11. The economics of low stabilisation: implications for technological change and policy

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Summary
The European Union (EU) is committed to the goal of keeping the increase in global temperatures from pre-industrial levels to no more than two degrees Celsius with a better than even chance. Achieving this 2°C target would require stabilising greenhouse gas concentrations at less than 450ppm. This Chapter examines whether and how this can be done by probing the technological and economic feasibility of reaching such a low level of stabilisation with acceptable means. We explore both aspects for three carbon dioxide equivalent concentration levels, set at 550, 450, and 400 parts per million (ppm) carbon dioxide equivalents, which have different probabilities of reaching the 2°C target. To investigate the robustness of results on mitigation costs and technological options, we compare findings from different state-of-the-art energy-environment-economy models for the time horizon 2000-2100. An in-depth sectoral analysis of how the transformation of the energy system could proceed in Europe follows this global analysis.

Our results suggest that low stabilisation is feasible in terms of technologies and moderate in costs. A broad range of technologies can be used to achieve stabilisation targets such as 550ppm that have only a low likelihood of reaching the 2°C goal. Much more ambitious reduction targets, such as 400ppm however, rely heavily on the availability of Carbon Capture and Storage (CCS) in combination with biomass as options for removing carbon from the atmosphere and on the expansion of renewable energy. This target alone has a high likelihood of reaching the 2°C goal.
Overall, global mitigation costs, expressed as cumulative Gross Domestic Product (GDP) losses until 2100 relative to the baseline, are found to be below 0.8 percent for the 550ppm target, but nearly 2.5 percent for the most ambitious of the three stabilisation targets, 400ppm. These costs could be twice as high if biomass availability was smaller than first assumed or if the CCS storage potential was more limited. One model reports GDP gains for all stabilisation pathways as it incorporates existing inefficiencies.

A detailed analysis of the transformation of the energy systems in Europe leads to the conclusion that improving energy productivity and substituting renewable energy for fossil fuels are the most important means for achieving the 2°C goal.

11.1 Introduction

Reaching the target of climate stabilisation at no more than 2°C above pre-industrial levels by the end of this century – a goal embraced by the EU – is a historic challenge for humankind. To make it likely that this challenge will be met, greenhouse gas concentrations have to be limited to well below 450 parts per million (ppm) carbon dioxide equivalents. This presupposes a portfolio of mitigation options, in particular, options to remove carbon from the atmosphere as well as early and deep emission cuts.

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. For this reason we estimate the economic costs of achieving different intermediate stabilisation targets that lead with different probabilities to the 2°C final target. In addition, we evaluate the technological feasibility of reaching these stabilisation targets and explore the importance of individual technologies.

Specifically, we try to answer two key questions:

*What is the most ambitious carbon dioxide (CO2) reduction target that is economically and technically feasible with the ability to achieve the 2°C target?* We explore three different CO2 stabilisation scenarios that have different probabilities of reaching this target, described more fully in Section 11.3.1. The probabilities of achieving the target increase from approximately 20 percent for stabilisation at 550ppm, to 50 percent at 450ppm, and 80 percent at 400ppm, depending on the climate sensitivity (Hare and Meinshausen, 2006). Achieving the latter level
of stabilisation is especially challenging because it would involve both early and rapid
decarbonisation of the world’s energy system, or negative emissions by the end of the
century.

What are some of the technological barriers or economic and political obstacles that could
jeopardise the intended emissions stabilisation outcome? For example, what can still be
achieved if some of the technology options fail or are ruled out? Moreover, some of the
technologies that may be indispensable for reaching very low emission paths, such as large-
scale use of biomass, CCS, or nuclear power, may be saddled with high risks and adverse side
effects.

In order to assess these key questions, five global regionalised energy-environment-economy
models are compared in the Regional Modelling Comparison Project, within the ADAM
project. Model comparison analysis can help to identify a range of pathways to a low carbon
economy and shed light on the robustness of the associated cost estimates and technology
options. Recent examples of model comparisons are Edenhofer et al. (2006) with focus on
endogenous technological change, or Weyant and Hill (1999) and other contributions to the
Stanford Energy Modelling Forum (EMF). So far, low emission pathways have rarely been
subjected to such comparisons. In the Intergovernmental Panel on Climate Change (IPCC)
Fourth Assessment Report (AR4), for instance, only three models were used to produce
results reported for the lowest IPCC stabilisation scenario with radiative forcing of 2.5-
3.0Wm$^{-2}$ corresponding to a 445-490ppm CO$_2$ equivalent level (Fisher et al., 2007).

