Technology options and effective policies to reduce greenhouse gas emissions and improve security of supply

Final report CASCADE MINTS Part 2

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Abstract
A more sustainable energy system requires a portfolio of innovative technological options. The problems faced by Europe and the world are of a magnitude for which no single technology is the solution. Some of the options benefit both the climate problem and security of supply, and thus provide synergies, while others represent trade-offs for the policymaker. This report presents results of Part 2 of the CASCADE MINTS project. In this project, 15 renowned modelling teams in Europe, the US and Japan have provided an outlook to possible transitions of the energy system in Europe and at the global level. The objective of this project was to use a wide range of existing operational energy and energy/economy models in order to build analytical consensus concerning the impacts of policies aimed at sustainable energy systems. The emphasis is placed on evaluating the effects of policies influencing technological developments. Technologies assessed are renewables, nuclear power, CO_2 capture and storage and hydrogen. There are synergies and trade-offs when applying these options for the main policy objectives of climate change mitigation and improving security of supply. This report provides a synthesis of the various policy briefs that were written for each of the individual transition pathways.

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Summary

A more sustainable energy system requires a portfolio of innovative technological options. The problems faced by Europe and the world are of a magnitude for which no single technology is the solution. Some of the options benefit both the climate problem and security of supply, and thus provide synergies, while others represent trade-offs for the policymaker. This report presents results of Part 2 of the CASCADE MINTS project. In this project, 15 renowned modelling teams in Europe, the US and Japan have provided an outlook to possible transitions of the energy system in Europe and at the global level. The objective of this project is to use a wide range of existing operational energy and energy/economy models in order to build analytical consensus (to the extent possible) concerning the impacts of policies aimed at sustainable energy systems. The emphasis is placed on evaluating the effects of policies influencing technological developments. This report provides a synthesis of the various policy briefs that were written for each of the individual transition pathways.

Main objective of the approach chosen was to perform a synthesis of the policy cases analyzed by various models. Some of these models have comparable methodologies and scope, while others complement each other, such as economic models and energy system models. Next, consensus among the modellers has been sought concerning the results presented and the main policy messages. The policy briefs bundled in this report reflect the consensus found over different policy cases. Although all models confirm these messages, there are sometimes significant differences among individual model results, reflecting the different dynamics and assumptions and indicating the impact of uncertainties in the future energy system. The graphs show projections from different models, and should be regarded as illustrative of the discussed trends, by no means the only possible paths.

Baseline
This final report gives an overview of all policy cases analysed in the project. Part 2 of the project has started with formulating a common baseline projection. Given the diversity of the models, a moderate level of harmonisation was chosen. A number of quantitative assumptions - economic and demographic developments, oil prices and current policies - have been harmonised, whereas technology-specific assumptions have not been harmonised. A consistent basis for harmonisation of a baseline scenario was provided by the SRES ‘B2 marker scenario’ (IPCC, 2000). Oil prices reflect assumptions of low to moderate resource availability. In the period 2000-2050, the world oil price is projected to increase from ca. 26 to 38 $US\$_{95}$/barrel (4.2 to 6.2 €/GJ). Obviously there is a great deal of uncertainty to this assumption. Natural gas prices within Europe, although not explicitly harmonised among the models, are projected to increase from on average 2.3 to 5.4 €/GJ in 2000-2050. Finally, some representation of climate policy or emission trading for the region of Europe has been included, reflected in a generic carbon tax of 10 €/tCO_2 from the year 2012 onwards.

Because other important driving forces, such as technological change and average improvement of energy efficiency, were not harmonised, the set of baseline results from CASCADE MINTS is broader than the B2 group of scenarios. The added value of these variations is that they reflect uncertainty about future developments. Moreover, the diversity of the models will provide different views on the effectiveness of the policy approaches.

Renewables
Next, the role of renewables in solving global and European energy and environmental issues has been analysed. The feasibility of a 20% renewables target in 2020 for Europe has been assessed, and seems to be within reach provided energy demand reductions are pursued simultaneously. Bioenergy is one of the key renewable options because of its large potential and its different possible applications. A strong growth of biomass deployment is required for achieving ambitious renewables and climate targets. Policies in different areas such as energy, agriculture, and environment should be further streamlined in order to overcome current barriers. Efforts di-

rected towards the transport sector combine several benefits, because the substitution of oil with biofuels improves both security of supply and reduces carbon emissions. Implementation of renewables is currently most straightforward in the power and transport sector, but to achieve further growth towards 2020, applications should involve other end-use sectors. For instance the potential in the building sector, including renewable heating and cooling options, such as solar thermal water heaters or biomass-based district heating should be further exploited. Finally, subsidy schemes should offer differentiated support and stimulate learning effects. It is important to target the subsidies correctly. If only one sector is subsidized, the renewable share in this sector will be high, but there may be 'carbon leakage' to other sectors, due to a shift in application of biomass, and the share in primary energy is only mildly affected.

Nuclear
Next, the results are presented of an analysis of the conditions under which nuclear power can become environmentally and economically feasible. Two contrasting scenarios have been analysed, comparing the impacts of a phase-out of nuclear power capacities to a situation where conventional nuclear power plants achieve a 25% investment cost reduction, both under a rather strong climate policy. Two main conclusions can be drawn. First, the analyses have shown that a nuclear phase-out in Europe is feasible, even in a future with a strong climate policy. However, in this case, renewables, natural gas and advanced coal-fired plants with CCS are key options, and achieving climate goals is more costly. Consequently, the dependency on natural gas imports would increase even further than already expected in a business as usual scenario. Secondly, nuclear energy could be an important component of carbon mitigation strategies, under the condition that the risks related to reactor safety and proliferation are dealt with or accepted, and that long-term solutions for the disposal of radioactive waste are found. With the assumption that carbon prices reach a level of 100 €/tCO_2 in 2030, nuclear power plants could marginally reduce the import dependency of natural gas, and could contribute to up to 50% of Western Europe's power generation mix.

CO_2 capture and storage
CO_2 capture and storage (CCS) is increasingly mentioned as one of the options in the portfolio to mitigate climate change. Three policy approaches have been compared in order to address the question how to achieve significant CO_2 emission reductions through the application of CCS technologies. The analysis shows that CCS can provide an important contribution to mitigating climate change. Up to 30% of global CO_2 emissions could be captured in 2050, while for Europe, due to a more limited growth of the power sector than in some other world regions, this would amount to some 22% of total CO_2 emissions. Furthermore, the application of CCS is essential for a successful market introduction of fossil-based hydrogen in a carbon constrained world.

Trade-offs and synergies
In this case study the possible role and impact of enhanced technological progress in the energy system has been analysed, combined with variations of CO_2 values and oil & gas prices. It concludes that the global energy system can meet the challenge of a strong climate policy, with carbon prices up to 100 €/tCO_2, through a mix of options. In the power sector, penetration of renewable and nuclear technologies up to 50% combined with the deployment of CO_2 capture and storage can result in emission reductions up to 40%. Similarly, in Europe, CO_2 emissions can be reduced with 21% - 54% in 2050. This range among the models is largely due to the uncertainty around the future contribution of coal, as it depends on the estimates for costs and potential for CCS. The implications of high oil and gas prices are not necessarily environmentally favourable, as there is a tendency towards coal, even though renewables also benefit. The additional effect of enhanced technological progress is strongest in the transport sector, where it can stimulate hydrogen, but also biofuels, to reduce the dominance of petroleum-based automotive fuels. Enhanced technological progress - modelled in terms of investment cost reductions due to additional R&D policies - appears to have the most significant impacts on hydrogen production, storage and consumption and on the use of renewables (wind and solar PV) for power generation.

1. Introduction

This report presents results of Part 2 of the CASCADE MINTS project. In this project, 15 renowned modelling teams in Europe, the US and Japan have provided an outlook to possible developments in Europe and at the global level. The objective of this project is to use a wide range of existing operational energy and energy/economy models in order to build analytical consensus (to the extent possible) concerning the impacts of policies aimed at sustainable energy systems. The emphasis is placed on evaluating the effects of policies influencing technological developments.

The CASCADE MINTS project also involves modelling, scenario evaluation and detailed analysis of the prospects of the hydrogen economy. This is done in Part 1 of the project, as depicted in Figure 1.1. The ultimate aim of this part of the project is to enable perspective analysis of the conditions under which a transition to an energy system dominated by hydrogen is possible.

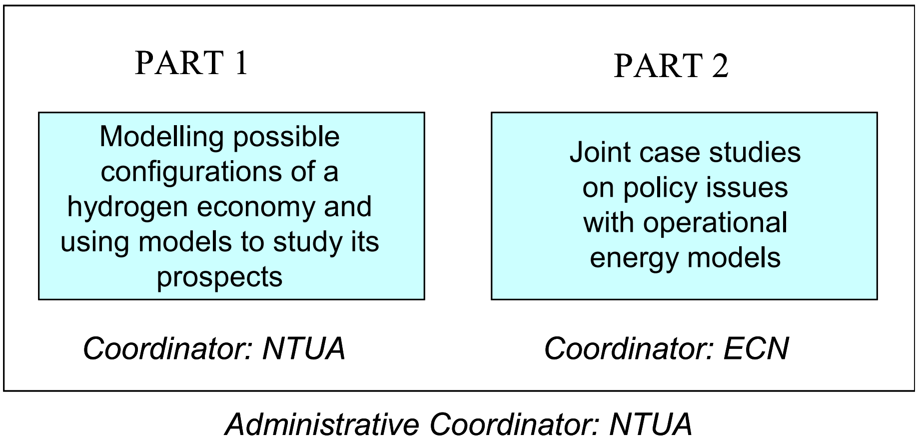

Figure 1.1 *Overview of the CASCADE MINTS project*

1.1 Approach

In CASCADE MINTS Part 2, the approach has been chosen to make syntheses of the policy cases analysed by different models. Some of these models have comparable methodologies and scope, others complement each other, such as economic models and energy system models. Next, consensus among the modellers has been sought concerning the results presented and the main policy messages. The policy briefs bundled in this report reflect the consensus found over different policy cases. Although all models confirm these messages, there are sometimes significant differences among individual model results, reflecting the different dynamics and assumptions and indicating the impact of uncertainties in the future energy system. The graphs presented in the policy briefs show projections from different models, and should be regarded as illustrative of the discussed trends, by no means the only possible paths.

1.2 Overview of participating models

As a background to the description of the model results, Table 1.1 gives an overview of the models involved, classified along their methodology. Generally, energy system models have a detailed technology representation and these have been used to analyse the impact of CCS technologies. Still, a variety of methodologies, including ‘hybrid’ modelling approaches is represented. The equilibrium models participating in the case study have made use of the results of one of the energy system models. Note that not all of the models have participated in all policy cases. More information on the models can be found in (Uyterlinde et al., 2004).

Table 1.1 *Overview of the models participating in the CASCADE MINTS project*

<table>
<tr><th></th><th colspan="2">Top down</th><th colspan="2">Bottom up</th></tr>
<tr><th></th><th>Macro-economic</th><th>Computable General Equilibrium</th><th>Energy System Optimisation</th><th>Integrated Energy System simulation</th></tr>
<tr><td rowspan="2">Global,
US, Canada</td><td rowspan="2"></td><td rowspan="2">AIM
NEWAGE-W
PACE</td><td>DNE21+
ETP
GMM
MESSAGE</td><td>POLES
NEMS
MAPLE</td></tr>
<tr><td colspan="2">PROMETHEUS
(stochastic)</td></tr>
<tr><td>Europe</td><td>NEMESIS</td><td></td><td>MARKAL Europe
TIMES-EE</td><td>PRIMES</td></tr>
</table>

1.3 Report overview

Baseline

This final report gives an overview of all policy cases analysed in the project, as illustrated in Figure 1.2. Part 2 of the project has started with formulating a common baseline projection. Given the diversity of the models, a moderate level of harmonisation was chosen. A number of quantitative assumptions - economic and demographic developments, oil prices and current policies - have been harmonised, whereas technology-specific assumptions have not been harmonised. A consistent basis for harmonisation of a baseline scenario was provided by the SRES 'B2 marker scenario' (IPCC, 2000). Oil prices reflect assumptions of low to moderate resource availability. In the period 2000-2050, the world oil price is projected to increase from ca. 26 to 38 $US\$_{95}$/barrel (4.2 to 6.2 €/GJ). Obviously there is a great deal of uncertainty to this assumption. Natural gas prices within Europe, although not explicitly harmonised among the models, are projected to increase from on average 2.3 to 5.4 €/GJ in 2000-2050. Finally, some representation of climate policy or emission trading for the region of Europe has been included, reflected in a generic carbon tax of 10 €/tCO_2 from the year 2012 onwards.

Because other important driving forces, such as technological change and average improvement of energy efficiency, were not harmonised, the set of baseline results from CASCADE MINTS is broader than the B2 group of scenarios. The added value of these variations is that they reflect uncertainty about future developments. Moreover, the diversity of the models will provide different views on the effectiveness of the policy approaches. Chapter 2 presents the main results and conclusions of the baseline analysis. More information can be found in (Uyterlinde et al., 2004).

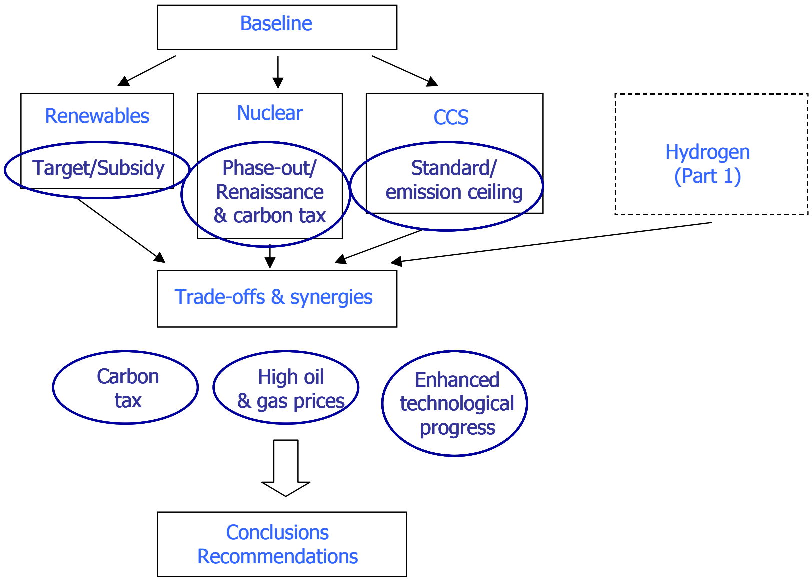

Figure 1.2 *Overview of the policy cases and policy instruments analysed in CASCADE MINTS Part 2*

Renewables
Next, the role of renewables in solving global and European energy and environmental issues has been analysed. The feasibility of a 20% renewables target in 2020 for Europe has been assessed. The main conclusion, as described in Chapter 3 of this report, is that renewable energy can make a substantial contribution to reducing greenhouse gas emissions and improving diversification of the European energy production portfolio, although other technologies will also be needed in order to achieve post-Kyoto targets. See also (Uyterlinde et al., 2005) for a complete account including the results of the individual models.

Nuclear
Chapter 4 assesses the conditions under which nuclear power can become environmentally and economically feasible. Two contrasting scenarios have been analysed, comparing the impacts of a phase-out of nuclear power capacities to a situation where conventional nuclear power plants achieve a 25% investment cost reduction, both under a rather strong climate policy. The complete report has been published separately (Uyterlinde et al., 2006a).

CO_2 capture and storage
CO_2 capture and storage is increasingly mentioned as one of the options in the portfolio to mitigate climate change. Based on the results of 10 advanced energy models, Chapter 5 provides an overview of the results of the scenarios analysed in the CASCADE MINTS project. Three policy approaches are compared in order to address the question how to achieve significant CO_2 emission reductions through the application of CCS technologies. The analysis shows that CCS can provide an important contribution to mitigating climate change. Up to 30% of global CO_2 emissions could be captured in 2050, while for Europe, due to a more limited growth of the power sector than in some other world regions, this would amount to some 22% of total CO_2 emissions. The complete report has been published as (Uyterlinde et al., 2006b).

Trade-offs and synergies
Chapter 6 analyses the possible role and impact of enhanced technological progress in the energy system, combined with variations of CO_2 values and oil & gas prices. The complete report has been published as (Uyterlinde et al., 2007). It concludes that the global energy system can meet the challenge of a strong climate policy, with carbon prices up to 100 €/tCO_2, through a mix of options. In the power sector, penetration of renewable and nuclear technologies up to 50% combined with the deployment of CO_2 capture and storage can result in emission reduc-

tions up to 40%. Similarly, in Europe, CO_2 emissions can be reduced with 21%-54% in 2050. The contribution of coal remains uncertain, as it depends on the estimates for costs and potential for CCS. Secondly, the implications of high oil and gas prices are not necessarily environmentally favourable, as there is a tendency towards coal, even though renewables also benefit. The additional effect of enhanced technological progress is strongest in the transport sector, where it can stimulate hydrogen, but also biofuels, to reduce the dominance of petroleum-based automotive fuels. Third, enhanced technological progress - modelled in terms of investment cost reductions due to additional R&D policies - appears to have the most significant impacts on hydrogen production, storage and consumption and on the use of renewables (wind and solar PV) for power generation.

