their mitigation capabilities and to be able to reach this low emission level. The next section will focus on the mechanisms and interactions involved in achieving these targets.

In the mitigation scenarios (Figure 4, middle and right columns), the energy mix and the underlying strategies for a specific model is closer across its own 550ppm and the 400ppm targets than in comparison with other models for any given target. It shows that each model in fact emphasizes a particular strategy (vis-à-vis the other models): MERGE and E3MG rely primarily on renewable energy sources, TIMER on CCS, POLES on energy efficiency, and REMIND relies on CCS mainly in combination with biomass. This demonstrates that the energy mix is a function principally of each model's assumptions about the available technologies, learning rates, and resource prices.

A partial exception to this insensitivity of the energy mix at least in the timing of the strategies to the level of stabilization is ***MERGE***. In this model, the flexibility provided by having its own climate module and not being restricted to the prescribed CO_2 path (cf. Table 3) allows the transformation of the energy system to be postponed in the case of the less ambitious target. The main mitigation options that eventually start to be exercised are renewables and biomass. Hydrogen production from solar thermal, and for non-electric consumption, is an option in MERGE that becomes extremely important with stricter targets. Improvements in energy efficiency also play an important part.

In ***TIMER, POLES*** and ***REMIND***, the use of fossil energy without CCS is very similar as here the emission path is constrained by the exogenous time series for CO_2 emissions (cf. Table 3). The carbon-free contributions to the energy mix, however, vary between the models:

(1) In POLES, reduction of energy use is an important strategy as POLES has demand-side energy efficiency improvements in a bottom-up representation. In general, higher energy prices can spur technological improvements that lead to energy savings in production, and they can also produce changes in behavior, as in residential uses and private transportation, which lead to energy savings in consumption. Inertias in the energy system lead to smooth transitions;

(2) In TIMER, CCS with coal is the main option (CCS with biomass is only allowed in the most stringent stabilization scenario). With more CCS than in any of the other models, TIMER uses a CCS storage potential of 520 GtC, compared e. g. to 280 GtC in MERGE. In TIMER, despite high learning rates in the beginning of the century (see Table 2), renewables are quite expensive and do not play a larger role in the mitigation scenarios compared to its level in the baseline;

(3) REMIND shows a steady increase of primary energy consumption because decarbonization is available at moderate cost with CCS and renewables. Due to this low cost, energy efficiency improvements, here in a top-down representation, play only a minor role. Here the option of combining biomass use with CCS to remove CO_2 from the atmosphere becomes an important option. Biomass in REMIND is associated with a high flexibility in its use (see Table 2). In the policy scenarios, the primary energy consumption from biomass-CCS is connected mainly with H_2 production for transport (as this allows the combination with CCS) and not biomass-to-liquid, as in the baseline scenario.

In ***E3MG***, renewables increase in importance from the 550ppm to 400ppm scenario. In the former scenario the main option is increasing energy efficiency, which is an important demand-side option in E3MG. There are incentives for improving the energy efficiency of private residences and household appliances. Furthermore, regulatory policies pressing for decarbonization of the transport sector through electrification of the vehicle fleet play a major role. In the 400ppm scenario, the renewables and biomass options become more and more important. Because of learning curves, economies of scale, and Keynesian multiplier effects throughout the global economy (via trade and low-carbon technology spill-over effects) creating additional employment of resources that would otherwise have been unemployed in the baseline, the costs associated with increased reliance on renewables are much reduced. This induces large-scale adoption of low-carbon technologies.

Three further findings are especially noteworthy:

(1) In some models nuclear energy appears to be important as an *interim* energy source around the middle of this century. The fraction of nuclear power increases in most models until 2050 and then declines, at least in some models, due partly to the depletion of uranium.[5]

(2) In POLES and REMIND, and to a lesser extent also in TIMER and MERGE, the total amount of CCS shows little variation with the emission stabilization target. For the stricter target, CCS is combined with biomass rather than coal. This is because one way to remove carbon from the atmosphere and to obtain "negative emissions" is to combine biomass with CCS. In the case of the 550ppm scenario, negative emissions are not needed, and the use of coal and gas in combination with CCS suffices to reach the stabilization target.

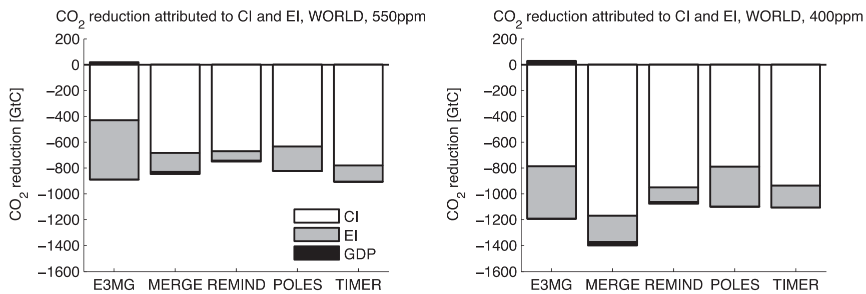
(3) Compared to its use in the baseline, the use of oil decreases minimally in some models, moderately in others (TIMER) and very extensively in E3MG. The position of oil in the transport sector is relatively strong. In the models in which oil continues to be used extensively, it is in fact still used for transport at the end of the century and is the major source for the remaining CO_2 emissions.

One way to analyse the changes in emissions is to decompose the different trends using Kaya's identity (Kaya, 1990). Any CO_2 changes from baseline that are required to achieve the mitigation target can take the form of reductions in (1) carbon intensity, CI, defined as CO_2 emissions per primary energy, (2) energy intensity, EI, defined as primary energy per GDP, or (3) growth of GDP. A decomposition analysis facilitates quantifying the contributions of these different factors (see Figure 5). In nearly all cases reducing CI is the most important strategy, particularly in the strict stabilization targets.