Exploring the lower limit of stabilisation is the overarching challenge and focus of the model
comparison in this Chapter. Section 11.2 presents the models and scenarios used. Section 11.3
then applies the models and compares the economic and technical results for harmonised
baselines with the mitigation scenarios. It discusses alternative ways to achieve low
stabilisation, assuming global cooperation and participation by all major players, and explains
how individual technology options can be valued. The focus then shifts to the European
Union (EU) in Section 11.4 to provide a case study detailing how the required transformation
of the energy system can be achieved at regional and sectoral levels. The conclusions drawn
in Section 11.5 show how a top-down modelling perspective can be supplemented with a
bottom-up analysis considering different sectors, technology options, and policy measures for
additional insights.
The results presented here are based on the work by Edenhofer et al. (2009) in a Special Issue of The Energy Journal devoted to The Economics of Low Stabilisation. This work provides more information on technical details of the models and analytical specifics underlying most sections of this Chapter.

11.2 Models and reference scenario

11.2.1 The models

This model comparison uses the macro-econometric simulation model E3MG (Barker et al., 2006; 2008), the optimal growth models MERGE-ETL (Kypreos and Bahn, 2003; Kypreos, 2005, hereinafter called MERGE) and REMIND-R (Leimbach et al., 2009, hereinafter called REMIND), and the energy system models POLES (European Commission, 1996) and TIMER (Bouwman, 2006). A more detailed description of all models is given in the Appendix and in Edenhofer et al. (2009).

MERGE and REMIND are hybrid models with a top-down macroeconomic model and a bottom-up energy system model. Both are optimal growth models where a social planner with perfect foresight maximises global welfare over a given period. Solved at equilibrium, these optimisation models yield least-cost energy systems under a set of constraints. In contrast, the modelling approach in E3MG, also incorporating a macroeconomic and an energy system component, is based on past observations and aims to provide projections and future scenarios consistent with historical data and trends. POLES and TIMER are bottom-up energy system models with a high resolution of different technologies. They seek to minimise the costs of transforming the energy system without assuming perfect foresight. The macroeconomic part of these models is exogenous.

All scenarios are analysed 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).
11.2.2 The baseline scenario

As far as possible, the building blocks for the baseline without climate policy were harmonised for comparability across the different models particularly with regard to population projections and economic growth. For this, we used the ADAM baseline scenario, the underlying assumptions for which are detailed in Chapter 3, van Vuuren et al.

![Baseline results for WORLD](image)

**Figure 11.1:** Baseline results for WORLD. Projected values aggregated to the global level are reported for population, GDP, total primary energy use, and CO$_2$ emissions from the energy and industry sector (CO2-En). E3MG reports lower GDP values as it does not assume long-term convergence in per capita GDP between the regions, with GDP values being reported in constant market prices and not in purchasing power parity (PPP) terms. GDP growth rates are between 2.1 and 2.4 percent per annum for the other models. Source Edenhofer et al. (2009)

Due to the very different modelling assumptions, full harmonisation of all variables between all models is not possible. As **Figure 11.1** shows, all models use the same exogenous
projections for global and regional population (based on data from the United Nations, 2003, see Figure 11.1). The economic profile is a medium growth scenario, but with high growth rates for India and China (see Chapter 3, van Vuuren et al.). Models with exogenous GDP profile (POLES and TIMER) use this projection directly as an input on both the global and the regional level. All other models except E3MG stay close to the reference GDP baseline in Figure 11.1.

Regardless of their adoption of common regional and global GDP baselines, the models differ in their projections of CO₂ emissions. This can be explained by large differences in fossil-based energy prices among the models (see Figure 11.2) affecting the energy mix and the CO₂ emissions in the baseline. In MERGE for instance, the CO₂ emissions increase is greater than in other models due to low fossil fuel prices encouraging continued use of coal, gas and oil. Conversely, the low CO₂ emission pathway for REMIND arises from the assumption of an expensive price path for fossils so that a switch away from coal to renewables is already captured to some degree in the baseline. E3MG already has a large amount of renewables in the baseline and therefore shows decreasing CO₂ emissions from 2060 onwards.

**Figure 11.2:** 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 that are not comparable to spot market prices. In POLES, the price depends on market fundamentals, namely the differential dynamics of supply and demand and the relative amount of spare capacities. For E3MG, historical trends, not prices, are the main driver. In it the real price of oil is an input that follows the POLES price path up to 2050 and then declines by about 2 percent per annum. For E3MG, the coal price is the average of hard coal and other coal (for USA). Source Edenhofer et al. (2009)
11.3  Low stabilisation: opportunities and risks

11.3.1  Long-term stabilisation targets

From the range of emission stabilisation targets that have different probabilities of satisfying the objective to keep global warming to no more than 2°C, we choose targets characterised as being ‘unlikely’, of ‘medium likelihood’, or ‘likely’ in IPCC terminology. These intermediate targets are associated with stabilisation at 550, 450 and 400 parts per million CO₂ equivalents, respectively, referred to as ‘550ppm’, ‘450ppm’ and ‘400ppm’ in this Chapter.  