Conclusions
Chapter 7 gives an overview of the conclusions and recommendations by individual models. Finally, in Chapter 8, the overall conclusions and findings from the case studies are generalized and summarized.

2. Baseline trends for Europe in a global perspective

In the coming decades, Europe's energy system is facing a number of challenges. Some of these, such as the enhanced greenhouse effect and depletion of fossil fuel resources have a worldwide dimension. Consequently, the strategies for tackling these issues must be designed taking worldwide developments into account. Alternative energy sources and new technologies will have to play a key role. In the analysis of the potential impact of new technologies and the evaluation of possible policy options, energy - economy - environment (E3) models can provide useful insights. In the CASCADE MINTS project, twelve of these E3 models have been used to evaluate possible developments of the world energy system and the implications for Europe.

This policy research comes at a time when the EU has started a reflection on the actions on climate change for the post-2012 period[1], especially considering the benefits and costs and taking into account both environmental and competitiveness concerns.

The policy brief provides an outlook on global and European energy developments towards 2050, summarising the main results generated by these models (Uyterlinde et al., 2004). It reflects the scientific consensus among modellers concerning the baseline presented and the main policy messages included in this brief. Although all models confirm the major trends, there are sometimes significant differences among individual model results, reflecting the different dynamics and assumptions and indicating the impact of uncertainties in the future energy system. The graphs, presented in this policy brief, show projections from different models, and should be regarded as illustrative of the discussed trends, by no means the only possible paths. The models used in the baseline projections are: PRIMES, PROMETHEUS, MARKAL, MESSAGE, POLES, GMM, PACE, TIMES-EE, NEWAGE-W, NEMESIS, NEMS and DNE21+.

2.1 Developments against a background of moderate economic growth

The outlook is based on a common, harmonised baseline scenario. The baseline will serve as a benchmark against which policy scenarios will be compared in later stages of the project. It is based on the B2 scenario from the IPCC Special Report on Emissions Scenarios, because this scenario is characterised by a moderate economic and demographic growth. Some assumptions of major importance in this scenario are listed below.

[1] See http://europa.eu.int/comm/environment/climat/future_action.htm.

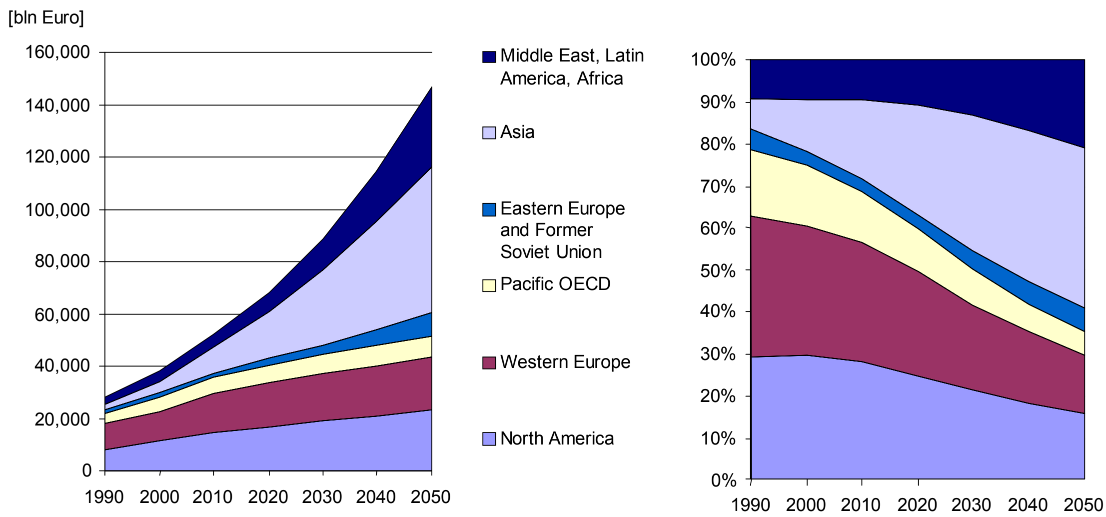

Figure 2.1 *Development of GDP per region and share of these regions in world GDP*

In all regions of the world, the average GDP growth in the period 1990-2050 is lower than in 1950-1990. Asia shows by far the highest growth, while the economies in Western Europe, North America, Japan and Australia grow at a lower pace than the other world regions. This increasing dominance of the developing countries has a direct impact on energy consumption and greenhouse gas emissions. Despite the economic 'catch up', income differences between industrialised and developing countries remain significant.

Population growth is in line with current population trends and based on the UN median population projections from 1998. Global population increases to about 9.4 billion people by 2050. Population growth is highest in the developing countries in Africa, Latin America, and the Middle East. It is significantly lower in Asia and North America, whereas the population of both Europe and the Former Soviet Union remains almost constant until 2050.

Oil prices reflect assumptions of low to moderate resource availability. In the period 2000-2050, the world oil price is projected to increase from 4.2 to 6.2 $€_{2000}$/GJ, which is equivalent to a range of ca. 26 to 38 $US\$_{95}$/barrel. Obviously there is a great deal of uncertainty to this assumption.

Only instrumented policies in force or approved on December 31st 2003 have been included in the baseline scenario. Moreover, some representation of climate policy or emission trading for the region of Europe has been included. This is reflected in a generic carbon tax of 10 $€_{2000}$/tCO_2 as from the year 2012.

2.2 A continuing worldwide reliance on fossil fuels

World primary energy consumption is expected to more than double in 2000-2050. This is a consequence of the assumptions regarding moderate economic and population growth, implying that a larger growth would also be possible. In line with the assumptions, Asia grows fastest, and quadruples its energy consumption by 2050.

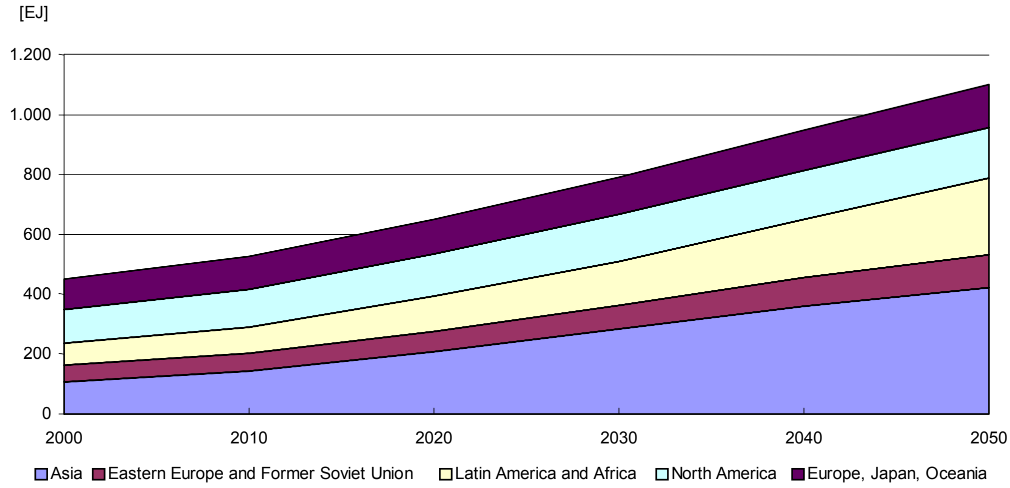

Figure 2.2 *Development of primary energy consumption by regions*

All models indicate that fossil fuels are expected to remain dominant in the world fuel mix by supplying 65-80% of primary energy use (Figure 2.3). Combined with the growth in primary energy consumption, this will result in an even faster depletion of the global natural resources than today. Although Europe's primary energy consumption shows a much slower growth than the world average - some 20% until 2030 - its reliance on fossil fuels (70-75% of the primary energy mix, depending on the model), is comparable to the rest of the world.

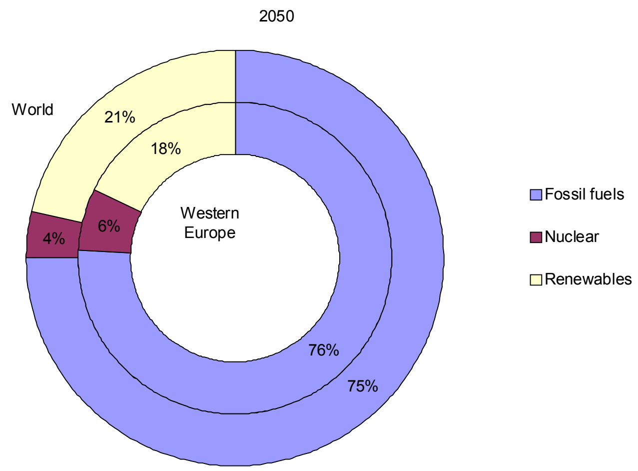

Figure 2.3 *Fuel mix of primary energy consumption in the world and Western Europe, 2050*

Although the models show a consistent picture of the share of fossil and non-fossil fuels in future primary energy mix, they deviate on the contributions of individual fuels. In Europe, particularly the prospects of solid fuels and nuclear energy differ, due to different assumptions on technological development and costs. The power generation sector plays a key role in these fuel and technology choices. Coal consumption is expected to stabilise or grow. Some models expect nuclear energy to be phased out, due to high costs. There is a certain consensus on Europe's consumption of natural gas for power production, which is expected to increase significantly, and on the moderately increasing consumption of oil, mainly in the transport sector. Developments of energy prices may play a key role here.

On world level, a similar variation in projections exists. One of the models includes constraints on sulphur emissions, which induce a smaller share of particularly solids, and a substitution with nuclear and renewables.

These observations have the following implications for Europe:

- Europe will encounter more competition on increasingly scarce fossil resources. Given the limited domestic resource base, the growing dependency on imported fuels, particularly oil and natural gas, will bring about more risks of high prices and supply disruptions.
- The differences in projections of the primary energy mix indicate that there is room for fuel switch, particularly in the power sector. The results indicate that the future development of use of energy sources may substantially be influenced by policies, such as emissions regulations and stimulating non-fossil fuels. Moreover, high oil and gas prices might accelerate changes in Europe's energy mix.

2.3 Energy savings increasingly important

Europe's energy intensity is among the lowest in the world. In the current baseline projections, Europe is expected to maintain this leading role. However, as illustrated in Figure 2.4, the scope for further efficiency improvements is more limited than in other world regions. On the other hand, Europe's energy consumption per capita is more than twice the world average, and keeps increasing. The increasing trend is in line with developments in other world regions.

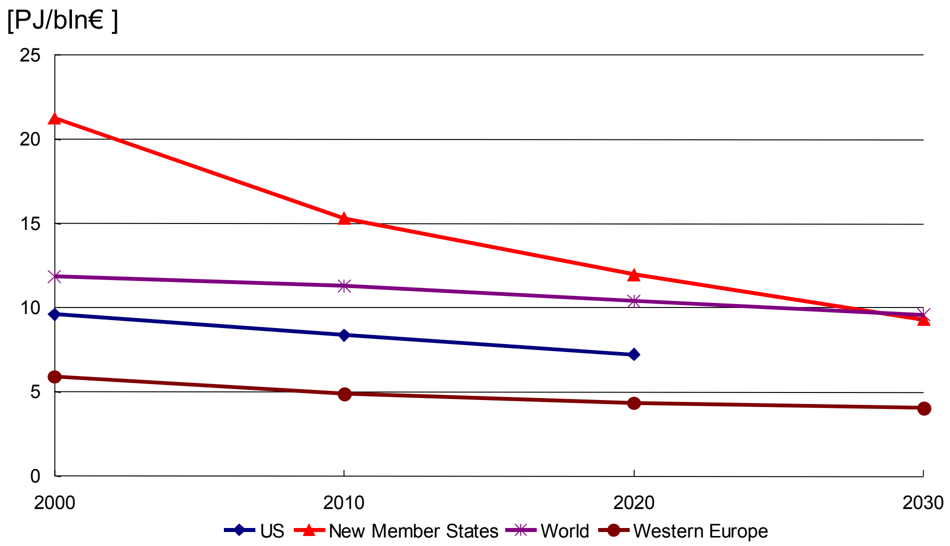

Figure 2.4 *Europe's energy intensity of GDP compared to other world regions*

- Recognising that Europe's energy consumption is substantial but relatively efficient, policy measures should focus on stimulating energy savings in order to slow down the steady growth in energy consumption of the average European citizen.

2.4 Security of supply becomes a key issue

Given the continuing global reliance on fossil fuels, an important issue in the years to come will be the increasing dependence on oil from the Middle East. Although the models show different projections of the evolvement of oil production, they agree that the contribution from the Middle East region grows, and becomes substantially larger. Given the large uncertainty on future oil price developments, confirmed by one of the models indicating that there is a substantial probability of sudden increases in the oil price, this may lead to increased concerns about the security of oil supply on the longer term, particularly in view of the present uncertain political situation in the Middle East.

For Europe, trends are in line with the global developments. Europe's oil consumption is expected to stabilise at about a third of its primary energy consumption in 2030. Domestic production however is expected to decrease due to limited reserves and high production costs, thereby introducing a greater reliance on imports up to 85% (Figure 2.5).

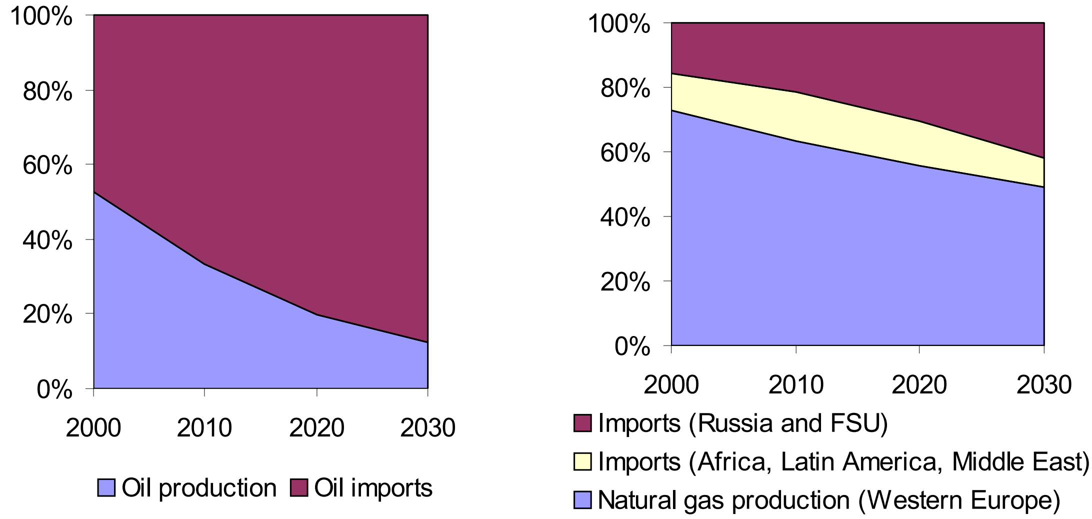

Figure 2.5 *Shares of production and imports of oil and natural gas (Western Europe)*

For natural gas, Europe's external dependency will also grow in the next decades. A continuing growth in gas consumption combined with a decrease of gas production in the UK, the Netherlands and Norway, will lead to a higher share of imports from the two main suppliers Russia and Algeria. Additionally, the accession of the new Member States and their heavy reliance on supplies from Russia increases the risks related to gas supply security.

There is another dimension to security of supply than dependency on imported fuels. The level of diversification is inversely related to the dependence on a few primary fuels, and is related to the correlation between the fuels in terms of costs and availability. The level of diversification may further influence the sensitivity of Europe to fuel supply disruptions.

- Europe's dependence on oil from the Middle East is expected to increase significantly in the next decades. Given the prospect that other world regions will also increasingly rely on oil from this region, this may indeed lead to further oil price increases, which will affect all economic sectors.
- An increase in diversification - for instance a growing contribution from renewables - may to a certain extent alleviate the increase in external dependence for oil and gas. In the current analysis, the models show large differences in their projections of Europe's future fuel mix, and thus in the expected level of diversification. This suggests that new policies may be required to stimulate an increased uptake of renewables or other sources.

2.5 The challenge of climate change remains

It is highly likely that global warming is attributable to human activities, in particular to emissions of greenhouse gases. All models project a continuing growth of these emissions, of which CO_2 is the most important one. Overall, the CO_2 emissions in 2030 are expected to be approximately twice the level of 1990, the base year of the Kyoto protocol. The largest growth is expected to occur in the developing world, in particular in Asia. There is a large variation in emissions projections between models, related to the differences in the primary energy mix, particularly the share of fossil fuels. These differences are due to different assumptions on technological development and the associated technology costs.