Except for E3MG, the reduction of EI plays only a minor role as a mitigation option. One issue to note here is that all models pay considerably less attention to end-use energy efficiency technologies than to supply side technologies (which could create a bias towards favouring CI improvement). Moreover, energy intensity reduces in the baseline from 0.8% to 1.2% per annum across the models, which is in line with the historical record (e.g. Nakicenovic et al., 2000, Fig. 3-13; Fischer et al., 2007, Fig. 3.6). It should be noted that POLES has – among the models – the most explicit bottom-up representation of demand

5 In the standard policy case, fast breeders are not considered as an option in the models. The models do not assume a fixed resource limit on uranium but resource extraction costs increase in some models with cumulative amount of extracted resource.

Figure 5. CO_2 Reductions Attributed to Reduction of Carbon Intensity (CI), Energy Intensity (EI) or GDP for 550ppm (left) and 400ppm (right)



Reductions are always given relative to baseline. Positive values represent increases from the baseline (i.e. GDP effects in E3MG).

side improvements such as a switch to electric or hybrid cars or to low energy buildings.

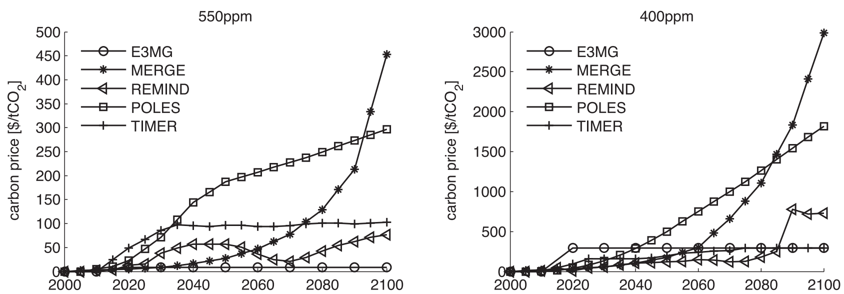
4.2 Mitigation Costs

In general, four different types of mitigation costs can be distinguished (IPCC, 1995): direct engineering costs, economic costs for a specific sector, macroeconomic costs and welfare costs. These different cost concepts are laid out in Edenhofer et al. (2006). The costs reported for our models fall into different categories. For the energy system models, POLES and TIMER, the costs for the transition of the energy system (abatement costs) are provided, as GDP is prescribed exogenously. For the three other models, macroeconomic costs, welfare costs and abatement costs can be provided in principle. To allow for a comparison between the different cost concepts of the models, we report here mitigation cost[6] as net present value sums to 2100 of reduction of global GDP (of abatement costs for POLES and TIMER) relative to the like sum of baseline GDP values. We apply a discount rate of 3%. It should be noted that these costs concepts are not the same – and therefore one should be careful when comparing them. However, earlier comparisons showed that in relative terms the two seem to correlate reasonably well across different scenarios and for different regions (Hof et al., 2009).

In all models, the carbon price drives investments in carbon-free technologies (in E3MG the recycling of revenues of auctioning also plays a role,

6. In the following, we use "mitigation costs" for both losses (+) and gains (-) in the discounted GDP due to mitigation.

Figure 6. Carbon Price for the 550ppm and 400ppm Scenario



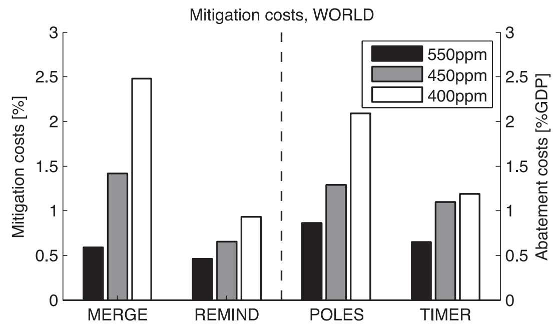
see section 4.2.2). The price for CO_2 rises over time in most models, and, at any time, the price in the 400ppm scenario is more than five times as high as in the 550ppm scenario (Figure 6). But although the high price by the end of this century affects only a small amount of CO_2 emissions (see Figure 3, left), it still prevents fossil fuels from re-entering the energy system.

4.2.3 Mitigation Costs

The mitigation costs for the three reference mitigation scenarios for four of the models are given in Figure 7. Figure 8 shows the corresponding time paths of *annual* mitigation costs expressed in percent of GDP. The costs calculated by the E3MG model are discussed separately in Section 4.2.2. In this model the baseline is not assumed to be fully efficient. This leads – in contrast to the other models – to the possibility of net gains from mitigation and needs a different appraisal of the costs. Concerning Figure 7 and Figure 8, it is important to note that the scenarios are not performed in a cost-benefit mode but – depending on the model – in a least cost approach or cost-effective mode. We only take into account the costs for mitigation and not for adaptation or avoided impacts. The focus of this analysis is on the appraisal of different mitigation options to reach a certain stabilization target. The models do not include costs of adaptation or saved costs due to the avoidance of damaging effects. Note also that a full appraisal of the options would include considerations of safety and risk issues (nuclear, CCS), energy security and public acceptability (nuclear, CCS).

All models in Figure 7 show that costs increase with the stringency of the stabilization target. The costs for all stabilization targets are moderate, with aggregate losses for this century below 2.5% of GDP for the most stringent scenario in the case of MERGE and REMIND. The abatement costs in POLES and TIMER are of a similar order of magnitude. Interestingly, the annual costs displayed in Figure 8 are moderate until about 2040 but increase in all four models during the transition phase of the energy system and nearly stabilize or even decline thereafter. Overall, the cost estimates are comparable to those appearing in the IPCC AR4 (Fisher et al., 2007, Fig. 3.25, p. 205). In IMCP

Figure 7. Mitigation Costs for the 550ppm, 450ppm and 400ppm Scenario



For MERGE and REMIND the mitigation costs are given as cumulative GDP losses up to 2100 relative to baseline in percent of baseline GDP.[a] POLES and TIMER report the increase of abatement costs relative to baseline in %GDP. The discount rate is 3%. NPV values are calculated on the basis of the year 2000. With a base year of 2005, costs would increase by about 5%.