Figure 11.3 shows that the 550ppm scenario (den Elzen et al., 2007) yields an increasing concentration path up to (and beyond) 2100. In the 450ppm scenario (IMAGE/TIMER 2.9, den Elzen and van Vuuren, 2007), CO₂ equivalent concentrations reach a maximum by 2045 and declines slowly thereafter. In the 400ppm scenario (IMAGE/TIMER 2.6, van Vuuren et al., 2006; 2007) concentration also peaks around 2045, but at a lower level, and then declines more rapidly than in the previous scenario.

In REMIND and POLES, the CO₂ emissions pathway from the energy and industry sector is taken as the binding cap for each scenario. Emissions from land-use and from other greenhouse gases are given exogenously in all models\(^1\). The data for the CO₂ emission cap from the energy and industry sector, the land-use emissions, and the emissions from other greenhouse gases are provided by the IMAGE/TIMER model (van Vuuren, 2007) for these three stabilisation scenarios. The CO₂ equivalent emission pathway is therefore consistent

\(^1\) In TIMER this exogenous path is consistent with the optimal emission path evaluated with the FAIR model linked to TIMER.
with the data given by IMAGE/TIMER. MERGE is run with a climate module and binds the climate forcing for each scenario. In E3MG, the cumulated energy-related emissions by 2100 are taken as the binding limit. In POLES, the other greenhouse gases from the energy and industry sector are calculated endogenously, while land-use greenhouse gases are applied from the IMAGE/TIMER model.

The first major result is that each of the models can achieve the three stabilisation targets, even in the case of the 400ppm stringent mitigation scenario. This is a very important result because, as noted in Section 11.3, not many modelling results have been reported for such low emissions stabilisation targets. Inflexibilities in the energy systems, shortcomings in the realisation of mitigation technologies, and myopic investment behaviour are among the reasons why low concentration pathways have so far been assessed and achieved by only a small number of models. 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.

### 11.3.2 Storylines of decarbonisation

This section contrasts the mechanisms and interactions involved in the baseline with those relied upon for meeting the stabilisation targets of 550 and 400ppm. Although some consistency is achieved through shared data on population, GDP, total energy use and CO₂ emissions (see Figure 11.1), the models reveal very different strategies for meeting future energy demands and favour different energy carriers and technologies (see Figure 11.4). Different assumptions driving the models, for example concerning the price of fossil fuels or learning rates and availability of certain technologies, lead to very different pictures of the primary energy mix in the baseline and mitigation scenarios.

**The baselines for each model**

The several models included in the comparison exercise span a range of possible pathways to the future. In a scenario without climate policy, fossil fuels continue to dominate the energy system throughout the century (see Figure 11.4, left column). MERGE and TIMER rely mostly on coal; renewable energy is not important. In POLES, the extent of decarbonisation is very slight. The baseline energy mix in REMIND, however, is characterised by strong
decarbonisation using biomass and the introduction of renewable energy sources. 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 available, scarcity of these resources becomes a key constraint on any longer-term role for nuclear energy. The cost of wind power technology shows moderate improvements 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 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. The use of renewables expands, even in the baseline scenario of the POLES model, because of their cost efficiency in the long term. Wind energy

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2 Here and in what follows, renewables include solar, wind, and hydro-electric power. Biomass is reported separately.
is capped by its technical potential in relation to land availability and population density. For decentralised 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 hydrogen transmission lines.
Figure 11.4: Global energy mix for the baseline, the 550ppm and the 400ppm scenario (from left to right) for the five models MERGE, TIMER, POLES, REMIND and E3MG (from top to bottom). Note that biomass is listed separately and not as part of renewables which only include energy from solar, wind, and hydro-electric power. For the balancing of renewables we apply the direct use concept. In E3MG, biomass includes combustible waste (about 80
percent of the total biomass use) such as primary solid biomass used for heating in the residential sector in developing countries. Source Edenhofer et al. (2009). (Colour figures available at the end)

REMIND takes renewables, in particular biomass, into the baseline. The biomass and renewables option becomes competitive because of increasing fossil fuel prices in the second half of the century (see Figure 11.2). Biomass is a general-purpose energy carrier; it can be converted into all secondary energy carriers. Biomass-to-liquid is available at costs comparable to coal-to-liquid but helps to conserve coal for a later use and for conversion into other secondary energy carriers, such as electricity production. 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 decarbonisation of the global economy, projecting the historical trend of falling carbon intensity 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. Increasing deployment of low-carbon, rather than high-carbon, technologies further stimulates cost reduction through economies of scale in new energy-producing industries.

*What the models tell about decarbonisation*

In the mitigation scenarios (Figure 11.4, middle and right columns), the energy mix for a specific model is similar for the 550ppm and the 400ppm target, so that each model follows its own strategy under either stabilisation target. This shows that the energy mix is principally a function of each model’s assumptions about the available technologies, learning rates, and resource prices.