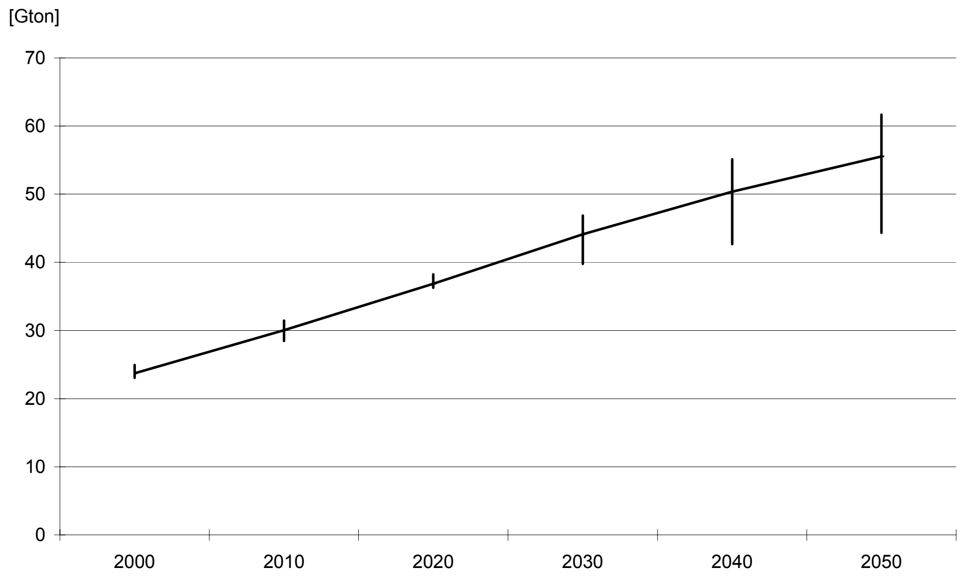

Figure 2.6 *Range among models in average energy related CO_2 emissions projections*

In Europe, CO_2 emissions grow moderately, when compared to trends at world level (Figure 2.7). Still, Western Europe is not on track towards the targets agreed under the Kyoto Protocol. Western Europe is committed to achieving an 8% reduction of CO_2 emissions by 2008-2012, as compared to the level in 1990. This means that in this period, the level of total CO_2 emissions (including non-energy uses) should not exceed approximately 3100 Mt/yr. However, all models indicate that the energy-related CO_2 emissions alone are already expected to exceed this level. The carbon tax of 10 €/tCO_2, included from 2012 onwards to reflect the assumption that some type of climate policies will be implemented, does not suffice to curb the growing trend in greenhouse gas emissions.

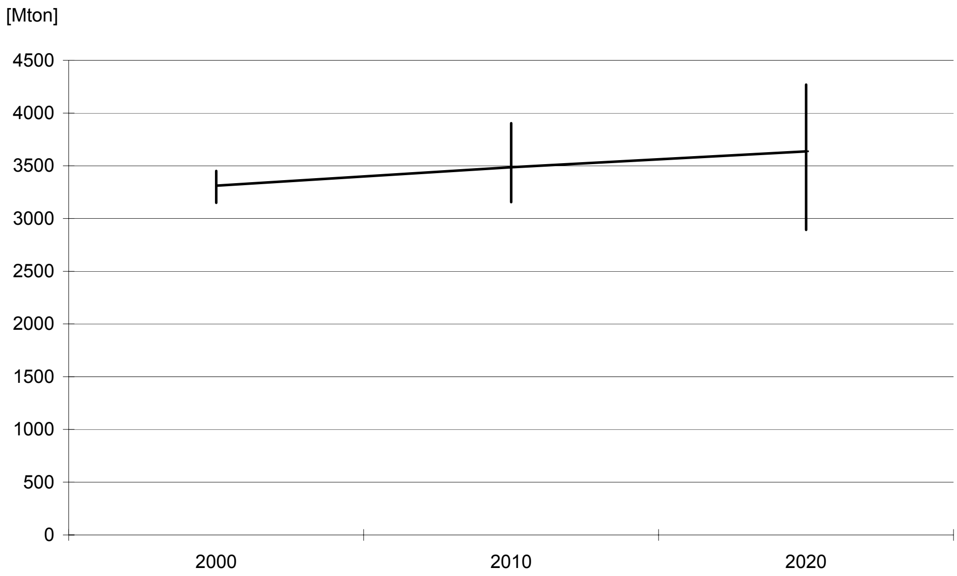

Figure 2.7 *Range among models in average energy related CO_2 emissions projections in Western Europe*

- The results clearly indicate that under current policies, Europe will have severe difficulties achieving its Kyoto target. Therefore, additional instruments, such as emissions trading with countries outside Europe (Annex A), based on the JI and CDM instruments, may have to play a key role in meeting Kyoto commitments.
- Beyond 2012, a moderate carbon tax appears to be insufficient for curbing the trends in Europe, as emissions are expected to continue their growth with some 0.4% annually. In the rest of the world - in the absence of international incentives or regulation for mitigation - carbon emissions are expected to increase at a much higher pace, particularly in the developing countries. Therefore post-Kyoto policies will need to be developed. Given the large inertia in the energy system, short-term action is needed to foster the introduction of advanced and cleaner technologies, in order to enable these technologies to play a significant role in the long term.

3. Renewables can contribute significantly to a future sustainable energy system

This policy brief provides an overview of the main results from the scenarios analysed in the CASCADE MINTS project to assess the role of renewables in solving global and European energy and environmental issues (Uyterlinde et al., 2005). The main conclusion is that renewable energy can make a substantial contribution to reducing greenhouse gas emissions and improving diversification of the European energy production portfolio, although other technologies will also be needed in order to achieve post Kyoto targets. This policy brief outlines the impacts, costs and benefits of ambitious renewables targets for Europe in the medium term. It also presents lessons learned from taking the global perspective. The models used in the projections are: PRIMES, PROMETHEUS, MARKAL, MESSAGE, POLES, GMM, PACE, TIMES-EE, NEWAGE-W, NEMESIS, NEMS and DNE21+. Figures are based on results of different models, and can be regarded as representative of the trends described.

3.1 Impacts on carbon emissions and import dependency

In May 2004, the Commission issued a Communication on 'The share of renewable energy in the EU' (European Commission, 2004), in which it 'acknowledges the importance of providing a longer-term perspective, considering in particular the infant nature of the renewable energy industry and the need to ensure sufficient investors' security. Acknowledging the outcome of the currently available feasibility studies, however, the Commission considers it necessary to more thoroughly assess the impacts of renewable energy resources, notably with regard to their global economic effects before deciding on adopting targets beyond 2010 and before taking a position on the 20% target for the share of renewable energy in 2020'. The CASCADE MINTS project aims at contributing to this impact assessment by analyzing the feasibility and consequences of a 20% renewables share in Europe's primary energy consumption in 2020[2].

3.1.1 Emission reduction in 2020 up to 20%

If the share of renewables in Europe increases to (almost) 20%, the share of fossil fuels in Europe reduces roughly from 75% to 65%, which has positive implications for greenhouse gas emissions and security of supply. In 2010, energy-related CO_2 emissions are some 10% lower than in 1990 (according to PRIMES for the EU-25), indicating that Europe's Kyoto target is within range. In 2020, energy related CO_2 emissions are reduced with 9-21% compared to the baseline. The amount of emission reduction depends on the sectoral distribution of the renewables contribution and on which fossil fuels are substituted. These factors differ by model. Although the reduction is substantial, it is not sufficient for post Kyoto targets, and other mitigation measures must also be explored.

Despite the different regional coverage of the models, the indicators in Figure 3.1 provide comparable information. It confirms the significant impact of the 20% renewables target for Europe. The trend towards lower CO_2 emissions per unit of GDP is further reinforced. For the CO_2 emissions per capita, an increase is converted into a decrease, at least until 2020.

[2] The target is defined according to the Eurostat convention, and would correspond to some 23% in substitution terms.

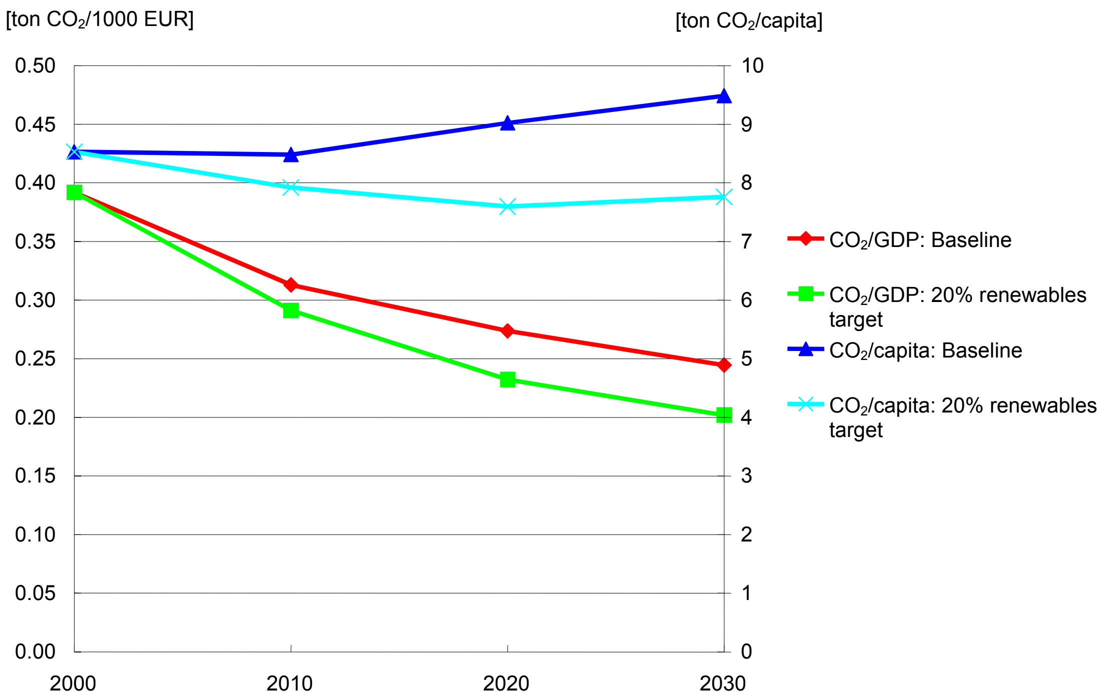

Figure 3.1 *Energy-related CO_2 emissions per capita and per GDP in Europe; averaged over results of POLES (EU-30), PRIMES (EU-25) and MARKAL (Western Europe)*

3.1.2 Positive impact on security of supply

As far as supply security is concerned, the impacts are positive, albeit limited. Only in case of large substitution of oil in the transport sector, import dependency is significantly reduced, as one of the models reports on a reduction of import dependency of 14% points. Regarding gas import dependency, the impact is more modest with 2-4% point reduction in 2020 compared to the baseline, which is not sufficient to counter the increasing trend in this indicator. On the other hand, the diversity of Europe's energy mix, as measured by the Shannon indicator[3], improves with 6-8% points to 76%, indicating that adding renewables helps to reduce future risks.

One of the models (PROMETHEUS) is a probabilistic one, which explicitly deals with uncertainties. It has calculated the probability of gas price shocks under the baseline and under a 33% renewables target in the European power sector in 2020. The model finds a lower probability of gas price shocks in the latter case, due to a higher penetration of renewables worldwide, which is in turn due to learning and spillover effects.

3.1.3 Economic impacts

The costs associated with the renewables targets are in the range of 0.5% of (baseline) GDP. In addition, the economic models show that the costs of renewables may lead to higher electricity prices, and to slower economic growth. On the other hand, welfare implications appear to be limited.

Increased penetration of renewables is often expected to lead to employment gains, because renewables energy production is more labour intensive than conventional energy production, and because it may substitute imported energy. The economic models do not agree on how the re-

[3] An indicator often used to measure species diversity in a community. It reflects not only the number of energy carriers present in the fuel mix, but also the relative abundances of different energy carriers.

newables target in the power sector may affect employment. One model reports a 1.8% overall increase in employment, while another model projects a 0.15% decrease for Europe. The third economic model is based on the assumption of full employment, but does report a clear shift towards employment in renewable electricity production sectors.

Some considerations should be added on how well employment effects can be evaluated with the economic models used in this project. It may be that the direct gains in employment due to the renewables targets are counterbalanced by job losses in other parts of the economy. This crowding out effect can be due to the scarcity of highly skilled labour or to the fact that the subsidies required for supporting renewable energy replace other subsidies. Therefore, net employment effects are strongly related to the structure of the labour market, wage determination and the differences in productivity in different sectors and types of labour force, and should be assessed by dedicated models that incorporate the structure of the labour markets in the different EU Member States, which is beyond the scope of the project.

3.2 How can Europe achieve 20% renewables in 2020?

Under baseline conditions, a 20% share of renewables in Europe's primary energy consumption in 2020 appears to be an ambitious target. Evidence from different models indicates that approximately 18-19% is achievable by 2020, and that it might require a few years more to arrive at 20%. Other studies, e.g. FORRES 2020 (Ragwitz et al., 2004), and 'European energy and transport - scenarios on key drivers'[4] suggest that energy efficiency measures that reduce energy demand growth may help to bring the target timely within range.

3.2.1 Allocation over sectors

If renewables sub-targets for different sectors were to be imposed, the analysis shows that the power sector offers most of the technology switching options. Most of the models demonstrate that a share of 33% renewable electricity consumption is achievable in 2020 (incl. large hydro). However, this should be contrasted with the current expectation that the 21% indicative target for 2010 for the EU-25, as stated in the Renewables Directive (2001/77/EC), will only be achieved if several Member States intensify current support policies.

The transport sector is expected to play an important role for various reasons. First, this is also a sector that offers good opportunities for increased penetration of renewables, e.g. biofuels for transportation. Secondly, the penetration of biofuels has a direct impact on the import dependency for oil, and on CO_2 emissions from transportation, which makes the promotion of biofuels a strategic choice for Europe. However, there may be future bottlenecks due to the limited availability of biomass, and the competition for biomass resources that can be applied both for power generation and converted to biofuels.

Contributions from other sectors will also be required to achieve the 20% target. Imposing a carbon cap on the emissions of the industry sector has shown that this sector does not have much room for a more renewable energy supply. The use of biomass in the industry would be possible, but suffers from competition with applications in the transport sector.

3.2.2 A key role for wind and biomass

Although the models show differences in their projections on which technologies will be necessary to achieve the 20% target in 2020, they agree that 40%-50% of the primary renewable supply is based on biomass, and 20-25% comes from wind energy. Figure 3.2 illustrates that one of the models projects a substantial share of solar energy, largely due to the implementation of so-

[4] http://europa.eu.int/comm/dgs/energy_transport/figures/scenarios/index_en.htm.

lar thermal water heaters. Although the share of hydropower is also significant, the potential for growth is limited to small installations.

Therefore wind energy and biomass will be the strategic options for achieving Europe's renewables targets towards 2020. Beyond that date, other options such as PV, solar thermal electricity, wave and tidal energy may show some penetration.

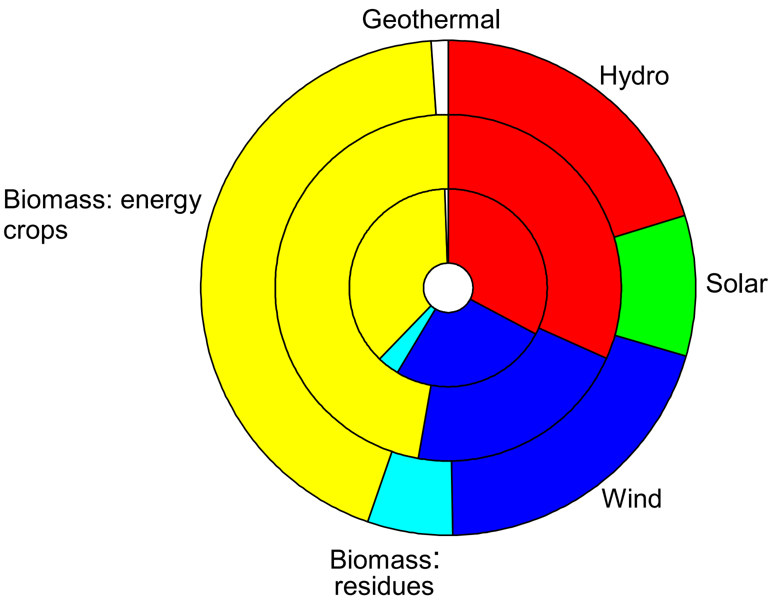

Figure 3.2 *Shares of renewable technologies and resources in Europe's primary energy consumption in 2020; from outer to inner circle: PRIMES, POLES and MARKAL*

Biomass: current stagnation needs to be overcome

The European Commission has set targets involving biomass for renewable electricity generation (Directive 2001/77/EC), and for the promotion of biofuels for transport applications by replacing diesel and petrol up to 5.75% by 2010 (Directive 2003/30 EC). The Communication 'The share of renewable energy in the EU' has concluded that the growth of biomass-based electricity stagnates and further efforts are needed in order to achieve the targets set for 2010. The Biomass Action Plan therefore aims at achieving a total biomass accumulated energy production of 130 Mtoe by 2010.

Against this background, the biomass growth path presented in Figure 3.3 seems even more ambitious, as it implies a further doubling between 2010 and 2020 required for the 20% target. The amounts of biomass deployed appear to be close to their potentials. Only one of the models (MARKAL) assumes imports of biomass (30% in 2020).