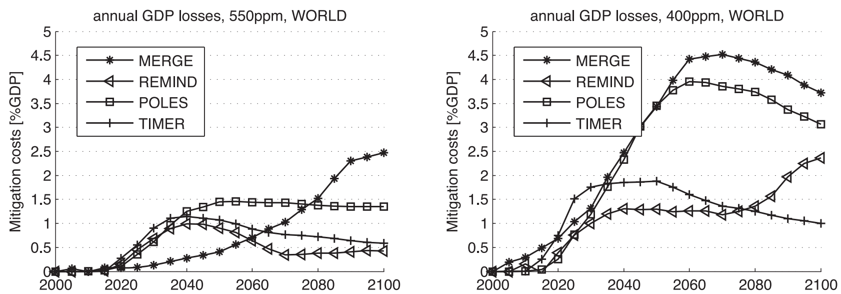
(Edenhofer et al., 2006) the costs were reported to be less than 1% of GDP for a target of 450ppm CO_2-only that lies between our 550ppm and 450ppm CO_2 eq target. Compared to these targets, this benchmark of 1% is also not exceeded here. The lower target of 400ppm shows higher costs but leads to a greater chance of achieving the 2˚C target. The costs increase approximately linearly with the probability of achieving the 2˚C target (not shown here but assessed similarly as in Schaeffer et al., 2008).

In the IMCP (Edenhofer et al., 2006), induced technological change (ITC), which can be stimulated by policy measures, greatly affected costs. All models analyzed here include endogenous technological change.[7] Without allowing for ITC, costs would be higher, as additional investigations show.

MERGE reports the highest costs for the 400ppm scenario but the lowest, at least until the middle of this century, for the 550ppm scenario. One reason is that due to an increasing use of coal, MERGE has much higher CO_2 emissions at the end of the century in the baseline (see Figure 1) so that emission cuts are comparatively large. Compared to the other models, REMIND yields the lowest average annual mitigation costs overall in part because the price path for fossil energy is assumed to be high (see Figure 2) and renewable energy sources are already incorporated in the baseline. In addition, REMIND provides a high degree of flexibility in the choice of low-carbon technologies.

7. The models have different representations of endogenous technological change. For instance, while all models include technology diffusion due to learning about different technologies and from applying them, some models include R&D spending as well. Details of endogenous technological change in the models are given in ADAM Deliverable D-M2.4.

Figure 8. Annual GDP Losses. POLES and TIMER Report Abatement Costs

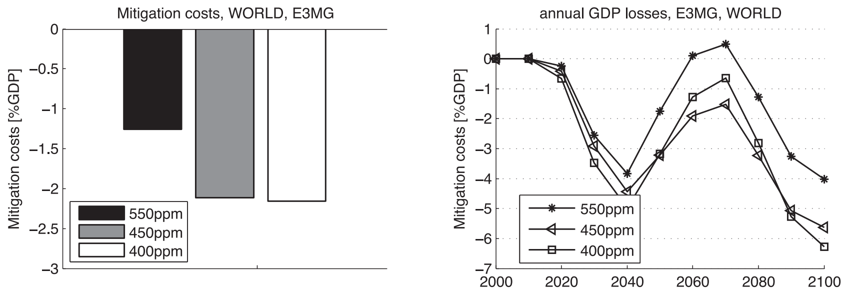


The fact that POLES includes only the costs for the transformation of the energy system but no macroeconomic costs might suggest that costs in POLES would be lower than in REMIND and MERGE. However, POLES reports relatively high costs of abatement. Here the recursive simulation process and the detailed sectoral description accounts for the short-term inertia in the substitution of capital to energy in the various sectors. In the longer term, POLES provides more flexibility due to demand side options. The increase in carbon price induces greater energy efficiency, mostly through demand-side technological innovation, but also through modifications in consumer behavior. In POLES, stepped-up energy efficiency improvements are essential to reach the set CO_2 mitigation objectives because decarbonizing the supply side alone will not be sufficient. Limiting factors are the amount of land available for alternative energy generation, e.g. wind power or biomass production as uranium is in short supply, and the mismatch between the most suitable production and consumption locations for alternative energy. All stand in the way of the supply side carrying the full load.

4.2.4 Mitigation Costs in E3MG

Unlike the other models, E3MG reports overall gains from low-level emissions stabilization (see Figure 9). In addition to the application of global carbon prices, a major driver of the mitigation strategy in E3MG is the recycling of revenues raised from the full auctioning of carbon permits to the energy sector and applying carbon taxes for non-energy activities. Key assumptions are that 40% of the revenues collected are recycled and used for R&D investments in renewables as well as for investments in energy savings and conversion of energy-intensive sectors towards low-carbon production methods. Revenue is also recycled via lowering indirect taxes to achieve fiscal neutrality. Moreover, the early introduction of electric plug-in vehicles has a major impact on the emission path. In contrast to the other models, E3MG is a simulation model without perfect

Figure 9. Mitigation Costs (left) and Annual GDP Losses (right) for E3MG



Negative numbers translate into benefits from mitigation.

foresight and optimization, where resources are not fully employed or optimally utilized in the baseline. The increase in investment induced by climate policy can therefore achieve net GDP gains. In other words, these gains are attributed to climate policy that induces and accelerates technological change towards low-carbon sources. It should be noted, though, that these gains can in principle be achieved by policies other than climate policy.

The mitigation benefits and costs reported by E3MG vary greatly over future decades (see Figure 9) because investment cycles in new low-carbon technologies reflect the dynamics and non-linearities inherent in complex E3 systems. The wave of early investments in plug-in vehicles, greater energy efficiency in buildings and low-GHG energy supplies lead to an acceleration of GDP growth to 2040, producing negative costs. GDP then falls below baseline for two decades, yielding positive costs as the first-generation investments reach maturity and require replacement, before reverting to net gains in the final decades of the century with a new wave of investments in innovative low-carbon technologies.. For a detailed discussion on the assumption and specification of the E3MG model and the investment cycles see Barker and Scrieciu (2010, this Issue).