A partial exception to this insensitivity of the energy mix to the level of stabilisation is MERGE. In this model, the flexibility provided by having its own climate module and not being restricted to the prescribed CO$_2$ path allows the transformation of the energy system to
be postponed in 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 their paths are constrained by the exogenous time series for CO₂ emissions. The carbon-free contributions to the energy mix, however, vary between the models. In POLES, reduction of energy use is an important strategy as POLES has demand-side energy efficiency improvements in a bottom-up approach. In general, higher energy prices can spur technological improvements that lead to energy savings in production, and they can also produce changes in behaviour, for example in residential uses and private transportation, which lead to energy savings in consumption. In TIMER, CCS is the main option, although CCS with biomass is allowed only in the most stringent stabilisation scenario. With more CCS than in any of the other models, TIMER subsumes a CCS storage potential of 470 GtC, compared to 280 GtC in MERGE. REMIND shows a steady increase of primary energy consumption because decarbonisation 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. In the policy scenarios, the primary energy consumption from biomass-CCS is connected mainly with hydrogen production for transport and not biomass-to-liquid, as in the baseline scenario.

In E3MG, the stories for 550ppm and 400ppm are quite different. 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 decarbonisation of the transport sector through electrification of the vehicle fleet play a major role. In the 400ppm scenario, the renewables and biomass options become increasingly more important. Because of learning curves, economies of scale, and Keynesian multiplier effects from the employment of resources that were unemployed in the baseline, the costs associated with increased reliance on renewables are much reduced. This induces large-scale adoption of low-carbon technologies.

Two further findings are especially noteworthy:
(i) Nuclear energy appears to be important as an interim energy source around the middle of this century in some models. 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\(^3\).

(ii) Concerning the CCS option, 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 stabilisation target. Rather, for the stricter target, CCS is shifted from coal combined with CCS to biomass combined with CCS. The reason is that 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 stabilisation target.

In general there are three factors that can contribute to changes in emissions according to 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 (i) carbon intensity (CI), defined as CO\(_2\) emissions per unit of primary energy, (ii) energy intensity (EI), defined as primary energy per GDP, or (iii) growth of GDP. A decomposition analysis enables quantification of the contributions of these different factors (see Figure 11.5). In nearly all cases reducing carbon intensity is the most important strategy, the more so the stricter the stabilisation target.

![Figure 11.5: CO\(_2\) reductions attributed to lower carbon intensity (CI) and 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). Source Edenhofer et al. (2009)](image-url)

\(^3\) In the standard policy case, fast breeders are not considered as an option in the models.
Except for E3MG, the reduction of energy intensity plays only a minor role as a mitigation option. The 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 in the baseline by around one percent per annum. This is in line with the historical record (e.g. Nakicenovic et al., 2000, Fig. 3-13; Fischer et al., 2007, Fig. 3.6). Lowering energy intensity in response to a more stringent target is more of an option in the energy system models POLES and TIMER as they provide little flexibility for substitution on the supply-side. Moreover, POLES accounts for an explicit bottom-up representation of demand-side technologies (see Section 11.5.2).

### 11.3.3 Mitigation costs

This section investigates whether there are robust findings, for instance concerning the cost of mitigation or the importance of certain technologies, despite the different model assumptions. Mitigation cost\(^4\) percentages are net present value sums to 2100 of shortfalls in global GDP or consumption relative to the like sum of baseline values.\(^5\) They are given in *Figure 11.6* for the three reference mitigation scenarios. *Figure 11.7* shows the corresponding time paths of annual mitigation costs expressed in percent of GDP. The energy-system models POLES and TIMER report abatement costs, i.e., the sectoral costs for the transformation of the energy sector.

Most of the models in *Figure 11.6* show GDP losses that are increasing with the stringency of the stabilisation target. The only exception is E3MG which is discussed later as a special case. For the other four models, the costs for all stabilisation targets are moderate, with aggregate losses for this century below 2.5 percent of GDP for the most stringent scenario. The annual losses displayed in *Figure 11.7* are moderate until about 2040 but increase in all four models during the transition phase of the energy system and stabilise 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).

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\(^4\) In the following, we will use the phrase “mitigation costs” simultaneously for both losses and gains due to mitigation.

\(^5\) Unless otherwise stated, we use a discount rate of 3 percent here.
All models include endogenous technological change\(^6\) which can be stimulated by policy measures to yield induced technological change (ITC) and make an important contribution to achieving CO\(_2\) stabilisation targets (Edenhofer et al., 2006). As additional investigations show, without the inclusion of ITC, the costs increase.

\(^6\) The models have different representations of endogenous technological change. All models include for example, learning in different technologies, and some models include research and development spending. Details of endogenous technological change in the models are given in ADAM Deliverable D-M2.4.
MERGE reports the highest costs for the 400ppm scenario but the lowest, at least until the middle of this century, for the 550ppm scenario. This is partly due to an increasing use of coal in the MERGE baseline causing much higher CO$_2$ emissions (see Figure 11.1) requiring increased emission reduction. Compared to the other three models, REMIND yields the lowest overall average annual mitigation costs partly because the price path for fossil energy is assumed to be high (see Figure 11.2) and renewable energy sources are already utilised to some extent in the baseline. In addition, REMIND provides a high degree of flexibility in the choice of low carbon technologies.