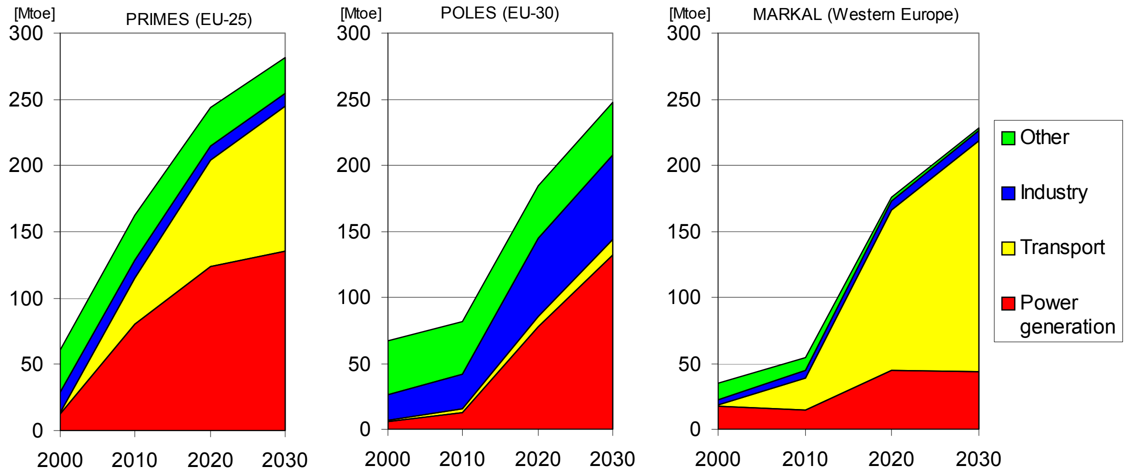

Figure 3.3 *Deployment of biomass and waste by sector according to different models*
Note: the sector definitions in POLES are not completely comparable to those in the other models and part of power generation falls in the category 'Other'; EU-30 here excludes Turkey).

Figure 3.3 also illustrates the large potential for application in different sectors, particularly for power generation and in the transport sector, but also heating and cogeneration. The prospects by sector differ by model, depending on whether a generic target was set for all renewables (POLES) or whether specific policies targeted at different sectors were implemented. A large penetration of biofuels in the transport sector is only achieved under targeted policies such as taxation of conventional transport fuels, because applications in the power sector seem more cost effective. According to PRIMES and MARKAL, the targets of the Biofuels Directive are more than achieved in 2010, while in 2020, biofuels account for 14-32% of final energy demand in the transport sector, respectively. In MARKAL this is due to an almost complete shift from diesel to biodiesel, which is produced from wood chips. The other models do not specify which processes are used for biofuel production.

Wind energy takes off
Under the 20% target, the amount of wind power production increases significantly, and the target set by the wind industry (EWEA, 2003) of 425 TWh in 2020 for the EU-15 seems within range. The differences in projections for 2020 are large, as illustrated in Figure 3.4, while the range is much smaller in 2030, indicating that technical potentials are becoming the limiting factor. In terms of generation capacity, there would be some 100-180 GW wind power installed in Western Europe, increasing to 190-215 GW in 2030. The average 11% share of wind power in total electricity generation is substantial, but generally within dispatchable ranges, although the shares in individual countries could be much higher.

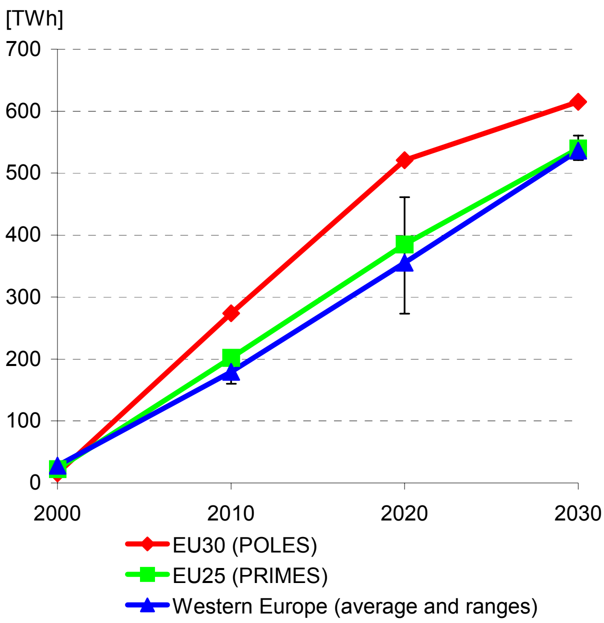

Figure 3.4 *Production from wind energy*

3.2.3 Policies to achieve ambitious renewables targets

A variety of policies have been implemented in the different models in order to achieve a high penetration of renewable energy sources. Most of the models have incorporated a separate target for the power sector of 33% renewable electricity consumption, and have reported on the subsidies required for achieving this target as shown in Figure 3.5. There seems to be some consensus on a subsidy level up to 40 €/MWh, a level that would be comparable to the electricity commodity price. However, the design of the policy instrument differs, as indicated in the graph, and therefore the support levels are not completely comparable.

Moreover, a well-designed policy should differentiate support instead of providing a flat rate for all technologies, implying that the average subsidy would probably be lower. The TIMES model has compared a scenario of certificate trade in the EU-15 to a scenario where all 15 Member States achieve their targets domestically. Trade leads to cost reductions for most of the countries, whereas expensive technologies, such as PV, experience a larger growth when the targets are met without trade.

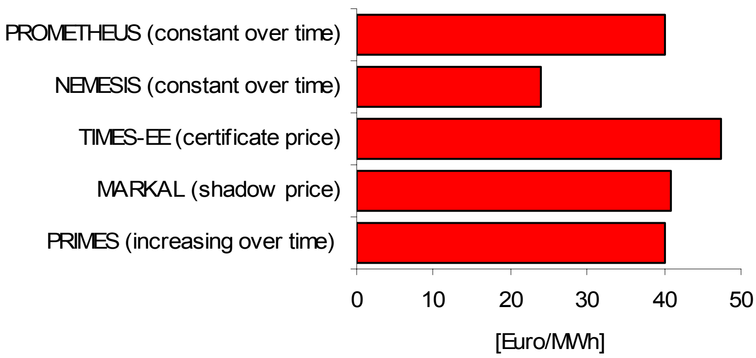

Figure 3.5 *Subsidies required for achieving 33% renewable electricity consumption in 2020*

POLES is the only model that has used a generic subsidy for all sectors, and its level of almost 60 €/MWh confirms that the cost of the 20% overall target is higher than that of only the power sector, where this model reaches a 44% renewables share in 2020.

3.3 Long term - the global perspective

When extending the focus to the longer term, say until 2050, a restriction of the efforts to the European Union only is unlikely to provide a realistic view on future prospects of renewable energy systems. Therefore, in the study three global models (DNE21+, GGM, and MESSAGE) have been used to analyze the long-term perspective for RES. These models show that when the industrial world takes the lead, global penetration of renewable systems may be achieved for those technologies that show an aptitude for cost decrease.

3.3.1 Penetration of renewables worldwide

Figure 3.6 presents the trends for three important options for renewable electricity production. These technologies are presented here, because the models largely differ in what they expect under the modest subsidy scheme of 20 €/MWh implemented in the power sector. The assumption is made that subsidies gradually decrease, so that in 2050 the systems are no longer subsidized. This subsidy scheme reflects a situation where the policy maker is willing to provide a subsidy for market uptake, but is decreasingly willing to support systems that are not entering the market by itself.

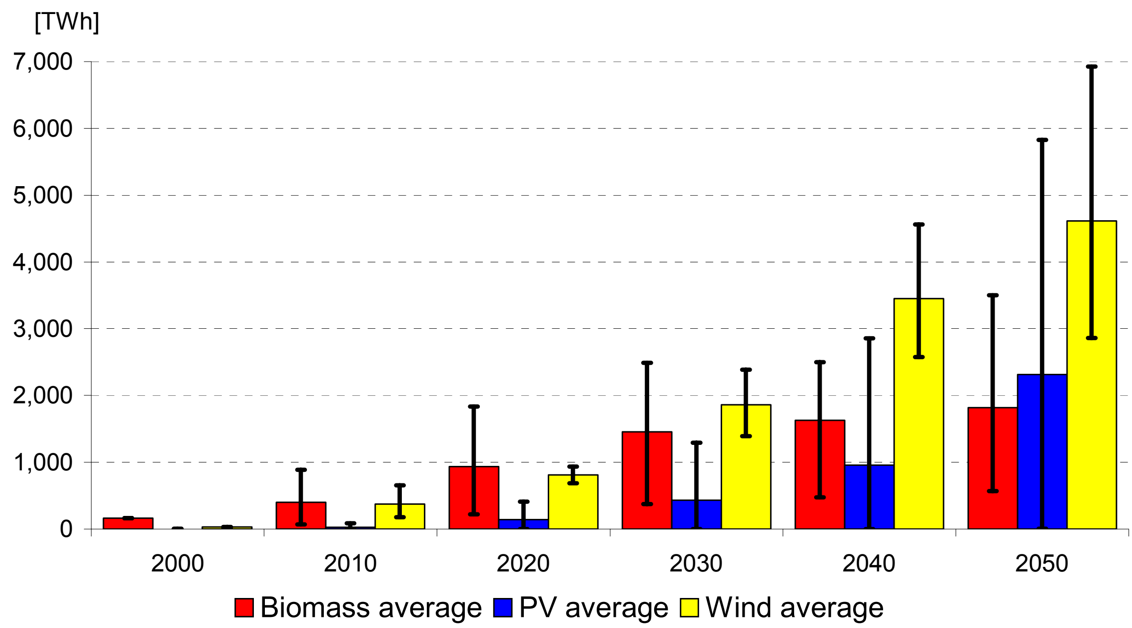

Figure 3.6 *Global electricity production from biomass, PV and wind under a subsidy scheme of 20 €/MWh, decreasing to zero in 2050; averages over three models and ranges*
Source: MESSAGE, GMM and DNE21+.

Biomass shows the most limited growth. This is partly due to the fact that biomass resources are also used for other applications, e.g. in the transport sector. Furthermore, the initial increase in application of biomass is annulled by the year 2050 in all models. This indicates that the low and decreasing subsidy level is insufficient to induce a lasting effect on the additional deployment of biomass. Only in the sensitivity scenario assuming subsidies together with learning by doing (LBD), analyzed with GMM, a lasting production increase was realised. This production increase was 3300 TWh in the regions of Asia, Eastern Europe, Former Soviet Union, Latin America, Africa and the Middle East, e.g. outside the OECD for the year 2050. This result suggests that early learning investments in systems like biomass in regions with large biomass potentials can accelerate introduction of renewable electricity technologies into the market.

For wind power, the GMM model projects the largest growth. Here the subsidy policy induces only limited impact on the technology penetration, since the wind turbines increase the contribution to the power generation mix substantially already in the Baseline, and further increase is limited by the upper bounds imposed on this technology. Most of the capacity is installed in the industrialised world. In the other two models the growth of wind energy in the baseline is more modest, and the relative impact of the subsidy therefore is larger.

For PV, the differences among the model results are extremely large, reflecting the uncertainties on how the costs of this technology will develop. In one of the models (MESSAGE) where it is assumed that R&D spending and direct investment in a broad portfolio of solar technologies has contributed to important reductions of the investment cost for the PV technology, a worldwide production of over 5000 TWh can be achieved already without additional subsidies. This corresponds to some 1700 GW capacity, which is installed mainly in Asia, Africa and South America, where the potentials are large. On the other hand, there is a model (GMM) with endogenously determined cost reductions due to learning by doing, which expects hardly any penetration of PV under the modest subsidy levels in the current case. This model has calculated that achieving a reduction in production costs down to a level of 50 €/MWh by 2040 requires 'learning investments' (e.g., cumulative undiscounted investment cost), of around € 260 bln.. This would correspond to a cumulative production of 15.000 TWh in the periods 2040-2050, or an installed capacity of 820 GW by the year 2050.

3.3.2 Learning can enhance effects of subsidies

Within the global perspective, the question arises what is likely to be the most cost-effective way in which Europe may subsidize renewable energy systems. The EU may choose to be initially leading in the stimulation, but this will only be acceptable if taking the lead in the long term will not induce negative side effects, such as decreased competitiveness. Thus, after an initial lead-time, other regions should follow the example, or the need for subsidy should decrease due to increased competitiveness of RES. In the present study, the subsidy scheme assumed follows these assumptions. It is shown that under these discussions the aims of the subsidy scheme are only reached if and when the RES show aptitude for learning, i.e. for cost decrease under increased deployment or research.

To evaluate the effectiveness of subsidy policies in terms of cost and achievable renewable electricity shares, one of the models has analysed an additional 'cap-and-trade' scenario that forces renewable electricity generation to reach a fraction of 35% in 2050. The resulting marginal cost of this renewable electricity amounts 3-6 €ct/kWh in the period 2010-2050, and can be interpreted as certificate prices. While in the subsidy scheme the subsidy is provided equally to each renewable source (with an exception for hydropower), under the renewable target the model finds the least cost solution that defines the supply curve of renewables.

While the three global models mentioned above only allow for the analysis of overall research, development and deployment effects, the stochastic PROMETHEUS model also enables an more particular analysis of either research or deployment stimuli. The framework of such an analysis has been the central theme of several EU-funded research projects, such as the SAPIENT and SAPIENTIA projects[5]. Using PROMETHEUS, a comparison between the effect of direct subsidies and additional R&D spending, shows that the effect of a subsidy of 40 €/MWh is comparable to doubling cumulative R&D investments (corresponding to an additional 48 billion $€_{2000}$) combined with a subsidy of 25 €/MWh. The R&D-scenario is some 30% more expensive than the direct support scenario. However, when the costs are expressed in

[5] http://www.e3mlab.ntua.gr/sapientia.html.

terms of avoided CO_2 emissions, the direct support policy is substantially more expensive. This is due primarily to the different nature of the spillover effects of the two policies. The R&D policy enhances the attractiveness of renewables throughout the world, while the direct support policy increases renewable penetration in Europe.

The global versus local effects of the two possible routes sketched above, also point at the need for further analysis. While the direct stimulation is likely to have positive side effects for the RES industry, the increased R&D spending not necessarily has similar beneficial local effects. Other regions, through a spill over of knowledge, may absorb the R&D gains, with possible consequences for European competitiveness.

3.3.3 Efficiency of subsidy schemes

The basic scenario studied here is one where a flat subsidy is provided to RES in the power sector. All of the global models have made additional analyses, using more complex schemes such as differentiated subsidies, international green certificate trade and extending the scheme to other sectors. When looking at the results of such more elaborate schemes, one generally can observe that a flat subsidy rate to all RES is not the most efficient way of increasing the contribution from RES.

Furthermore, one of the models has shown that biomass can play a role in various sectors, and that a stimulus in a particular sector may cause ‘carbon leakage’ to other sectors, due to a shift in application of biomass. In case of applying a subsidy only to renewable electricity generation, the transport sector shows a switch from biomass-based ethanol to fossil-based methanol in transport. Since the biomass resources are limited, it is more attractive to use biomass in the subsidized electricity production than in synthetic fuel production. Both methanol production and use lead to CO_2 emissions. Most of the additional methanol is produced with coal, and emissions from the transport sector may be up to 5% higher than in the baseline in 2050. Therefore, the extension of the subsidy beyond the power sector not only increases the efficiency of the stimulus, but also seems required to reduce CO_2 ‘leakage’ between sectors.

3.3.4 CO_2 emissions reductions

To give a more concrete understanding on the effect of the level of the subsidy on the CO_2 emissions, the cumulative emission reductions are calculated for the case where all energy carriers receive subsidies from 1 to 6 €ct/kWh, decreasing over time (Figure 3.7).

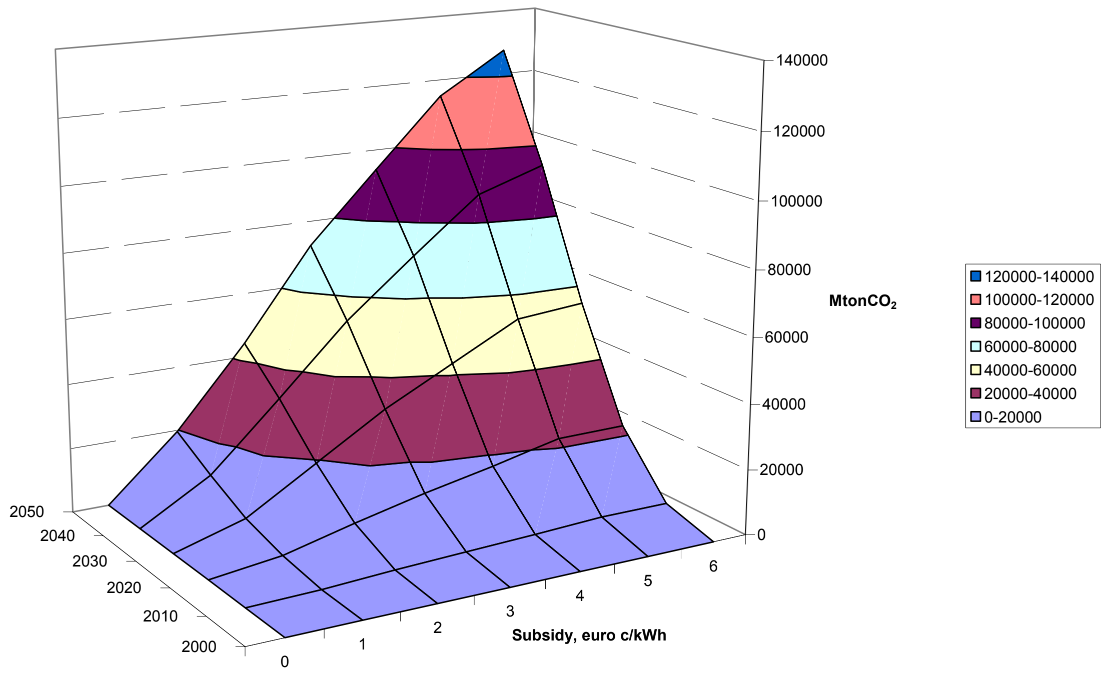

Figure 3.7 *Cumulative CO_2 reductions as a function of the subsidy level, renewable energy in all sectors subsidized*
Source: MESSAGE.