4.2.5 Regional Mitigation Costs

Regional mitigation costs are also important. They strongly depend on regional emission targets (so-called burden sharing regime) and the option of international emission trading. To provide an illustration of possible costs, we discuss here the results under a contraction and convergence regime with a convergence year of 2050 (i.e. the allocated emission permits on a per capita basis are equal in each region in 2050 before emission trading). We assume that emissions trading can be started in 2010 (see Figure 10)[8] and the costs are evaluated for two different targets of 550ppm and 400ppm. While costs

8 This is done only for the models MERGE, REMIND, POLES.

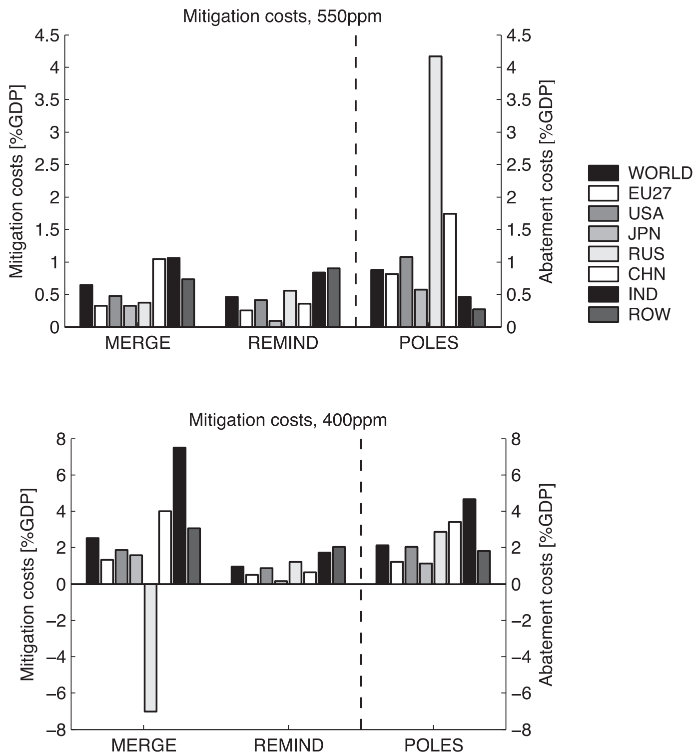
are primarily for illustration purposes, costs for the three developed country categories, EU27, USA, and Japan cluster closely together and are lower than for WORLD. The United States consistently has the highest costs of the three, but pairwise differences between costs of the industrialized countries are distinctly less than one percent within models and not much larger across models. By contrast, differences between the developing country groups or countries tend to show much larger variations between models and depend substantially on the target. China reports much higher costs than the world average in two out of three models. This could be an important sticking point in international negotiations, as China may demand compensation before consenting to high mitigation costs. India faces the highest mitigation costs in MERGE and POLES for 400ppm, and costs for India are higher than the World average in REMIND. In MERGE, Russia benefits substantially from its large biomass potential allowing it to sell emission permits, especially in the low stabilization case. By contrast, mitigation costs for Russia are higher than the World average in REMIND and POLES, especially for the 550ppm target. Hence results are difficult to generalize for developing countries, including ROW. The analysis shows that the mitigation costs depend very much on the assumptions about the availability of certain energy carriers in the specific regions, a result that is in line with other studies, e.g. by den Elzen et al. (2008). This suggests an area for further research.

Summing up, despite the very different assumptions and structures employed in the models, four out of five models show a similar pattern in costs. Global mitigation costs fall into a limited range if one disregards results from the Keynesian demand-driven simulation model E3MG, which projects, on the contrary, benefits from climate change mitigation. A robust finding, independent of the energy mix and the applied technologies, appears to be that global mitigation costs are moderate if the whole portfolio of technologies is available and if one assumes global participation. Regional mitigation costs, however, show a much wider range for specific regions. The next section investigates whether there are robust findings concerning the importance of certain technologies, despite the different model assumptions.

4.3 Technology Options

The previous section has shown that mitigation costs will be moderate if all technology options, including nuclear energy, the use of CCS, and a substantial increase of renewables and biomass, are available. However, there is a risk that some of the technology options will fail or the potential has been overestimated. These "2nd best" scenarios in view of technology availability and the values of particular technology options are explored in this section. To evaluate the "option value" of including a technology in a mitigation program, we start from conditions in which all mitigation options are available for use and then evaluate the extra costs that would arise from excluding any particular option from the full mitigation portfolio that would otherwise choose to contain it. Thus the benefits of having,

Figure 10. Regional Mitigation Costs (Contraction & Convergence)



say, CCS available for use in the mitigation program would be measured by the added costs of implementing such a program without it (scenario name "noccs"). We proceed in this way, one by one, when the deployment of renewables is fixed at baseline values ("norenew") or when the use of nuclear power generation is held at baseline ("nonuke"). To further explore the role of biomass and CCS, we run some additional sensitivity analyses where the biomass potential is fixed alternatively at 100 EJ p.a. ("biomin") and 400 EJ p.a. ("biomax") compared with the standard biomass potential of 200 EJ p.a. in all models. For a discussion of that potential see van Vuuren et al., (2010, this Issue). For CCS, a constraint is set that limits the CCS storage potential to 120 GtC ("ccsmin"), compared with 400 GtC in MERGE, or with no advance constraints at all in the other models in the standard mitigation scenarios. Additional analyses on the use of nuclear include a nuclear phase-out scenario ("nuke phaseout") and a scenario where the fast breeder option is available ("fbr").