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. This is because the increase of the carbon price induces greater energy efficiency mostly through demand-side technological innovation but also partly through different consumption behaviour. In POLES, stepped-up energy efficiency improvements are essential to reach the set CO$_2$ mitigation objectives because decarbonising the supply-side alone will not be sufficient. Limiting factors on the supply side are the amount of land available for alternative energy generation and biomass production or the shortage of uranium. Moreover, the most suitable renewable energy production sites are not located where most of the energy is consumed.

Unlike the other models, E3MG reports overall gains from low-level emissions stabilisation (see Figure 11.6). 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 auctioning carbon permits to the energy sector and applying carbon taxes for non-energy activities. Key assumptions are that 40 percent of the revenues collected are recycled and used for research and development investments in renewables as well as for investments in energy savings and conversion of energy-intensive sectors towards low-carbon production methods. In contrast to the other models, E3MG is not a supply-driven but a demand-driven model, where resources in a business-as-usual case are not fully employed or optimally utilised. Given the existence of worldwide idle capacities, unemployment, and underemployment of resources, mitigation policies may lead to overall gains if employment of these resources is then improved. The question remains whether these gains can be attributed to climate policy or are just an effect of existing inefficiencies in the baseline.
The mitigation benefits and costs reported by E3MG vary greatly over the coming decades (see Figure 11.7) because of investment cycles in new low-carbon technologies. The wave of early investments in plug-in vehicles, greater energy efficiency in buildings, and low greenhouse gas 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 are replaced, before reverting to net gains in the final decades of the century.

![Figure 11.8: Carbon price for 550ppm and 400ppm scenario. Note the different scales. Source Edenhofer et al. (2009)](image)

In all models, including to some extent in E3MG, the carbon price drives investments in carbon-free technologies. The price for CO$_2$ is rising over time in most models, and, at any time, costs in the 400ppm scenario are more than five times as high as in the 550ppm scenario (Figure 11.8). However, the high price by the end of this century affects only a small amount of CO$_2$ emissions (see Figure 11.3, left) and prevents fossils from re-entering the energy system.

It is important to note that despite the very different assumptions and structures employed in the models, mitigation costs fall into a limited range if results from the Keynesian aggregate-demand model E3MG are disregarded. A robust finding is that mitigation costs are moderate, independent of the energy mix and available technologies,

### 11.3.4 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. The values of particular technology options are explored in this section. To evaluate the ‘option value’ of including a particular technology in a mitigation program, we run the models including the full range of mitigation options and then evaluate the extra costs that would arise from excluding a particular option from the portfolio. Thus the benefits of having for example, 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, fixing the deployment of renewables at baseline values (‘norenew’) or holding the use of nuclear power generation is at baseline levels (‘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 yr\(^{-1}\) (‘biomin’) and 400 EJ yr\(^{-1}\) (‘biomax’) compared with the standard biomass potential of 200 EJyr\(^{-1}\) in all models. For CCS, a constraint is set that limits the CCS storage potential to 120 GtC (‘ccsmin’), compared with 400 GtC in MERGE, or no advance constraints at all in the other models in the standard mitigation scenarios. All technology options analysed are listed in Table 11.1. They are evaluated for the 550ppm as well as for the 400ppm scenario by the models MERGE, REMIND and POLES. The estimates of mitigation costs for the different technology options are given in Figure 11.9.

In the 550ppm scenario, each separate technology (CCS, renewable energy, nuclear energy) can be fixed to its use in the baseline without affecting the feasibility of that scenario, but this is lost in the case of low stabilisation. When CCS is not available or when renewables are held at their baseline values, the 400ppm target is not achievable by any of the three models. On the other hand, the 400ppm target can still be achieved when nuclear power is kept at baseline levels.
### Table 11.1: Technology options for the 550ppm and 400ppm target (white) and sensitivity scenarios (grey). For MERGE, REMIND and POLES it is shown whether the target is achieved for 550/400ppm. A plus (+) means that the stabilisation target has been met, a minus (-) means that the stabilisation target has not been met, a circle (o) means that this scenario is not run.