As the figure shows, the effect on CO_2 emissions is higher the more ambitious the subsidy scheme is (and this is also the case when only renewables in the power sector are subsidized). However, subsidizing all energy carriers provides much more potential for emission reductions. For example, to reach reductions of 40 $GtCO_2$ by the year 2050, an initial subsidy level of 3 €ct/kWh is needed if only electricity is subsidized. An initial subsidy level of approximately 1.8 €ct/kWh would be enough with the overall subsidy scheme (see Figure 3.7). Note also that although with the same initial subsidy level the absolute costs of the overall schemes would be higher, the price per ton CO_2, which measures the effectiveness of the policy in terms of emissions reductions, would still be lower. Given the assumptions in the baseline and on the (decreasing) aspiration levels for the subsidies, a reduction of about 140 $GtCO_2$ in cumulative emissions may be reached by the year 2050.

3.4 Key recommendations

Recently, Europe has shown large ambitions in setting renewables targets. Renewables indeed have the potential to contribute substantially to mitigating climate change options and their indigenous nature improves security of supply. To effectively increase the penetration of renewables up to 20% in 2020, the following recommendations apply:

- The 20% target seems to be within reach provided energy demand reductions are pursued simultaneously.
- Bioenergy is one of the key renewable options because of its large potential and its different possible applications. A strong growth of biomass deployment is required for achieving ambitious renewables and climate targets. Policies in different areas such as energy, agriculture, and environment should be further streamlined in order to overcome current barriers.
- Efforts directed towards the transport sector combine several benefits, because the substitution of oil with biofuels improves both security of supply and reduces carbon emissions.
- Implementation of renewables is currently most straightforward in the power and transport sector, but to achieve further growth towards 2020, applications should involve other end-use sectors. For instance the potential in the building sector, including renewable heating and

cooling options, such as solar thermal water heaters or biomass-based district heating should be further exploited.

Furthermore, some lessons on design of subsidies can be drawn.

- For the long-term growth of shares of renewable power generation, the elimination of all subsidies by 2050, as assumed in this case study, is probably not appropriate and may lead to a situation where promising new technologies such as photovoltaics remain locked-out.
- Subsidy schemes should offer differentiated support and stimulate learning effects. It is important to target the subsidies correctly. If only one sector is subsidized, the renewable share in this sector will be high, but there may be 'carbon leakage' to other sectors, due to a shift in application of biomass, and the share in primary energy is only mildly affected.
- R&D and demonstration projects can induce spill over effects to the rest of the world and thereby have a higher impact on global emissions reductions.

4. Nuclear energy - one of the options to address global energy challenges

Nuclear energy is a controversial subject for policy making on energy and environment because of arguments concerning radioactive waste, reactor accidents, nuclear proliferation, economic competitiveness and public opinion. The issues of climate change and supply security have provided a new rationale for its reappearance on the international political agenda. This policy brief provides an overview of the main results from the scenarios analysed in the CASCADE MINTS project to assess the role of nuclear energy in solving global and European energy and environmental issues (Uyterlinde et al., 2006a). The models used are: PRIMES, MARKAL, POLES and TIMES-EE for the European impacts, GMM, and DNE21+ to illustrate global developments, the economic models PACE, NEWAGE-W and NEMESIS, and finally NEMS for the US and MAPLE-C for Canada.

In the CASCADE MINTS analysis, two distinct, rather opposite scenarios have been considered. They highlight the consequences of either following a strict phasing-out path of nuclear power generation capacities, as opposed to the situation where nuclear technology exhibits a 25% investment cost drop. In this Renaissance case, the assumption is also made that improved safety characteristics lead to an increased acceptance of nuclear power. Both scenarios have been analysed in combination with a rather strong CO_2 policy, reflected in a CO_2 price (carbon value - CV) rising from 10 to 50 to 100 €/tCO_2 in 2010, 2020 and 2030 respectively. In comparison, the current CO_2 price of over 20 €/tCO_2 is relatively high due to the recent launching of the EU emission trading system and the high natural gas prices.

The scenarios are compared to a common, harmonised baseline scenario, characterised by a moderate economic and demographic growth, and based on the IPCC B2 scenario (see also Chapter 2). Oil prices reflect assumptions of low to moderate resource availability. In the period 2000-2050, the world oil price is projected to increase from ca. 26 to 38 $US\$_{95}$/barrel (4.2 to 6.2 €/GJ). Obviously there is a great deal of uncertainty to this assumption. Natural gas prices within Europe, although not explicitly harmonised among the models, are projected to increase from on average 2.3 to 5.4 €/GJ in 2000-2050. Finally, some representation of climate policy or emission trading for the region of Europe has been included, reflected in a generic carbon tax of 10 €/tCO_2 from the year 2012 onwards.

4.1 Would a technology cost reduction lead to a nuclear renaissance?

The *Renaissance & Carbon value* scenario assumes that a technology breakthrough reduces the investment costs of the cheapest type of nuclear power plant[6] with 25% by 2020, and that improved safety characteristics lead to a larger social acceptance of nuclear power. This way, the scenario can shed some light on the techno-economic potential of nuclear power in Europe and worldwide.

This scenario induces significant shifts in Europe's electricity generation mix. Figure 4.1 shows that the share of nuclear power could increase up to 30% while other models show even stronger increases up to approximately 50% of total power generation. Comparing the effect of the Renaissance & CV case to one where only the carbon tax is applied shows that the cost reduction does provide an important additional incentive for nuclear power in the period until 2030.

[6] In most models this concerns a conventional reactor type such as the Light Water Reactor; in POLES and GMM it concerns a general type of 'advanced' reactor expected to become available on the market beyond 2010, in the TIMES-EE model it concerns the European Pressurised Water Reactor (EPR).

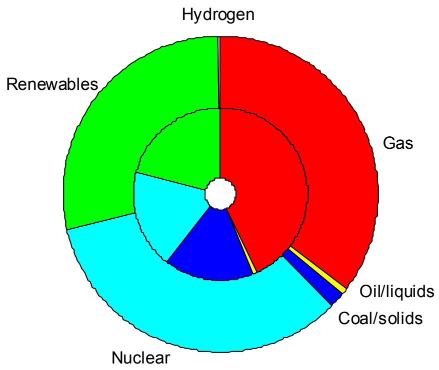

Figure 4.1 *Electricity generation mix in the EU-25 in 2030; baseline (inner circle) compared to Renaissance & Carbon value case (outer circle)*
Source: PRIMES.

Clearly, the higher share of nuclear is largely at the expense of coal-based power plants, while the natural gas share is also reduced in most models. These effects are partly also due to the post Kyoto policy that punishes high carbon containing solid fuels more than natural gas. Similarly, the high carbon value provides an incentive to renewables, which gain in all models. Interestingly, PRIMES expects the contribution of nuclear power to be larger in the EU-15 (35% of power generation) than in the New Member States (27%). Comparable shifts are shown for the US by the NEMS model, while it should be noted that some other models expect larger shares of coal in the baseline than illustrated here, e.g. over 40% in MARKAL.

Figure 4.2 also illustrates the effect that a strong CO_2 policy may have in combination with a cost reduction of nuclear power plants. For Europe, the use of fossil fuels for power generation is substantially decreased, while the global model shows that the strong overall growth of electricity production (with a factor 4 in 2000-2050) is dampened for fossil fuels by the increased contribution of nuclear power and renewables. The amount of fossil fuels is half of what it would be in the baseline.

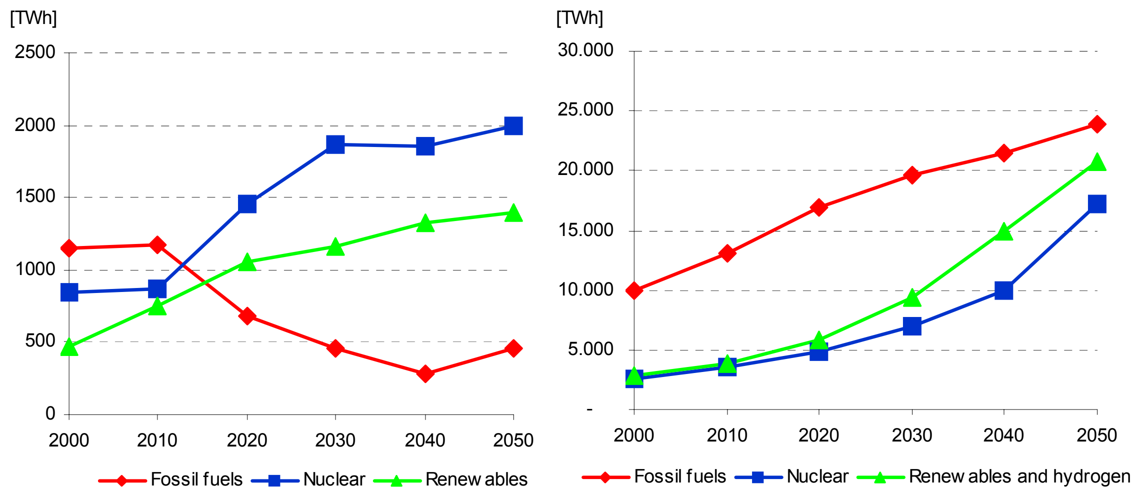

Figure 4.2 *Electricity generation by fuel for Europe and the world for the Renaissance & Carbon value case*
Source: MARKAL and GMM.

Costs of the nuclear renaissance
Generally the models report on lower total costs for the Renaissance & CV case than for the case where the carbon value alone is imposed. Consequently, the nuclear renaissance to some

extent compensates the negative impacts on the GDP and welfare of the carbon value. However, the realisation of the reduction in investment costs may require substantial investments in R&D. One of the models, NEWAGE-W has analysed the impacts of funding the cost reduction of the nuclear technology by a subsidy, at the expense of the household incomes. However, the negative impact on GDP of this is negligible.

Different models show different impacts of the investment cost reduction related to their technology characterisation. At low and medium interest rates, Light Water Reactors gain market share, but at 12% interest rate, the technology is not competitive anymore.

Proven uranium reserves utilized until 2050
In the Renaissance scenario, a strong enhancement of the use of nuclear power plants causes a substantial increase in demand for reactor fuel. Under today's reactor conditions, some 8-10 million ton of uranium would be needed worldwide in the period from 2000 to 2050. This indicates the need for technology advancement not only in price of a reactor, but also in efficiencies, as current estimates of reasonably assured reserves and additional reserves[7] together amount to 8.3 million ton. A further 12.1 million ton of speculative, and to date undiscovered resources might be needed in the long run.

Nuclear waste management
An issue of some concern may be the considerable increase in spent fuel, and hence nuclear waste, that goes along with the increased use of nuclear power. According to an analysis with the GMM model, the enhanced use of nuclear power in the renaissance case may amount to a doubling of the cumulative waste production by 2050 as compared to the baseline. This clearly indicates the need to address issues concerning waste management, particularly finding an acceptable form of long-term storage.

Furthermore, the MARKAL analysis indicates that even in the renaissance case the role of reprocessing remains marginal. The underlying reasons seem to be that reprocessing is more expensive than storage and that reprocessing does not lower the amount of radioactive waste, as it results in small amounts of plutonium, and the production of MOX for which it is used entails the creation of yet more (low-level) radioactive waste.

At least two channels exist through which the nuclear waste problem could be mitigated: reducing the radioactive lifetime and, thereby, the radio-toxicity of nuclear waste, and organising waste disposal internationally. The European Commission is preparing legislation that creates incentives and a regulatory framework for EU states to create timetables and undertake swift action to develop permanent (underground or aboveground) disposal facilities for high-level nuclear waste.

Proliferation
The civil use of nuclear energy inherently involves threats regarding the possible non-civil diversion of the technologies involved and the materials produced in the nuclear industry. Among nuclear energy's main dangers in terms of proliferation is, on the one hand, the use of enrichment facilities and, on the other hand, the production of fissile materials, during reactor operation, that remain embedded in nuclear waste. According to the models used in this study the increase will be strongest in the world regions that currently already deploy nuclear technologies, in case of a strong carbon policy. Therefore, the risks of proliferation are likely to be limited. Nevertheless, the enhanced use of nuclear fuel requires additional efforts in answering questions of waste management, as the total amount of spent fuel increases up to a factor two as compared to the baseline projection.

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7 Estimates of Additional Reserves (5.1 million ton of uranium) have a lower level of confidence than the Reasonably Assured Reserves (3.2 million ton). Source: (UNDP, 2000).

4.2 Is a nuclear phase-out feasible in a carbon-constrained future?

On the other side of the spectrum is the question whether a carbon constrained energy system is feasible without the nuclear option. The models have analysed this question using a nuclear phase-out path based on the assumption that existing plants are decommissioned after their economic lifetime and that no new nuclear plants are built. This scenario was examined under the same carbon value as in the renaissance case, of 50 €/tCO_2 in 2020, increasing to 100 €/tCO_2 in 2030 and further.

The return to gas, renewables and clean coal

Figure 4.3 shows the shifts in Europe's power generation mix in 2030 due to the combination of a high carbon tax and the nuclear phase-out. The amount of power generation from coal is substantially reduced, and is compensated by an increased contribution from renewables and natural gas. NEMS reports on shifts in the US electricity generation that renewables gain most from the nuclear phase-out in presence of a carbon value.

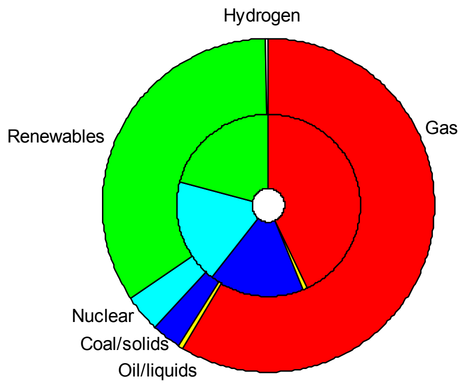

Figure 4.3 *Electricity generation mix in the EU-25 in 2030; baseline (inner circle) compared to Phase-out & Carbon value case (outer circle)*

Source: PRIMES.

In the longer run, coal plants equipped with CO_2 capture largely contribute to a carbon constrained generation mix without nuclear power, as shown in Figure 4.4. The MARKAL baseline shows only a small contribution of nuclear power, due to the (model-specific) technology costs assumptions and only a very modest climate policy.

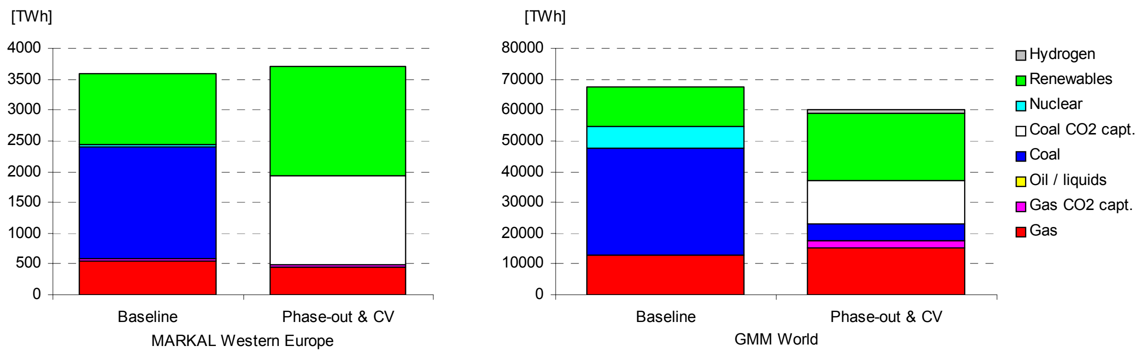

Figure 4.4 *European and global power generation mix in 2050; Phase-out & CV case*

Source: MARKAL and GMM.

The phase-out has negative impacts on the GDP and welfare that are slightly stronger than the impacts of the carbon value alone. As nuclear is one of the major power generation technologies, forcing this option out of the market while at the same time imposing high carbon taxes will lead to higher electricity generation costs and therefore also to higher input cost for electricity intensive production. According to the POLES model, countries characterized by substantial shares of nuclear and/or coal in their power generation will face electricity price increases of 10-30% by 2030.

4.3 Emission reduction induced by carbon tax

Both the renaissance and the phase-out case show a substantial decrease of CO_2 emissions as compared to the baseline, mainly due to a severe taxation scheme. Within this perspective, the effects of the developments of the nuclear technologies play a relatively modest role, as illustrated in Figure 4.5. In general, the nuclear renaissance adds to CO_2 emission savings, while phasing out nuclear technologies causes a limited increase in emission levels, indicating that within the time horizon studied other carbon abatement options can largely compensate. The figure shows large differences in the expectations of possible emissions reductions among the models. This is due to the differences that are already present in the baselines and to technologies included in the respective model databases. For instance, POLES does not include carbon capture and storage in its present technology database, and consequently shows less emission reduction than the other models, particularly in the phase-out case.