All technology options being analyzed are listed in Table 4. They are evaluated for the 550ppm as well as for the 400ppm scenario by the models MERGE, REMIND and POLES. E3MG and TIMER are not included in the

Table 4. Technology Options and Sensitivity Scenarios for the 550ppm and 400ppm Scenario

Scenario Name	Description	MERGE	REMIND	POLES
500ppm 400ppm	All options, unlimited CCS potential,[a] biomass potential limited to 200 EJ/yr	+/+	+/+	+/+
- norenew	Investments into renewable energy and biomass are fixed to baseline values[b]	+/−	+/−	+/−
- noccs	Amount of CCS is fixed to baseline values (zero)	+/−	+/−	+/−
- nonuke	Amount of nuclear energy is fixed to baseline values	+/+	+/+	+/+
- biomin	Biomass potential is limited to 100 EJ/yr	+/+	+/+	+/−
- biomax	Biomass potential is limited to 400 EJ/yr	+/+	+/+	+/+
- ccsmin	CCS storage potential is limited to 120 GtC	o/+	o/+	o/o
- nuke phaseout	No investments into nuclear from 2000 on	+/+	+/+	+/+
- fbr	Inclusion of the fast breeder option	+/+	+/+	o/o

For MERGE, REMIND and POLES it is shown whether the target is achieved for 50ppm/400ppm. A plus (+) means that the stabilization target has been met, a minus (-) means that the stabilization target has not been met, a circle (o) means that this scenario is not run. a: In MERGE, the CCS potential is limited to 400 GtC. b: In MERGE, only renewables (solar, wind, hydro) are fixed to baseline values.

determination of option values either because of conceptual incompatibility (E3MG) or practical implementation difficulties due to code constraints (TIMER). The estimates of mitigation costs for the different technology options are given in Figure 11.

The key findings are:

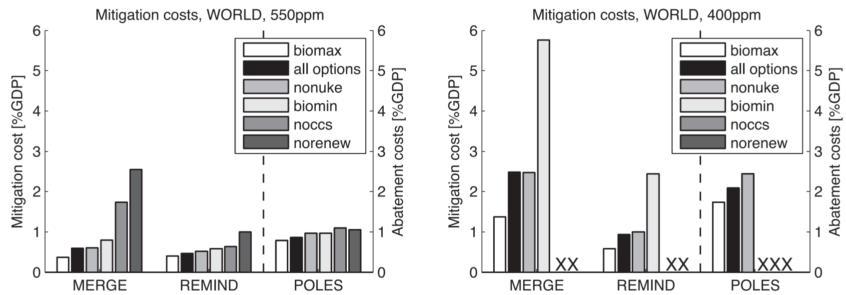
(1) Mitigation costs can increase considerably when some technology options are not available or when the potential is much lower than assumed. In some cases these 2nd best assumptions lead to infeasibilities in reaching the low stabilization target. This implies that the flexibility of substituting one technology with another is lost in the case of low stabilization.

(2) The ranking of options is robust across the models and across the two mitigation scenarios:

  a. Renewables and CCS are the most important technologies for mitigation because without them (i) the 400ppm target is not feasible and (ii) the 550ppm target gets very expensive.

  b. Nuclear is less important as a mitigation option as (i) 400ppm remains feasible without this option and (ii) the costs of

Figure 11. Mitigation Costs for Different Technology Options



Shown are the option values for different technologies for the 550ppm and 400ppm scenarios (see Table 4). Mitigation costs are given as aggregated GDP losses (MERGE, REMIND) or increase of abatement costs (POLES) up to 2100 relative to baseline in %GDP. Note the different scale for both figures. The black bar indicates the reference case where all options are available. "X" indicates where the target is not achieved. The mitigation costs of the sensitivity scenarios are always given relative to the respective baseline, e. g., a baseline run with a biomass limit of 100 EJ p.a. for the biomin run.

reaching both mitigation scenarios increase little when nuclear is held at baseline.

c. The biomass potential dominates costs in the case of low stabilization.

4.3.1 Biomass

For low stabilization at 400ppm, in all three models the biomass potential included exerts a strong influence (1) on the level of the mitigation costs (see Figure 11) and (2) on the structure of the energy mix (see Figure 12). For stabilization at 550ppm, the cost increase due to imposing biomin is moderate by comparison (see Figure 11). In MERGE and REMIND, costs more than double with a restriction of the biomass potential in the 400ppm scenario, leading to a cost increase of 3.3 and 1.4 percentage points of GDP. In POLES, the target cannot be achieved. This is mainly due to the capture ratio used for biomass plants being limited to 70% of CO_2 emissions. Conversely, for MERGE and REMIND, a higher biomass potential decreases the costs to nearly half compared to the reference 400ppm scenario. The same tendency is seen for POLES but the impact on abatement costs is much smaller.

The importance of biomass for low stabilization stems from its potential to remove CO_2 from the atmosphere when it is combined with CCS. The models apply different technologies for this option. In REMIND biomass can be used with the biomass-to-liquid option, for combined heat and power, as well as for H_2 production (see Table 2). In the baseline and the 550ppm scenario, the production of biomass-to-liquid is the main option for biomass use to supply the transport sector (cf. in this Issue, Leimbach et al., 2010; van Vuuren et al., 2010). Under low stabilization, especially in the biomin scenario, biomass is primarily applied to produce hydrogen, as this can be combined with CCS. As REMIND has no option for the electrification of the transport sector, imposing biomin means that less biofuels are available in the transport sector in the case of low stabilization. Hence the relative price of fuels for transport increases, transportation services demanded decrease, and economic costs rise. Applying the option of the electrification of the transport sector could probably reduce these high costs in the biomin scenario.