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>Description</th>
<th>MERGE</th>
<th>REMIND</th>
<th>POLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>500ppm / 400ppm</td>
<td>All options, unlimited CCS potential(^7), biomass potential limited to 200 EJ yr(^{-1})</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>- norenew</td>
<td>Amount of renewable energy is fixed to baseline values</td>
<td>+/-</td>
<td>+/-</td>
<td>+/-</td>
</tr>
<tr>
<td>- noccs</td>
<td>Amount of CCS is fixed to baseline values (to zero)</td>
<td>+/-</td>
<td>+/</td>
<td>+/-</td>
</tr>
<tr>
<td>- nonuke</td>
<td>Amount of nuclear energy is fixed to baseline values</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>- biomin</td>
<td>Biomass potential is limited to 100 EJ yr(^{-1})</td>
<td>++</td>
<td>++</td>
<td>+/-</td>
</tr>
<tr>
<td>- biomax</td>
<td>Biomass potential is limited to 400 EJ yr(^{-1})</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>- ccsmin</td>
<td>CCS storage potential is limited to 120 GtC</td>
<td>o/+</td>
<td>o/+</td>
<td>o/o</td>
</tr>
</tbody>
</table>

\(^7\) In MERGE, the CCS potential is limited to 400 GtC.

**Biomass**

The results in **Figure 11.9** show that the amount of biomass included in each of the three models is crucial to the level of mitigation costs. In MERGE and REMIND, costs are more than doubled when biomass potential is cut from 200 EJ yr\(^{-1}\) to 100 EJ yr\(^{-1}\) and in POLES the target cannot even be met. Conversely, a higher biomass potential of 400 EJ yr\(^{-1}\) decreases costs by almost half compared with the reference 400ppm scenario (for MERGE and REMIND). In general, the biomass potential is not only an important determinant of mitigation costs but it also affects the energy mix because biomass is competing with other renewable energy sources (for MERGE and REMIND). With higher biomass use, reliance on other renewable sources declines. For further analysis of the biomass potential scenarios we refer to Edelhofer et al. (2009).
Figure 11.9: Mitigation costs as cumulative GDP losses (MERGE, REMIND) up to 2100 relative to baseline; POLES reports the increase of abatement costs relative to baseline in percent GDP. The option values for different technologies for the 400ppm scenario are shown (see Table 11.1). The reference case is the scenario where all mitigation options are available (in black). None of the models achieves the target in the norenew and noccs scenario, POLES does not stay below the cap for the biomin scenario. The mitigation costs of the sensitivity scenarios are always given relative to the respective baseline, which for the biomin run for instance would be a baseline with a biomass limit of 100 EJ yr$^{-1}$. Source Edenhofer et al. (2009)

It is important to add that so far 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 stabilisation scenarios. Indeed, it could turn out that the costs of low stabilisation, incorporating all these factors, would be at the upper end of the numbers shown in Figure 11.9.
CCS

Without use of CCS, the low stabilisation target cannot be attained by any of the models. Limiting the CCS potential to 120 GtC (ccsmin) allows the target to be achieved but at high cost. In MERGE and REMIND, mitigation costs increase accordingly by about 1 percentage point which equates to a doubling of the costs in REMIND. Since additional costs of CCS, such as investments in regulatory frameworks regarding health, safety, and environmental risks, are not included in the models, the full costs certainly could be even higher than shown here.

Nuclear power

When limiting the use of nuclear power to the baseline values, costs increase only moderately for REMIND and do not increase at all for MERGE and POLES. Hence, the nuclear option is less important than renewables or CCS. This is due partly to the fact that nuclear energy is already attractive in the baseline scenario but cannot be further extended due to limited uranium resources (in MERGE and REMIND). An additional nuclear phase-out scenario, with no investment in nuclear power generation after 2000, raises costs 0.5 percentage points in MERGE, 0.1 percentage points in REMIND, and 0.7 percentage points in POLES. Therefore, at least in MERGE and POLES, the use of nuclear power is important in the baseline.

Two models also explore the option of implementing a fast breeder. With it, costs can be reduced by 0.3 percentage points for MERGE and 0.1 percentage points for REMIND compared with the standard scenario without this option. These benefits should be balanced against the increased risk of proliferation, safety, and more nuclear waste.

Overall, MERGE, REMIND and POLES provide similar assessments of the value of the individual technology options. Three key findings emerge that are shared by all three models: (i) renewables and CCS are the most important options because the 400ppm target is not feasible, and the 550ppm target is very expensive, without them; (ii) the biomass potential dominates costs under low stabilisation; and iii) nuclear energy is dispensable as a mitigation option as the 400ppm target remains feasible and mitigation costs increase only slightly when nuclear power is kept at its baseline level.
However, nuclear power is important up to the extent of its use in the baseline. A more detailed analysis of the option values and a comparison of the 550ppm with the 400ppm scenario are given in Edenhofer et al. (2009).

11.4 Spotlight on the EU: necessity and feasibility

Previous sections conclude that low stabilisation is feasible technologically and also economically from a global perspective. In this Section we will put the spotlight on the EU27 region to show how mitigation policy might be implemented in Europe. We first show top-down results from the model comparison introduced in the last sections for EU27 and then we present a disaggregated sectoral analysis of the 400ppm low stabilisation scenario.