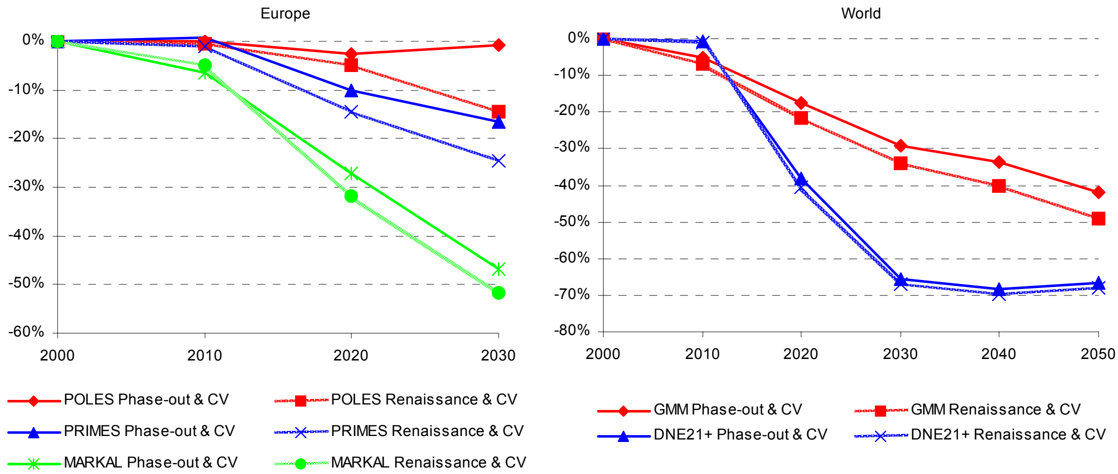

Figure 4.5 *Change in CO_2 emissions relative to the Baseline*

The importance of nuclear energy as compared to other options within the carbon mitigation strategy is illustrated in Figure 4.6, where a breakdown of different CO_2 reduction components is provided. In general, an inter-fossil fuel switching, e.g., substitution from coal to natural gas, plays the dominant role in the global CO_2 abatement process in all CO_2 constrained cases. However, important differences are observed for the role of nuclear energy, CO_2 capture and renewables. In the Renaissance & CV scenario, nuclear energy contributes by about 13% to the overall mitigation between 2010-2050 and is the second most important player in the cumulative carbon abatement. Exclusion of nuclear energy from the portfolio of abatement options in the Phase-out & CV scenario results in a rapid increase of the contribution of CO_2 capture (38% in 2050).[8] Similarly, the fraction of renewables and demand-reductions is higher as compared to carbon-taxed cases allowing for utilization of nuclear power. Implication of this result is that the policies in favour of nuclear power can shift the need to invest in other capital-intensive technologies, e.g., CO_2 capture or renewables, towards later decades.

[8] In the Phase-out scenario, the cumulative amount CO_2 captured and stored in the period 2010-2050 is 132 $GtCO_2$. This corresponds to about 13% of the global cumulative storage-potentials in depleted oil and gas fields estimated by IEA (2004).

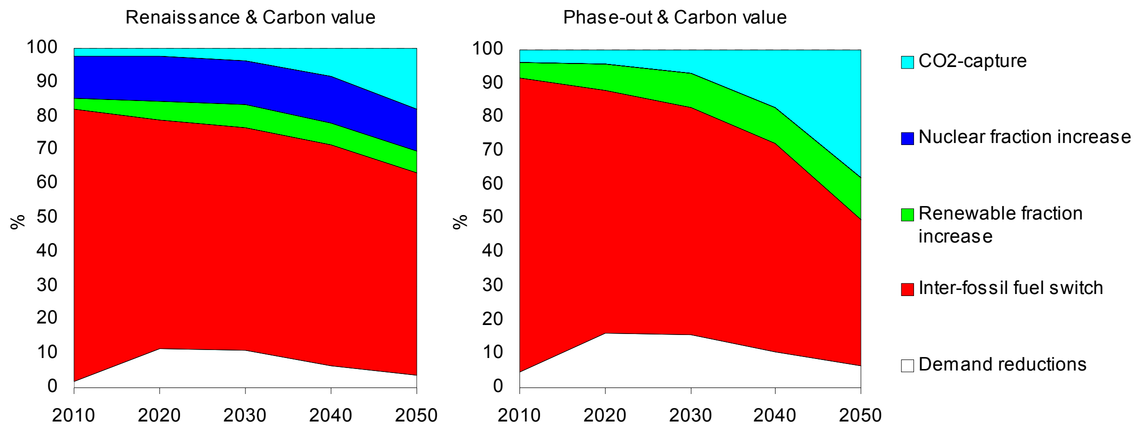

Figure 4.6 *Breakdown of CO_2 reduction components*
Source: GMM.

4.4 Impacts on security of supply mainly for natural gas and coal

For European models, the shifts in power generation mix visible in the renaissance case do have some impacts on the Europe's import dependency for coal, which is significantly reduced, and for natural gas, which slightly decreases in most of the models. The import dependence for oil is hardly affected. Of course, the growth in nuclear capacity in this scenario would require imports of uranium, but these would likely come from other world regions than the Middle East, relieving the dependence on this region. The diversity of Europe's primary energy mix increases slightly with 1% point on a 100% scale. Similarly, a nuclear phase-out in Europe would not affect the import dependency for oil, while it could lead to a small increase in the dependence on imports of natural gas. The diversity index gives a mixed picture - it might slightly improve due to a larger share of different renewable sources, or it might slightly deteriorate by the absence of the nuclear option.

4.5 Economic impacts

Welfare

Overall welfare losses[9] for Europe are small and mainly due to the carbon value, see Table 4.1. They are accelerated in the case of a nuclear phase-out and moderated in case of a nuclear renaissance. The magnitude of welfare losses is closely related to the electricity production costs associated with the different scenarios. The models agree on the negative effects of the CV and the stronger negative effect of the phase-out case, respectively. Interestingly, NEWAGE-W shows a positive welfare effect of the nuclear renaissance, while in PACE a negative effect on welfare remains. This may be dependent on the formulation of the model (inter-temporal or recursive dynamic), and on the time period considered. Another reason may be the assumption in NEWAGE-W that revenues of the carbon tax are recycled to households, which increases their consumption.

[9] Changes in welfare are expressed in percentage Hicksian equivalent variations in income, equivalent to percentage change in real consumption with respect to the baseline.

Table 4.1 *Welfare losses in terms of Hicksian equivalent variations (versus baseline)*

	PACE (EU-15, 2020) [%]	NEWAGE-W (WEU, 2030) [%]
Renaissance & CV	-0.1	0.8
CV only	-0.2	-0.1
Phase-out & CV	-0.3	-0.5

GDP

NEWAGE-W and NEMESIS report on the impact of the various policy scenarios on GDP. The main impacts appear to be due to the carbon tax, and are generally negative due to price increases of fossil fuels and electricity, although NEWAGE-W shows a small positive effect in 2010-2020, induced by increasing income of the households due to an increase in tax revenue. Again, the nuclear phase-out policy accelerates the negative GDP effect, while the technology renaissance for nuclear production leads to a positive impact. Due to the more efficient nuclear electricity production caused by a reduction in capital input costs, electricity prices decline and with it the cost for an important input factor for industrial production.

4.6 Conclusions

Nuclear power can be an important option for achieving CO_2 emission reduction while preserving acceptable electricity costs and welfare level; after 2050 speculative uranium resources will be required, unless novel reactor types and designs become available

Nuclear power technologies may be instrumental at achieving strong climate policies at acceptable costs, provided that a breakthrough in costs occurs. In that case the growth in the use of nuclear power can be substantial, and the annual average increase in installed capacity may surpass the height of the nuclear era in the early seventies. At the same time the realisation of the cost reduction may require substantial R&D expenditures. Still, it is evident that nuclear energy can constitute no panacea to the problem of global warming. Even with a massive expansion, nuclear energy can at best only be part of the solution, and should be complemented by drastic fossil fuel decarbonisation and a massive development of renewables, preferably in combination with far-reaching efficiency and savings measures. Until 2050, a substantial increase in nuclear energy use does not represent an acute threat to the cumulative uranium reserves if the speculative - and to date undiscovered - resources are considered. However, the cost of nuclear fuel supplies might increase.

Additional obstacles that are associated with the competitiveness of nuclear energy are the public acceptance, disposal of spent fuel and radioactive waste, proliferation, and risks of severe accidents. These issues might to some extent be addressed by the introduction of new nuclear technologies. Advanced nuclear reactors might see substantial higher reactor efficiencies, lowering the use of nuclear fuel. Alternatively, these may enable the use of alternative fuels such as thorium. Reprocessing may reduce the amount of dangerous waste as well as decrease the demand for raw nuclear resources. Finally, yet more unconventional concepts such as breeder technology or the combination with accelerator technology might address the resource problem and the waste issues at the same time. However, all of these require developments that go beyond the current state of affairs, and have not been analysed in this study.

While today not being a sustainable energy resource, nuclear energy - along with other presently available energy options - could play a transitional role towards establishing sustainable energy systems.

A future without nuclear power is possible, placing renewables and CO_2 capture and storage in a key position, and increasing Europe's dependence on natural gas imports

If all industrialised countries follow a strategy to retire their nuclear sites at the end of the economic lifetime, it is more difficult to achieve ambitious emission reduction targets, as one of the carbon-free options is removed from the energy system. The phase-out of nuclear generation capacities will partly offset the emission reduction achieved by increasing CO_2 prices. Renewables, natural gas and coal with CO_2 capture and storage are key options in a future without nuclear power plants. Natural gas consumption may increase, and can be up to 15% higher in 2030 compared to the baseline, causing Europe to be even more dependent on natural gas imports until 2030. In the long run, due to the limited gas reserves, this might not be a sustainable situation. The phase-out has negative impacts on the GDP and welfare that are slightly stronger than the impacts of the carbon value alone. Higher electricity generation costs will lead to higher input cost for electricity intensive production, and countries characterized by higher shares of nuclear in their power generation will face electricity price increases of 10-30% by 2030.

Although a nuclear phase-out in Europe appears to be feasible even in a Post Kyoto scenario, it is more difficult and costly to achieve strong CO_2 emissions reductions, and it requires a large penetration of renewables and advanced sequestration technologies. Moreover, although the impact of the phase-out in Europe seems to be relatively modest in the time frame until 2030, it might lead to more serious problems later.

Finally, improving international safeguards and institutions should have high priority, whatever the future share of nuclear energy in power production. The importance of the International Atomic Energy Agency (IAEA) in this is fundamental, as proliferation risks will remain even if the civil use of nuclear power were phased out entirely.

5. CO_2 Capture and Storage

Fossil fuel fired power plants play an important role in current global and European energy systems. Alternatives, such as renewables, are currently more costly than the more mature fossil technologies. Due to their 'add-on' nature, CO_2 capture and storage (CCS) technologies could work as transitional technology, reducing the CO_2 emissions from the energy sector before a transition to less carbon-intensive energy system is achieved. However, CCS still needs a price on carbon or another CO_2 reducing policy in order to be deployed.

This policy brief focuses on the role of CO_2 capture and storage technologies in the power sector, and provides an overview of the main results from a number of models used in the CASCADE MINTS project. The models used are: POLES, MARKAL and TIMES-EE for the European impacts, GMM, MESSAGE, ETP, DNE21+ and PROMETHEUS to illustrate global developments, the global economic model NEWAGE-W, and finally NEMS for the US. Three policy approaches (CCS standards, a CO_2 cap, and a CO_2 cap combined with a CCS subsidy) are analysed through these advanced energy-environment-economy models to address the question how to achieve significant CO_2 emission reductions through the application of CCS technologies. The models do not take into account non-economic aspects of CCS that may inhibit the deployment, such as public acceptance, risks and safety regulations and upstream environmental impacts.

Earlier scenario work in the CASCADE MINTS project has again underlined the challenges faced by Europe's energy system in the decades to come. Most of these are related to the continuing worldwide reliance on fossil fuels, which is likely to contribute 70-75% to the primary energy mix in 2030. This would lead to a worldwide doubling in CO_2 emissions in 2030 compared to 1990, with a particularly large expected growth in Asia. Although CO_2 emissions in Western Europe show moderate growth as compared to the global trend, they are not on track towards the target agreed under the Kyoto Protocol. Beyond 2012, assuming that some climate policy is in place in Europe, reflected in a moderate carbon tax of 10 €/tCO_2, emissions are expected to continue their growth with ca. 0.4%/yr. Furthermore, Europe's dependence on oil from the Middle East is expected to increase to 85%, and for natural gas, external dependency will also grow in the next decades. A continuing growth in gas consumption combined with a decrease of gas production in the UK, the Netherlands and Norway, will lead to a higher share of imports, probably still from the two current main suppliers Russia and Algeria.

5.1 What is CO_2 capture and storage?

CO_2 capture and storage is increasingly mentioned as one of the options in the portfolio to mitigate climate change. CCS involves the capture of CO_2 from a large point source, compression, transport and subsequent storage in a geological reservoir, the ocean, or in mineral carbonates.

As illustrated in Figure 5.1, capture can be done at large point sources of CO_2 such as electricity plants, refineries, hydrogen production units, or cement and steel factories. Several capture processes are available or are being developed. Post-combustion systems separate CO_2 from the flue gases after combustion, while pre-combustion systems extract the C as CO_2 from the fossil fuel and combust or use the resulting hydrogen. Oxyfuel combustion, which involves combustion with pure oxygen as opposed to air, is still in the demonstration phase. In most cases, the capture and compression step represents the bulk of the total energy use and cost of a CCS operation.

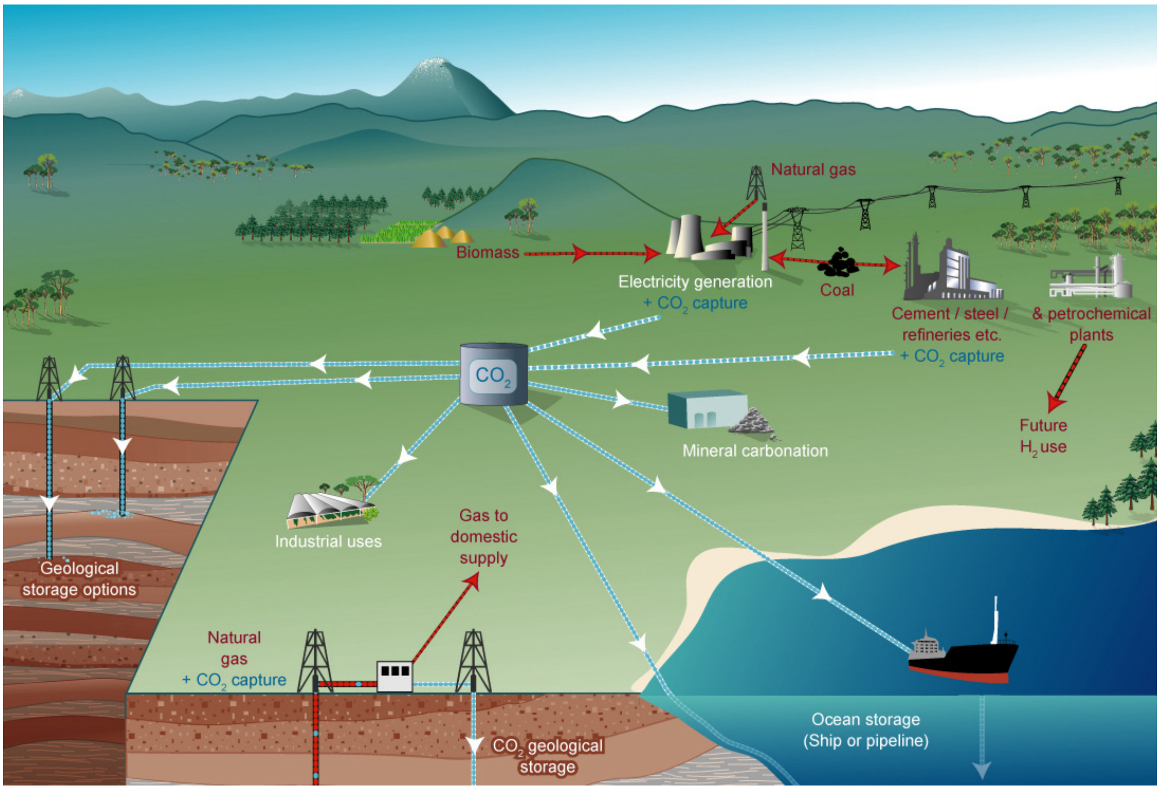

Figure 5.1 *Overview of CO_2 capture, transport, and storage options*
Source: IPCC, 2005.

The captured CO_2 is compressed and transported to a storage location, normally by pipeline, but in case of over-sea transport and large distances, transport by ship could become more attractive. The CO_2 is normally injected in a supercritical state. Once in the reservoir, the CO_2 is slowly immobilised through several trapping mechanisms, such as dissolution, residual gas saturation, and mineralisation.