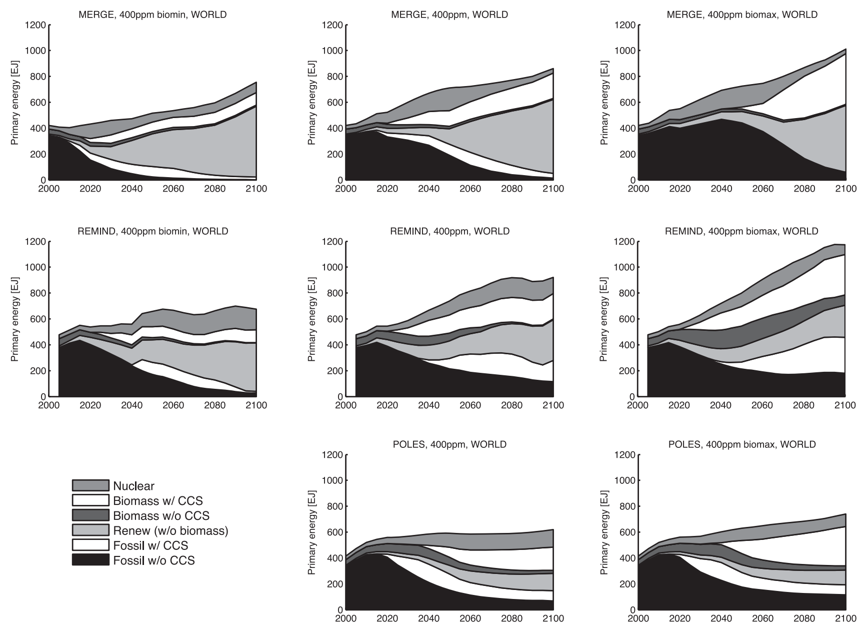
In MERGE, it is mainly biomass use for combined heat and power (CHP) that is affected when limited amounts of biomass are available. Hydrogen production from biomass in combination with CCS enables the removal of CO_2 from the air. POLES only has the option of biomass combined with pre-combustion, so in POLES the type of biomass use is not dependent on the biomass potential. In all cases it is mainly for production of CHP.

The biomass potential stipulated in each case also affects the energy mix that results. It turns out that biomass is competing with other renewable energy sources in MERGE and REMIND (Figure 12). When increasing the biomass potential, the models take advantage of this possibility, whereas the amount of other renewable sources decline. Moreover, the transformation of the energy system is postponed in MERGE as biomass becomes available later on. On the other hand, restrictions placed on the biomass potential, speed development and the introduction of the other renewables.

The reason for this is that a high biomass potential facilitates the removal of CO_2 from the atmosphere. Greater reliance on this clean technology then opens the door to greater acceptance of gas and oil (MERGE) or coal (REMIND) into the energy mix. In MERGE, high availability of biomass and flexibility of the climate module enables the required emission reductions to be postponed to later in the century. Until then more fossil energy can be used. With a lower biomass potential, the emission reduction would have to start much earlier, raising mitigation costs. Similarly in REMIND, increasing use of coal in combination with CCS is the solution under biomax as rest-emissions from CCS use, i.e. emissions that cannot be captured, can then be accepted. With a lower biomass potential, however, the residual emissions remaining after CCS would still be sufficient to make the use of coal unattractive. In POLES, the effect of the biomass potential on the energy mix is not so explicit.

With a reduced biomass potential, the models show increased energy efficiency and higher amounts of other renewables. In REMIND, additional experiments indicate that a potential of 80 EJ p.a. increases the costs up to 3.7% compared with Figure 11. With biomass potential restricted to 70 EJ p.a., the emission path cannot even be reached for stabilization at 400ppm. For 550ppm the target can still be achieved for 60 EJ p.a., and costs increase only moderately (to 0.6%).

Figure 12. Energy Mix for Increasing Biomass Potential (from left to right: 100 EJ, 200 EJ, 400 EJ p.a.) for the Models MERGE, REMIND and POLES (from the top down)



POLES does not reach the target for the biomin scenario.

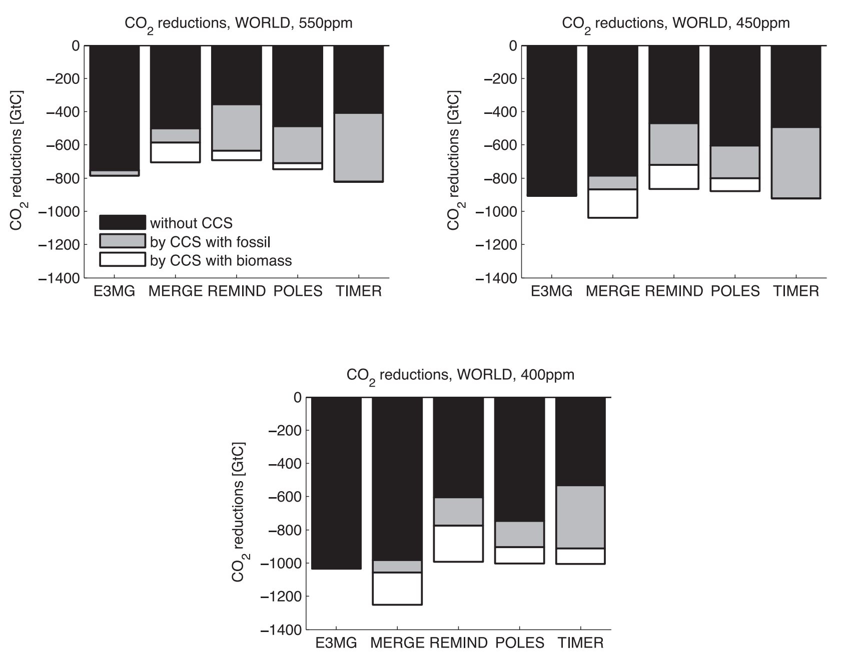
It is important to add that until now, only the technical potential has been varied in the model. Thus for biomass production, conflicts with other types of land use, in particular food production and biodiversity protection, as well as the question of whether a given biomass harvest can be sustained, have not been investigated. Cost effects of higher land prices due to increased demand have so far not been accounted for in the models. Furthermore, zero emissions are attributed to bio-energy use, thus neglecting emissions from direct and indirect land-use changes and the biomass production process itself. Certain types of land-use changes, such as converting wetlands or clearing tropical forests, lead to increased greenhouse gas emissions rather than emission reductions. Neglecting these emissions not only hides possible additional climate damage, but also yields an overly optimistic assessment of the economic potential of biomass in scenarios including carbon pricing. All these points are crucial for the assessment of low stabilization scenarios. Indeed it could turn out that the costs of low stabilization, incorporating all these factors, would be at the upper end of the percentages shown in Figure 11. To complete the analysis of biomass use, some of these issues will be assessed in van Vuuren et al. (2010, this Issue).