11.4.1 Top-down analysis: Energy mix and mitigation costs

We now explore the regional results from the different models. The energy mix for the EU27 is shown in Figure 11.10. Although the energy mix differed greatly by model for the WORLD region (see Figure 11.4), for Europe the baseline is very similar for all models except E3MG. The strategies of decarbonisation for Europe, however, differ among the models. They revolve around reduction of energy use and implementation of CCS and appreciable expansion of renewables in only two of the five models, MERGE and REMIND. TIMER and REMIND concentrate on the use of CCS, whereas the mitigation solution in POLES involves greater use of biomass relative to baseline. In E3MG, the large increase in energy use is due to the assumed GDP growth rates and fossil fuel price increases raising the demand for energy so that renewables increase substantially in the baseline.
Figure 11.10: Energy mix for Europe (EU27) for the baseline (left) and the 400ppm CO$_2$e scenario (right). Note that MERGE reports results only for EU15. Note the different scale for E3MG. Renewables include solar, wind, and hydro-electric power. For the balancing of renewables we apply the direct use concept. (Colour figures available at the end)
To evaluate the mitigation costs for EU27 in relation to the other world regions, we applied an emission trading scheme to three of the models, where emission permits for each region are allocated according to a contraction and convergence scheme (see Figure 11.11). The associated costs for this transition in all three models are lower for EU27 than for WORLD.

China reports much higher costs than the world average in two of the three models. This could be an important sticking point in international negotiations, as China may demand compensation before consenting to incur high mitigation costs.

India faces the highest mitigation costs in MERGE and POLES, and costs for India are higher than the World average in REMIND. In MERGE, Russia benefits substantially from its large biomass potential and can therefore sell emission permits. By contrast, mitigation costs for Russia are higher than the World average in REMIND and POLES. Hence, results are difficult to generalise for developing countries, including ROW.

Costs for the three developed country categories, EU27, USA, and Japan, however, cluster closely together. The United States consistently has the highest costs of the three, but pairwise differences between their costs 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 (not shown here).

![Figure 11.11: Regional distribution of mitigation costs for the 450ppm scenario. Results are shown for a contraction & convergence allocation scheme with full emission trading. Note that MERGE reports results for EU15.](image-url)
11.4.2 Bottom-up analysis for residential & service, industry and transport sectors

We used POLES to provide a detailed bottom-up sectoral analysis of the 400ppm stabilisation scenario until 2050 (Jochem et al., 2009). Final demand in all energy sectors in Europe differs from the baseline to the mitigation scenario through additional energy conservation and more efficient energy use in mitigation (see Figure 11.12, left). While projected European final energy demand increases by one third to about 70 EJ in 2050 in the baseline, in the 400ppm scenario it peaks in 2020 and then decreases slightly to 50 EJ in 2050, which is less than the level in 2000.

In the baseline scenario, final energy demand rises slowly in two of the three sectors identified in Figure 11.12. However, it declines slightly in the transportation sector through substantial improvements in energy efficiency and stagnating population. This decline arises despite continued growth in GDP.

Several factors may contribute to energy demands decreasing in the second half of this century, as projected in nearly all models’ baselines shown in Figure 11.10. They include saturation with energy-using equipment, a levelling-off in standards of personal comfort, limited time-budgets for personal transport, and significant oil price increases. Stricter technological efficiency standards for buildings, electrical appliances, and road vehicles, and structural change toward less energy-intensive industry branches and service sectors also play a role in lowering energy demand. The absolute decline of fuel demand in the transport sector after 2020 may suggest that Europe will soon be entering a second phase of increased energy efficiency, following that for stationary energy services. Electricity is the only energy carrier which continues to grow by some 1.5 percent annually, and still at 1.1 percent per annum between 2030 and 2050.

In the 400ppm CO₂e scenario, climate policies have a marked impact on European final energy demand in all sectors (see Figure 11.12, right). Industrial energy demand continues to increase, but at a slower pace. Energy demand of the transport and residential & service sectors decreases after 2020 to 38 percent and 74 percent respectively by 2050, compared with the corresponding energy demand in the baseline (see Figure 11.12). In the transport sector, new propulsion technologies and lighter vehicles advance the development of cleaner cars. The stock effects, due to economic longevity of capital assets, are less important than for buildings. Due to the impact of higher oil prices, conventional cars steadily lose market share against hybrid, electric, hydrogen, and hydrogen fuel cell technologies after 2020, even in the
baseline scenario. In the 400ppm stabilisation scenario, these changes in the market for transport fuels occur more rapidly. In the industry sector, advanced technologies such as waste heat recovery, small cogeneration, new processes based on physicochemical techniques and bio-technology, and advances in recovering brake energy by power electronics contribute to efficiency improvements in the stabilisation scenario.