Underground storage of CO_2 can be done in geological formations such as oil or gas fields, saline formations, or coal beds. The oil and gas fields could be depleted, but much is expected from enhanced hydrocarbon recovery by injecting CO_2 in a producing field, which would generate additional revenues.

5.2 Assumptions in the models

Assumptions on costs of CCS technologies are highly determining for their penetration into the energy system. All models have made assumptions regarding variables like investments costs, O&M costs, the energy penalty, the CO_2 capture efficiency, and the learning rate of CCS technologies for power plants, which are documented in this report.

Most models have applied approximately the same set of capture technologies. There are differences in how transportation and storage of CO_2 is modelled. Some models have a wide array of storage options with capacities whereas others have a generic storage technology with infinite capacity. This does have an effect on the results, since for some models, the revenues related to hydrocarbon recovery greatly contribute to making CCS viable. The modelling of transportation costs also varies.

The CCS policy cases are compared to a common, harmonised baseline scenario, characterised by a moderate economic and demographic growth, and based on the IPCC B2 scenario. Oil prices reflect assumptions of low to moderate resource availability. In the period 2000-2050, the world oil price is projected to increase from ca. 26 to 38 US$$_{95}$/barrel (4.2 to 6.2 €/GJ)[10]. Obviously there is a great deal of uncertainty to this assumption. Natural gas prices within Europe, although not explicitly harmonised among the models, are projected to increase from on average 2.3 to 5.4 €/GJ in 2000-2050. Finally, some representation of climate policy or emission trading for the region of Europe has been included, reflected in a generic carbon tax of 10 €/tCO_2 from the year 2012 onwards.

5.3 How much can CCS contribute to mitigating climate change?

The first policy case analysed, 'CCS standards', requires that from 2015 onwards, all new fossil fuelled power plants have to be equipped with a CO_2 capture facility. These standards are not applied to peaking plants with an utilisation rate of up to 20% and small CHP-plants. Due to the exclusive nature of the standards, this policy shows the largest CCS penetration. This section focuses on the results of this scenario, because it indicates how much CCS deployment could be achieved until 2050.

5.3.1 Up to 30% of global CO_2 emissions captured

Under the assumption of the regulatory CCS standards, 16% to 30% of global CO_2 emissions can be captured in 2050, as illustrated in Figure 5.2. According to the different global models used, this corresponds to a range of 7 to 19 GtCO_2 captured and stored in 2050. One of the factors underlying this range is the large variation in emissions projections among the models, which is related to the differences in the projected primary energy mix, particularly the share of fossil fuels. Other important explanatory factors are the assumptions related to technology learning and future costs of CCS technologies and renewables, as well as the growth constraints or potentials of the main carbon-free energy sources, nuclear and renewables.

The CCS standards not only induce the large-scale introduction of CCS systems in the electricity sector, but they also accelerate the penetration of nuclear and renewable energy sources. This 'substitution effect' is due to the fact that the application of CCS makes electricity generation more expensive and therefore other options become more competitive. For this reason, the emission reduction compared to the baseline is even larger, up to 40%, in most models. Generally, it more than compensates the 'energy penalty', e.g. the energy use and related emissions due to the additional energy needed for the CO_2 capture and storage processes themselves. However, one of the models (MESSAGE) points out that imposing CCS standards within the power sector may lead to a considerable shift ('leakage') of emissions to other sectors. The increase of biomass use for power production, for instance, induces more use of fossil methanol instead of bio-ethanol in the transport sector.

[10] This is in line with results of the European WETO project, although it is relatively low in comparison to current prices. A forthcoming scenario in the CASCADE MINTS project will include higher oil and gas price projections.

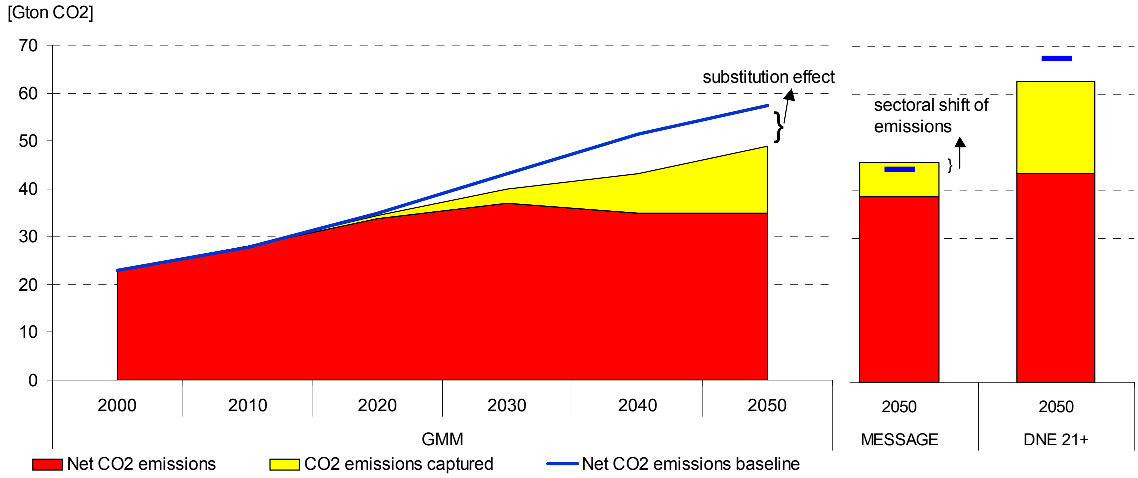

Figure 5.2 *Global net CO_2 emissions and amount of CO_2 captured in the CCS Standards case compared to net CO_2 emissions in the baseline*

For Europe, comparable emission reductions can be achieved through the CCS standards. By 2050, approximately 21%-23% of total CO_2 emissions would be stored. Compared to the baseline, the reductions are higher due to the shift to renewables and nuclear. Model analysis for the US, with a time horizon until 2025, shows that CCS technologies remain largely uneconomic within this period. The technologies that gain most from the obligation to install CCS with new fossil power plants are those not affected by the CCS standards - peak production gas turbines and renewables.

5.3.2 More CCS with coal than with gas-fired power plants

Most of the models indicate that coal-based power plants with CCS dominate, particularly Integrated Gasification Combined Cycle (IGCC) plants with pre-combustion capture, implying more limited CO_2 capture at gas-fired power plants. This is related to the high costs associated with capture technology applied to gas-fired power plants. It should also be noted that IGCC itself (even without CO_2 capture) is currently not a fully developed technology; there are only a couple of commercial IGCC plants operational in the world today. There are exceptions in specific policy cases and specific regions, where CCS applied to gas-fired power plants has a relatively large role. This is the case in Europe, as illustrated in Figure 5.3. Biomass gasification combined with CCS offers prospects for negative emissions. However, it is the least likely option for a major CCS introduction because of the considerable risks of high capital cost.

The addition of CCS only to new plants slows down CCS penetration, pointing at the inertia in the power sector. Even in 2050, sizeable capacities without capture technologies remain in the system. They consist of gas-fired, peak-load capacities excluded from the standard and remaining coal capacities close to the end of their lifetime.

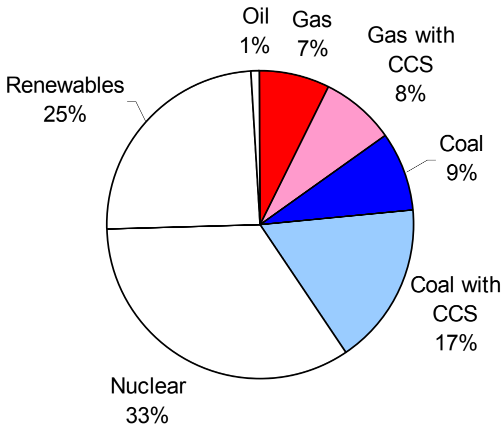

Figure 5.3 *European electricity generation mix in 2050 in the CCS Standards case*
Source: POLES (EU-30).

5.3.3 Storage potentials appear to be more than sufficient in 2020-2050

There is an ongoing scientific debate on how the CO_2 storage capacity should be estimated. Any site needs a detailed geological survey in order to make a reliable estimate of the suitability of the reservoir for storage of CO_2. Although acknowledging the controversies in the scientific literature on this issue, the CASCADE MINTS project used conservative estimates in line with the IPCC Special Report, and arrives at the conclusion that the availability of storage capacity does not impose limits to the amount of CO_2 stored in the time frame to 2050.

The global models report that under the CCS standards policy for new fossil power plants, the global, cumulative amount of CO_2 captured and stored in 2020-2050 is in the range of 170-260 GtCO_2. Acknowledging that the power plants built towards 2050 will need enough storage capacity for the decades to come, this still seems well below IPCC estimates (IPCC, 2005) of 675-900 GtCO_2 of cumulative potential for CO_2 storage in global gas and oil fields. Only one of the global models (DNE21+) has reported on the type of reservoir used. Geological storage in saline formations and oil fields combined with EOR prevails, while ocean storage is mainly utilized in Japan. This is related both to physical storage potentials and to the political acceptance of this option.

As far as the regional distribution is concerned, the global models suggest that although in 2030, comparable amounts of CO_2 are captured in Asia and the OECD, the emphasis shifts to Asia after 2050, due the large expansion of new power plants in this region, which would be equipped with CCS technologies as a result of the standards policy.

Also in Europe, storage potentials appear to be sufficient. There are differences among the models in what kind of reservoirs are used. These differences are closely related to the uncertainties in storage potentials as a result of the huge variety in local geological circumstances.

The TIMES-EE model has projected the amount of CO_2 to be captured and stored for individual EU Member States under the different policies, see Figure 5.4. Most CO_2 is expected to be stored in Germany, followed by Poland and Spain. The country differences are explained by regional storage potentials, the contribution of coal in the electricity production of individual Member States, and differences in the extent to which countries can shift to nuclear or renewables. The total amount is a factor 4-5 lower than what is expected by the other European models POLES and MARKAL, because this model ‘anticipates’ on the standards by projecting an increase in natural gas capacity in the years before the CCS standards become binding. Although the latter effect is related to the modelling methodology (‘perfect foresight’), it does suggest that market actors may try to circumvent anticipated policy measures.

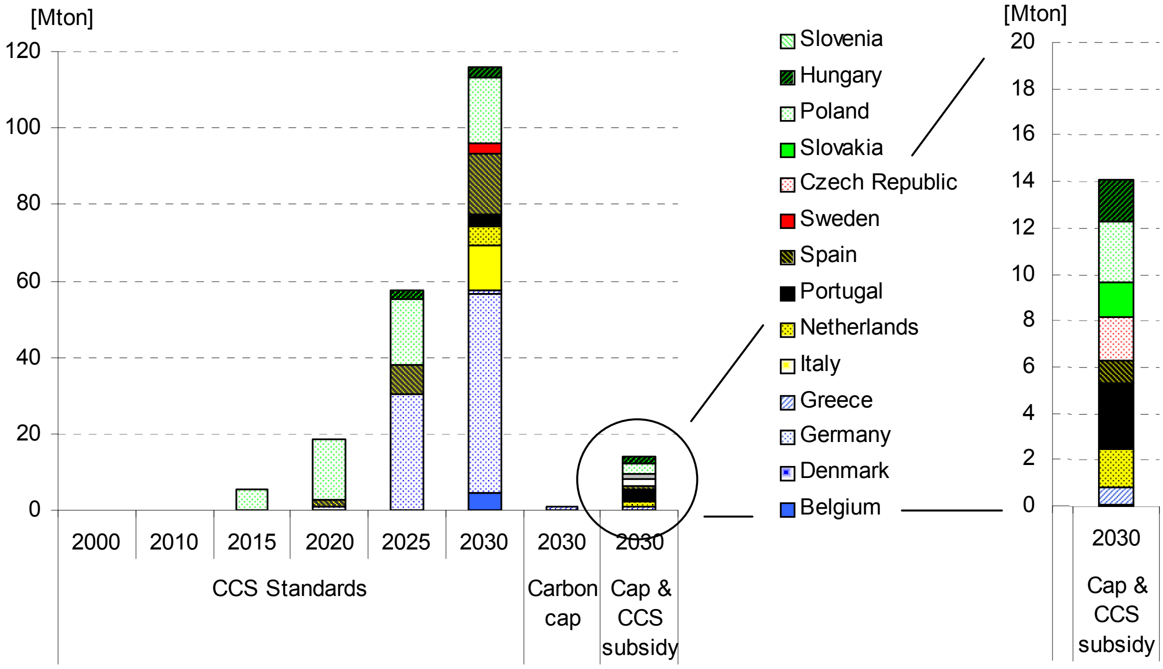

Figure 5.4 *CO_2 storage in the EU-25 by country and policy case (Member States where no storage takes place omitted from the graph)*
Source: TIMES-EE.

5.4 Which policy instruments are most effective?

Three policy approaches are compared in order to address the question how to achieve significant CO_2 emission reductions through the application of CCS technologies. The first case, 'CCS standards' has already been described. The second case, 'CO_2 cap' takes the emission level from the CCS standards case as an upper bound for the overall emissions, but allows flexibility as to which technologies in which sectors are used to achieve this emission reduction. The third case, 'CCS subsidies' uses the same CO_2 emission cap as in case 2. In addition, a subsidy on CO_2 capture technologies is given. This subsidy is 35% of the investment cost at its introduction in 2015 and is reduced by one percent each year until it is zero in 2050.

5.4.1 A standards policy leads to highest CCS penetration

Figure 5.5 presents the cumulative amounts of CO_2 stored under the different policy cases, for the three world models that have reported on this. As discussed before, obliging CCS for new fossil fuelled power plants, as in the CCS Standards case, is focused on the power sector, where it does lead to the highest CCS penetration among the cases analysed.

A global CO_2 emission cap results in a lower penetration of CCS technologies, but reaches the same emission reduction at lower costs. A cross-sectoral policy scheme may also prevent 'carbon leakage' among sectors. Generally, this policy instrument induces a stronger increase in the contribution of renewable energy sources and nuclear power. There are clear differences between the models concerning the timing and extent of CCS penetration, related not only to the differences in projected fuel mix, but also to the severity of the CO_2 cap, which is derived from the emission reduction realised in the CCS standards case.

The third policy instrument analysed, is a combination of the CO_2 cap with a direct subsidising of capture technology. According to most of the models, the subsidy does have a strong impact on short-term investments, and thus does speed up the introduction of CCS. However, by 2050, the difference with the previous policy case - CO_2 cap alone - is small, so this decreasing subsidy scheme appears not to be sufficient to have a very lasting effect on CCS technology development and cost reduction. This is mainly due to the limited uptake of CCS under the carbon cap. Still, subsidies may have an effect on the choice of CCS technologies.

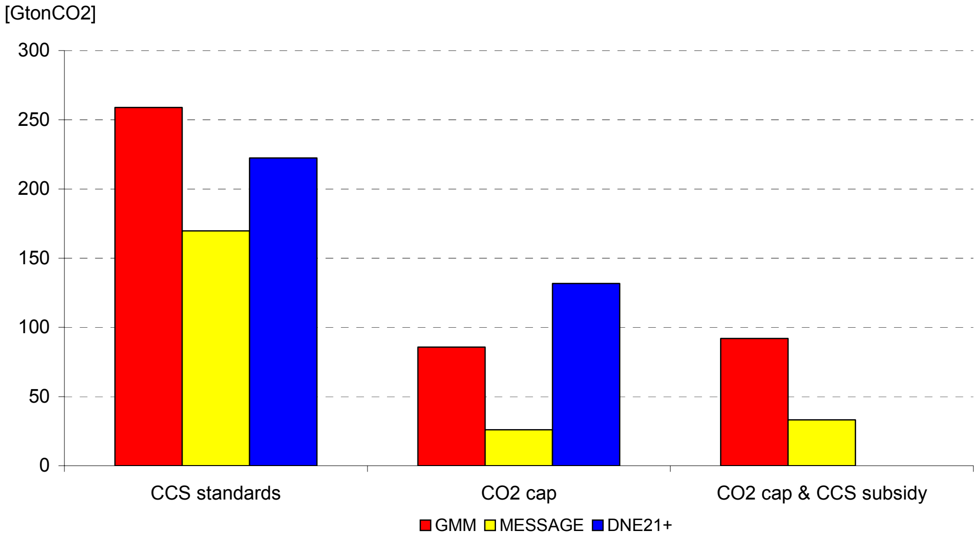

Figure 5.5 *Cumulative amount of CO_2 stored in 2020-2050*[11]

5.4.2 A carbon cap is more cost-effective

The CCS standards case is for most models the most expensive one and the CO_2 cap case, where it is left to the market to find the most cost-effective way of reducing CO_2 emissions, the cheapest. Generally, the latter case has 7-8% lower system costs than the CCS Standards case.

One of the models, PROMETHEUS, explicitly takes uncertainties into account, and points out that there is a probability that climate policy in future years becomes sufficiently ambitious to make large scale application of CCS cost-effective without the additional policies considered here.

Furthermore, the general equilibrium model NEWAGE-W reports that the obligation to use CCS technologies for conventional fossil power plants leads to a decrease in GDP. By 2030, the gross domestic product for Western Europe would be approximately 1.5% lower than in the Business as Usual scenario without a CCS standard, not taking into account indirect effects on GDP such as the export of CCS-related technologies to other countries.