4.3.2 Renewables

The norenew scenario is implemented differently by the models. In REMIND the investments into solar, wind and hydro and additionally the investments into bioenergy are fixed to baseline values. This leads to much higher costs in the 550ppm scenario and an infeasibity for the 400ppm scenario. As the amount of biomass is quite high in the baseline in REMIND, this constraint does not cause the infeasibility of the norenew scenario in case of low stabilization. The limiting factor is that no investments into bioenergy use combined with CCS, being an important option in REMIND, are allowed in this scenario. Fixing only solar, wind and hydro to baseline values means the 400ppm scenario can be achieved at slightly increased costs (Leimbach et al., 2010, this Issue) as these renewables are already well represented in the baseline (see Figure 4). Therefore, the norenew scenario in REMIND mainly shows the effect of the unavailabilty of bioenergy in combination with CCS.

In POLES the total amount of biomass rather than the investments, are fixed to baseline, so that the biomass plus CCS option is available. This leads to just a slight increase of the costs for the 550ppm scenario, although the low stabilization target cannot be achieved as a much higher amount of biomass with CCS is needed (see Figure 4). In both the REMIND and POLES models, nuclear

Figure 13. Amount of CO_2 Captured by CCS Compared to the Total CO_2 Reductions for the Three Different Stabilization Targets



energy is more important in the norenew scenario than in the case where all options are available.

In MERGE, only the investments into solar, wind and hydro are fixed to baseline values; investments into bioenergy are not fixed. This should give the model more flexibility to reach the target, but in the case of the 550ppm scenario, the costs increased more than in the two other models and the 400ppm target is not achievable. This is because the amount of renewable energy is very low in the baseline (see Figure 4). This also means that the H_2 production directly from solar thermal (see Magné et al. 2010, this Issue), being important in MERGE, is not an option and is what prevents the 400ppm target being achieved. In the 550ppm scenario this limit can be absorbed by costly demand reductions and an increasing use of bioenergy in combination with CCS.

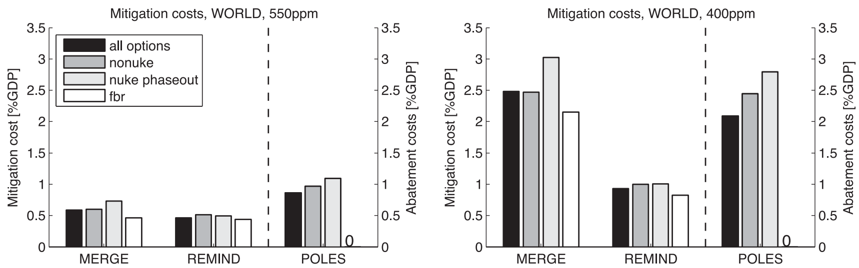
4.3.3 CCS

Without the use of CCS, the low stabilization target cannot be achieved as options to remove CO_2 from the atmosphere are required. A limited CCS potential (ccsmin) achieves the target but also raises costs. In MERGE, the costs increase to 3.6%, in REMIND to 2% of GDP. In POLES the ccsmin scenario cannot be run due to code constraints.

The CO_2 abatement attributable to CCS compared to total emission reductions is depicted in Figure 13. With a more stringent target, the use of CCS increases only slightly for MERGE and REMIND while remaining constant for POLES and TIMER even though the last three models place no limits on the CCS potential, and the potential in MERGE is not fully used. This implies that after a certain point the marginal costs for CCS become uncompetitive with other abatement options so a (near-)constant amount of CCS is used, regardless of the stabilization target. Overall, the amount of CO_2 that is captured with CCS ranges from 275 GtC in POLES to 520 GtC in TIMER for the low stabilization case. In the scenario with a reduced CCS potential, capturing about 120 GtC is sufficient to reach the low stabilization goal. It is important to note that for MERGE and POLES a saturation of the captured CO_2 is observed by 2050. In TIMER and REMIND captured CO_2 increases until 2080 and then declines, not limited by storage potential, but because the emissions for CCS from coal decline. CCS technologies in E3MG penetrate the market only to a limited extent due mostly to their high costs relative to other low carbon technologies. E3MG shows how it is possible to do without CCS through deep and early emission cuts compatible with maintaining positive emissions. CCS is not then as important as when assuming pathways with negative emissions.

The E3MG model aside, stabilizing GHG emissions with only limited or no CCS either precludes reaching an ambitious climate protection target or raises the costs of such an achievement considerably. Costs are holding back the use of CCS rather than its technical potential. A robust conclusion from all models is that a potential between 120 and 500 GtC is required to achieve low stabilization

Figure 14. Mitigation Costs in Dependence of Different Nuclear Options for 550ppm (left) and 400ppm (right)



targets. This is below the assumed technical capacity of 545 GtC in geological storage indicated by the IPCC (Metz et al. 2005).

Further, it is important to note that with the stricter stabilization target, the use of CCS in combination with biomass rather than coal becomes increasingly important (see Figure 13). This could mean that part of the storage potential should be reserved for use with biomass as only this option facilitates removal of CO_2 from the atmosphere.

4.3.4 Nuclear Power

When limiting the use of nuclear to the baseline values, the costs increase only moderately for REMIND and do not increase at all for MERGE and POLES, so the nuclear option seems to be less important than renewables or CCS. This is partly due to the fact that nuclear energy is already incorporated in the baseline scenario but is actually less attractive in the mitigation case for some models (POLES and MERGE, see Figure 14). The reliance on nuclear power as an "interim-technology" decreases after the middle of this century as a result of depletion of uranium (represented in MERGE and REMIND). Keeping the use of nuclear power at baseline leads to more coal-based power generation coupled with CCS or reduced energy use. Nuclear power becomes an important mitigation option only when the biomass potential is assumed to be low.

When no investments are made in nuclear power after the year 2000 (i. e., assuming an extreme nuclear phase-out scenario), costs increase moderately in the 550ppm scenario but by up to 0.7 percentage points under low stabilization. Two models explore the option of introducing a fast breeder. With it costs can be reduced from 2.5% to 1.9% for MERGE and hardly at all for REMIND compared to the standard scenario without the fast breeder option. While reducing mitigation costs, the fast breeder may increase the risk of nuclear proliferation. Moreover, costs for the storage of nuclear waste are not included in any of the models. Including them would make the nuclear option less attractive in all scenarios including the baseline.