In Europe, the largest reductions in per capita energy demand occur in thermal uses in residential and non-residential buildings (see Figure 11.13). In the baseline, this particular demand trajectory is flat because the effects of increased energy efficiency driven by higher fuel prices roughly offsets the use of more floor area per capita. Price incentives are too weak to trigger much development of low-energy and passive buildings, so their market share remains small. By contrast, results from the 400ppm CO$_2$ equivalent scenario incorporate strong growth in the construction of low-energy or passive buildings, lifting their share to 40 percent of the building stock by 2050. Current experience in many countries, particularly in the north of Europe, indicates that such buildings use only one tenth to one half as much energy per unit as the existing European building stock. Investments in zero-energy or even positive-energy buildings, for example, with integrated solar PV panels, are also factored in.
On the other hand, per capita demand for electricity in the European residential and service sectors increases almost proportionally with per capita GDP in the baseline and even in the 450ppm stabilisation scenario (see Figure 11.13). In this scenario, the impact of higher energy efficiency is offset in part by additional electricity demands for ventilation systems and heat pumps for low-energy and passive buildings. The net result is only a slight decrease in per capita electricity demand or electricity intensity compared to the baseline scenario (see Figure 11.13).

The transformation in the energy system directly affects the energy-related CO₂ emissions. Without any climate policy, greenhouse gas emissions would increase 1.3-fold in Europe (see Figure 11.14, left). Regarding energy-related CO₂ emissions in the stabilisation scenario, ambitious climate policies could cause European CO₂ emissions to peak at about 4.2 Gt CO₂ around 2020 and thereafter impose a decrease of about three percent annually to some 0.9 Gt CO₂ in 2050 (see Figure 11.14, right). This is about one fifth of the current level of CO₂. All sectors contribute to this decline in emissions, but the major contribution comes from electricity generation in the energy producing ‘transformation’ sector in Figure 11.14. This is
due to the rapidly rising use of renewables and CCS technologies in power generation and coke ovens, and the use of nuclear energy in some European countries.

Figure 11.14: European energy-related CO\textsubscript{2} emissions by energy sector in GtCO\textsubscript{2}, for the baseline (left) and the 400ppm scenario (right) for 2000 to 2050. Source: Jochem et al., 2009.

11.5 Conclusions

This Chapter shows that it is likely that the 2°C target embraced by the EU will be achievable, at moderate costs, if the full suite of technologies is available and effective policy instruments are applied. The model comparison identifies a number of different pathways by which a low stabilisation target of 400ppm 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 giving rise to some loss of flexibility in the choice of technologies to achieve the more ambitious climate protection targets.

From the top-down global perspective, the most important mitigation options are biomass, CCS, and renewables (wind, solar, and hydro-electric power). Nuclear power turns out to be a less important option for mitigation. The bottom-up analysis for Europe points to improving energy productivity and substituting renewables for fossil fuels as the most promising approaches to achieving a sustainable energy system in Europe until 2050. Improvements in energy efficiency and using fossil fuels substitutes would create new economic opportunities, reduce energy import dependency, enhance human welfare, and reduce energy costs and greenhouse gas emissions. Europe has an significant opportunity to improve energy productivity, with substantial benefits for both its own economy and the global climate.
Although some policy measures and markets function best with global participation on shared terms, there can be many pathways to a carbon-free economy. Countries or entire regions can choose those approaches to decarbonisation best suited to them. Further modelling work could usefully explore extreme scenarios that place disproportionate reliance, say, on renewables or nuclear power. This would allow deeper analysis of the national or regional context-specificity of alternative low-carbon technologies and mitigation options.

One approach would be to seek better integration of top-down with bottom-up models when assessing the technical feasibility and implications of mitigation. In addition, each portfolio of mitigation options has social and economic consequences that are not fully captured in quantitative models, and these would need to be assessed with other methods. Thus extensive use of biomass, wind, solar or nuclear power would have to be investigated in terms of attitudes to risk, other aspects of social and political acceptance, and delayed dynamic effects in society.

Finally, model results do not normally consider barriers to the timely implementation of optimal policies with the best technical instruments. Moreover, significant energy efficiency improvements would require the implementation of new technologies and need policy instruments to stimulate this development. Calculating option values for policy instruments, i.e. analysing the impact of single policy measures, would be an important next step in informing policymakers and the public about the cost of ruling out any particular measure in the efficient set. Such evaluations could enable the re-examination of pre-existing obstacles and political taboos that may conceivably be overcome.

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Global Energy mix for the baseline, the 550ppm and the 400ppm scenario (from left to right) for the five models MERGE, TIMER, POLES, REMIND and E3MG (from top to bottom). Note that biomass is listed separately and not as part of renewables which only include energy from solar, wind, and hydro. In E3MG biomass includes combustible waste (about 80 percent of the total biomass use) such as primary solid biomass used for heating in the residential sector in developing countries.
Energy mix for Europe (EU27) for the baseline (left) and the 400ppm CO$_2$-eq scenario (right). Note that MERGE reports results only for EU15. Note the different scale for E3MG. Renewables include solar, wind, and hydro.