5. CONCLUSIONS

This synthesis paper reports results from the ADAM[9] model comparison of five energy-environment-economy models and their mitigation strategies and costs. The analysis compared three different stabilization scenarios, ranging from 550ppm and 450ppm to 400ppm CO_2 eq, to a business-as-usual (baseline) scenario where no political action is taken to mitigate climate change. We investigated in detail the technological feasibility of a low stabilization scenario of 400ppm CO_2 eq under various constraints and compared this scenario with the other less ambitious stabilization targets in terms of mitigation costs, reduction strategies and the energy mix. The focus was on gauging the option values of different technologies and estimating the competitive potential of certain technologies/ resources, i.e., the biomass potential or the cost-effective storage potential under carbon capture and storage (CCS).

The models compared in this exercise are quite different in their basic modeling approach and their assumptions about the availability of certain technologies. Nevertheless, some results appear robust across models. We showed that low stabilization of CO_2 emissions is found to be achievable, at moderate costs, in all models used if the full suite of technologies is available, all regions participate in emission reduction and effective policy instruments are applied. The model comparison identifies a number of different pathways by which a low stabilization target of 400 ppm CO_2 eq for atmospheric greenhouse gas emissions can be achieved by 2100. However, stricter mitigation targets bring greater dependence on selected technologies, such as CCS and biomass. This implies some loss of flexibility in the choice of technologies to achieve the more ambitious climate protection targets. However, without the availability of CCS or the considerable extension of renewables, the most ambitious mitigation pathway is not feasible.

5.1 Economic Viability of Low Stabilization

The costs for stabilising concentrations at such a low level are moderate in all models. In MERGE and REMIND losses of GDP range from about 0.9% to 2.5% by 2100 relative to the baseline, compared to a range of 0.5 to 0.9% in case of the 550ppm scenario. The abatement costs generated by TIMER and POLES are of a similar order of magnitude. The uncertainties and costs grow at an increasing rate with lower stabilization targets, but the costs for all scenarios reported here are in the lower to medium range compared to the values given in the IPCC AR4. E3MG reports clearly different results concerning the mitigation costs. In this model, gains due to mitigation of up to 2.1% can be observed for all stabilization pathways. Furthermore, such economic gains are expected to increase with lower stabilization targets. The reason lies in the different model set-up of E3MG, which does not assume market clearing, or equilibrium and full employment of resources in the baseline. The climate policies partly solve the

9 EU project ADAM (Adaptation and Mitigation Strategies), www.adamproject.eu

inefficiencies in the baseline but it remains disputable whether these gains can be attributed to climate policy alone.

5.2 Technological Feasibility of Low Stabilization

In the 550ppm scenario the models allow flexible use of a variety of technologies as either complements or substitutes in achieving this target. This technological flexibility is to some extent lost in the low stabilization scenario where some key technologies become indispensable for reaching the policy target. Renewables (solar, hydro, wind), CCS and biomass on the one hand, and energy efficiencies and other demand-side regulatory measures on the other, play a very important part in reaching this low stabilization level.

Concerning technology options, the models investigated show a very similar picture leading to robust conclusions about the ranking of the mitigation options in terms of costs. The use of biomass, other renewables and CCS are the most important technology options. Without them the low stabilization at 400ppm CO_2 eq is not attainable at all.

- 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 in some models the use of biomass competes with the other renewable sources: the more biomass that is available (and used), the lower 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 may increase. With greater biomass use, potential conflicts with food production, biodiversity conservation, water availability, and additional emissions associated with large-scale energy-crop production also have to be considered.
- The *CCS* potential also has an influence on the feasibility of low stabilization and the resulting mitigation costs. Without any CCS, low stabilization is not possible and with a level of CCS that is low but sufficient to meet the low stabilization target, costs are still very high. Storage capacity of 120 GtC turns out to be such a level.
- *Nuclear* power does not play an important additional role in mitigation scenarios in any of the models beyond the role it plays in their baselines where nuclear energy is attractive in most models; fixing nuclear power to its baseline values leads only to a marginal increase in costs. With a phase out of nuclear, however, costs do increase. However, this is less than with an economically severely limited CCS potential. Fast breeder reactors overcome resource depletion challenges of nuclear energy, and mitigation costs decrease slightly. However, the fraction of nuclear power in the energy mix increases substantially.

5.3 Summary and Outlook

The models surveyed illustrate ways in which a low stabilization target of 400ppm CO_2 eq for atmospheric GHG concentrations can be achieved at moderate cost. The analysis showed that the technical feasibility and economic viability of low stabilization depends crucially on the availability of particular technologies. For instance, the possibility of removing CO_2 from the atmosphere relies on the availability of the CCS technology and of a sufficient biomass potential. Institutional settings have to be designed so that biomass production will not conflict with food production or with conservation of nature and sustainability. Moreover, biomass use leading to deforestation would have adverse effects on emissions. Further research on these shortcomings and adverse side effects of bio-energy use or potential risks of CCS is needed to better address the caveats of these technologies in the models and to come up with a more balanced picture concerning the limits of these technologies.

Although model results show the technical and economic feasibility of low stabilization, there are additional political and institutional prerequisites for approaching that goal with a good chance of success. A future research task might be to design markets, certified products, and instruments that could incorporate emission certificates from the generation of biomass with CCS into an international emissions trading scheme. Moreover, massive R&D investments would still be needed before some of the low-carbon technologies here considered could become commercially viable and widely adopted. All models here assume global participation in climate policy in the near-term and shift technology transfer across regions. It will remain an enormous challenge in international climate policy to achieve these conditions. Such policy support is crucial for achieving low stabilization targets and cannot be covered by pure model analysis. Ideas to address institutional questions are given in Knopf et al. (2010, this Issue).

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