5.5 Other issues determining the prospects of CCS

CO_2 capture and storage is a new technology and faces barriers to implementation. It is important to realise that the actual deployment of CCS depends on how risks and environmental impacts, public perception, and the legal and regulatory framework are addressed. The outcomes of the models reported here assume perfect storage and do not take into account any potential barriers to CCS (or other mitigation options).

There are risks associated with CO_2 storage. Although it is likely that certain trapping mechanisms are more effective over long timescales, the possibility cannot be excluded that a reser-

[11] Cumulative CO_2 storage in the CO_2 cap & subsidy case is *not* zero according to the DNE21+ model; this model has not calculated the CO_2 cap & CCS subsidy case.

voir may become leaky due to an unforeseen event, with consequential damage to humans or the environment, and to climate change. These risks should be quantified and a framework needs to be developed to qualify the risks and to determine which risks are acceptable. As a new option, with risks possibly extending over long timescales, CCS needs a legal framework that takes into account long-term liability for the storage reservoir. It is likely that a distinction will be made between offshore storage, under jurisdiction of international legal treaties, and onshore storage, mainly within the scope of national legislation.

The direct environmental impacts of CO_2 storage in suitable reservoirs are expected to be low. The environmental impacts of capture and compression of CO_2, apart from that capturing CO_2 means building a middle-sized chemical factory, are mainly found in the extra energy requirements and the associated upstream impacts of additional fossil fuel use.

Public acceptance of CCS is uncertain, but it is clear that the public is not well informed on CCS. The initial response of environmental non-governmental organisations to CCS was reserved, but several have expressed support, although concerns are voiced that CCS diverts resources from renewable energy sources and energy efficiency, therefore slowing the R&D or deployment of those options. The model results, by the way, do not confirm this, depending on the policy choice.

In the Kyoto mechanisms and the EU Emissions Trading Scheme, CCS is currently not included, although efforts are underway to address this. To account for the reductions in CO_2, methodologies should be developed and eligibility of CCS under the policy instruments currently in place should be confirmed.

5.6 Conclusions and recommendations

From a comparison of the policies adopted and results obtained, a number of conclusions can be drawn. The most general observation is that the models investigated are broadly in agreement: they confirm that CCS is likely to play a role in cost-effectively reducing CO_2 emissions. However, the actual deployment of CCS not only depends on its technical and economical characteristics, as taken into account by the models, but also on several other important aspects. The importance of the availability of reservoirs near a point source of CO_2 was already mentioned. The potential and characteristics of CO_2 storage reservoirs remain uncertain, although several studies aim at reducing this uncertainty. Furthermore, several legal and regulatory issues, related to risks and liabilities still need to be dealt with, and not much is known yet about public acceptance. Finally, CCS has not yet established itself in the climate change negotiations, and it needs an accepted accounting methodology in the Kyoto regime.

The main policy instrument analysed, which obliges new fossil power plants to install CCS technologies as of 2015, shows that 16% to 30% of global CO_2 emissions could be captured in 2050, while for Europe, due to a more limited growth of the power sector than in some other world regions, this would amount to some 21%-23% of total CO_2 emissions. These amounts could be regarded indicative of the maximal CCS penetration achievable by 2050, as the more flexible global CO_2 emissions cap induces a much lower CCS uptake, while at the same time there are several mechanisms limiting the effectiveness of any policy focusing exclusively on CCS.

First, the inertia in the power sector will slow down the penetration of CCS technologies, as plants built before the introduction of the standards regime are allowed to operate until the end of their lifetime. Secondly, imposing a strict standard requirement on one sector alone leads in some cases to moving the carbon intensive fuels to sectors where no such requirements are imposed. Third, it is difficult to target such a policy well, as it may easily provide an incentive for fossil-based technologies not covered by the standard, such as peak-load gas plants. Finally, the introduction of a CCS standards policy is often much more costly than imposing a CO_2 cap that reaches the same emission reduction.

Therefore, a prerequisite for the implementation of this type of regulatory measure is that CCS technologies are both available and affordable for large-scale application. It is recommended to gradually adopt such a policy, in order to reduce the associated cost penalty.

Although a global CO_2 emissions cap, that reflects the same emissions reduction scheme across all sectors and options combined, is a more flexible, and therefore more cost effective policy instrument, implementing this type of policy, particularly globally, clearly faces many barriers. Still, it demonstrates that while CCS may be an important option for cost-effectively reducing CO_2 emissions, it is no 'silver bullet'. Therefore, it is recommended to continue considering other CO_2 reduction options and employ mixes between the different options available, also depending on prevailing regional circumstances.

CCS on coal-based power plants, notably IGCC, is preferred over gas-fired plants. This implies that especially for countries with a booming demand for cheap (often coal-based) energy, CCS could still allow for a low-carbon energy supply. The application of CCS could lead to an increased reliance on coal, thus increasing security of energy supply. Still, the single motivation for CCS is the mitigation of climate change.

6. Trade-offs and synergies in a world moving towards a more sustainable energy system

6.1 Background

In order to analyse the trade-offs and synergies between the various technologies for which particular policy measures were investigated previously in the project, this case focuses on the possible role and impact of technology progress in the energy system. At the same time, a close relationship to the policies of the EU is desired, and particularly to those related to greenhouse gas emissions or security of supply. Therefore, a set of policy cases has been designed as illustrated in Figure 6.1, based on assumptions on enhanced technological progress, combined with variations of CO_2 values and oil & gas prices.

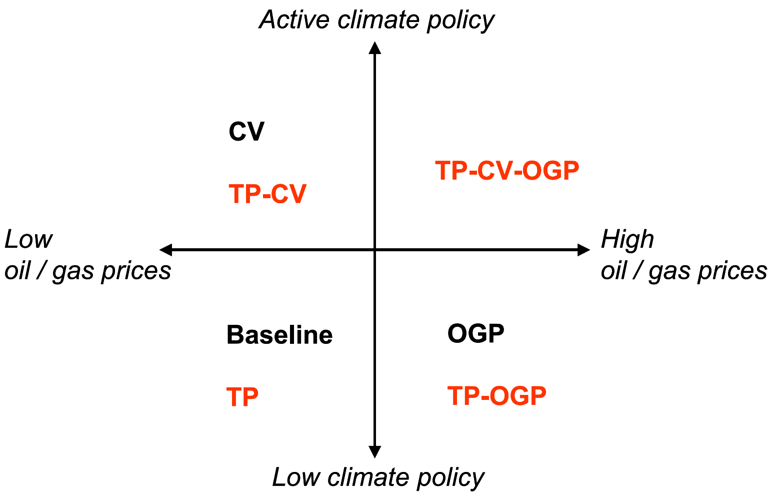

Figure 6.1 *Overview of cases analysed to determine the impact of enhanced technological progress (TP) under several background assumptions (CV=carbon value; OGP=oil and gas prices)*

Climate policy (CV)
Climate policy is reflected by a path for the CO_2 value going from 10 €/tCO_2 in 2010, 50 €/tCO_2 in 2020 to a level of 100 €/tCO_2 in 2030 and beyond. For non Annex-B countries, the policy starts in 2020 with 50 €/tCO_2 and increases in the same way.

Oil and gas prices (OGP)
In view of recent developments in the oil price, the current case study is used to address the highly relevant issue of the impact of higher energy prices on the energy system and on security of supply. The energy price scenario that stood at the base of the baseline scenario seems to be gradually less and less likely. Therefore this case study hooks up to the more recent scenario published in (WETO-H_2, 2006). The price path corresponds to the higher levels in Figure 6.2, based on the reference case in WETO-H_2. The gas price is coupled to the oil price, just as in the baseline scenario. The coal price remains unchanged. Compared to the baseline scenario, this price path provides a view on some of the effects of the current uncertainty in oil and gas prices, and particularly on the long-term impact thereof on CO_2 emissions and security of supply.

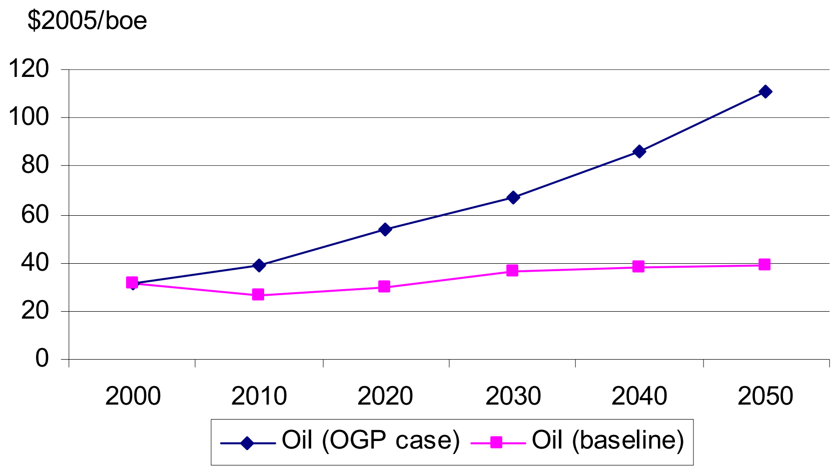

Figure 6.2 *Oil price projection in the baseline, and the higher levels in line with WETO-H_2 findings*

Enhanced technological progress (TP)
Enhanced technological progress of zero-emission power, H_2 and biofuel production technologies (fossil with CO_2 capture and storage - CCS, nuclear, and renewables) can amplify the effects of either a climate policy, or of high oil and gas prices. Enhanced technological progress in principle can come in many guises, for example as decrease of specific costs (i.e., technology learning), or improvements in other variables such as efficiencies. As central case the impact on the specific costs has been incorporated. Some models have exogenous cost projections, whereas other models treat technologies as learning endogenously by themselves or in clusters. The central approach is to investigate the impact of an increase with 50% of the cost decrease occurring in the baseline for each of the technologies of interest (see Table 6.1). For models that involve *endogenous learning*, this implies an increase of the progress ratio with 50%, i.e. the deployment elasticity (e.g. a technology with an existing progress ratio of 0.92 will now have 0.88). For both approaches, the floor cost (i.e. minimal technology cost achievable) remains at the existing level. It should be noted that this case set-up does not cover all possibilities for progress in the techno-economic characteristics of technologies.

Table 6.1 *Set of technologies to which the different models have applied the assumptions on enhanced technological progress*

	Renew-ables power & heat	Biomass power	Biofuels	Nuclear	CCS	H_2 pro-duc-tion	H_2 han-dling	H_2 con-sum-ption	Endo-genous learning	Regional coverage
DNE21+	✓ (only wind and PV)	×	×	×	✓	×	×	×	×	World
GMM	✓	✓	✓	✓	✓	✓	✓	✓	✓ (w/o clusters)	World
MESSAGE	✓	✓	✓	✓	×	✓	✓ (liq)	×	×	World
NEWAGE-W	✓ (no heat)	✓	×	✓	✓	×	×	×	×	World
POLES	✓ (excl PV)	✓	×	✓	✓	✓	×	✓ (cars)	×	World
MARKAL	✓	✓	✓	✓	✓	✓	✓	✓	Partly	Western Europe
PRIMES	✓	✓	✓	✓	×	✓	✓	✓	Partly	EU-25
TIMES	✓	×	×	✓	✓	×	×	×	×	EU-25
PACE	✓ (excl. PV)	✓	×	✓	×	×	×	×	×	EU-15

Figure 6.3 gives an example, taken from the MARKAL model, of how the assumptions of enhanced technological progress affect technology costs. As technological learning is endogenous in this model, technologies that do not penetrate in the baseline, such as liquid H_2 storage, see no cost reduction, whereas in the TP case this technology sees its cost reduced to about 12%.

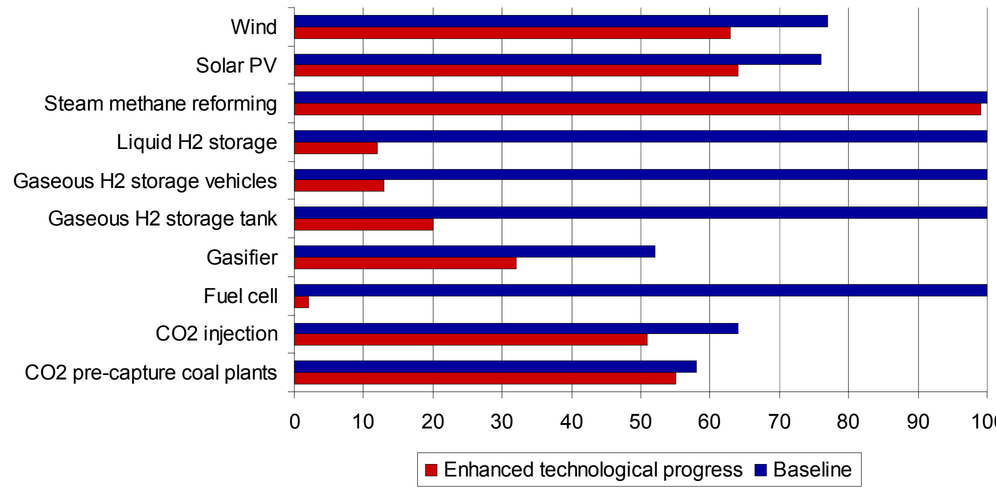

Figure 6.3 *Cost levels in 2050 as a % of the investment costs in the year 2000*
Source: MARKAL.

Baseline

The policy cases are compared to a common, harmonised baseline scenario, characterised by a moderate economic and demographic growth, and based on the IPCC B2 scenario[12]. Oil prices reflect assumptions of low to moderate resource availability. In the period 2000-2050, the world oil price is projected to increase from ca. 26 to 38 $US\$_{95}$/barrel (4.2 to 6.2 €/GJ), as illustrated in Figure 6.2. Natural gas prices within Europe, although not explicitly harmonised among the models, are projected to increase from on average 2.3 to 5.4 €/GJ in 2000-2050. Finally, some

[12] More information on key assumptions, 'business as usual' trends and developments for Europe can be found in the CASCADE MINTS baseline report on http://www.ecn.nl/library/reports/2004/c04094.

representation of climate policy or emission trading for the region of Europe has been included, reflected in a generic carbon tax of 10 €/tCO_2 from the year 2012 onwards.

Stochastic analysis
The stochastic model PROMETHEUS has done a complementary analysis and has considered the likelihood of the carbon value assumed and the fuel prices projected in this case study. While the carbon value is considered to be rather unlikely, it being on the high side of the probability distribution[13], it is quite likely that the world will see energy prices like the ones projected in the high oil and gas price scenario. The probability that oil price will be higher than the projected level is 36% whilst the same probability for the gas price is 12%.

6.2 Strong climate policy

The primary aim of a strong carbon policy is to reduce the emissions of CO_2 so as to minimize the effects of the enhanced greenhouse effect. In the case study considering such a policy, an increasing carbon value has been assumed, rising to 100 €/tCO_2 in 2030 and beyond. The models are unanimous about the decreasing share of oil and particularly coal in the primary energy consumption as a result of the policy, although there is some uncertainty over the size of the reduction. The potential role for natural gas in a world with a strong carbon policy is strongly linked to the success of its competitors: renewables and nuclear.

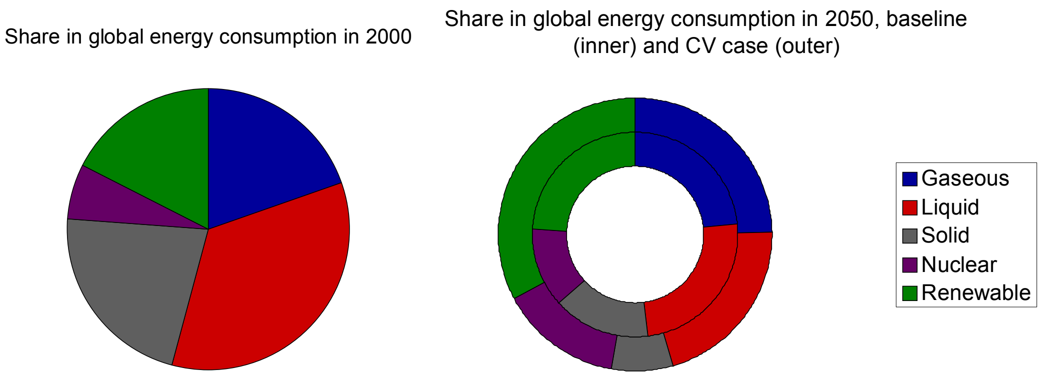

Figure 6.4 *Global energy consumption in 2000 and 2050 under baseline conditions and in a scenario with a CO_2 price of 100 €/tCO_2*
Source: MESSAGE

Power sector
The shifts are most prominently visible in the power sector. The extent to which coal still plays a role in electricity generation, depends on how the models estimate the costs and potential of CCS. Some growth for nuclear power is foreseen, mainly depending on the maximum growth limits imposed by the models, reflecting the public and political acceptance of nuclear energy. The models agree that renewables, particularly wind and biomass, gain considerably. When enhanced technological progress is assumed, some models show an accelerated growth of solar PV due to the combined impact of the CV and TP.

[13] This probability distribution is based on consultation of experts in a Delphi exercise carried out in the SAPIENTIA project (2004), and indicates that experts regard the take-off of worldwide climate policy of this ambition level unlikely.

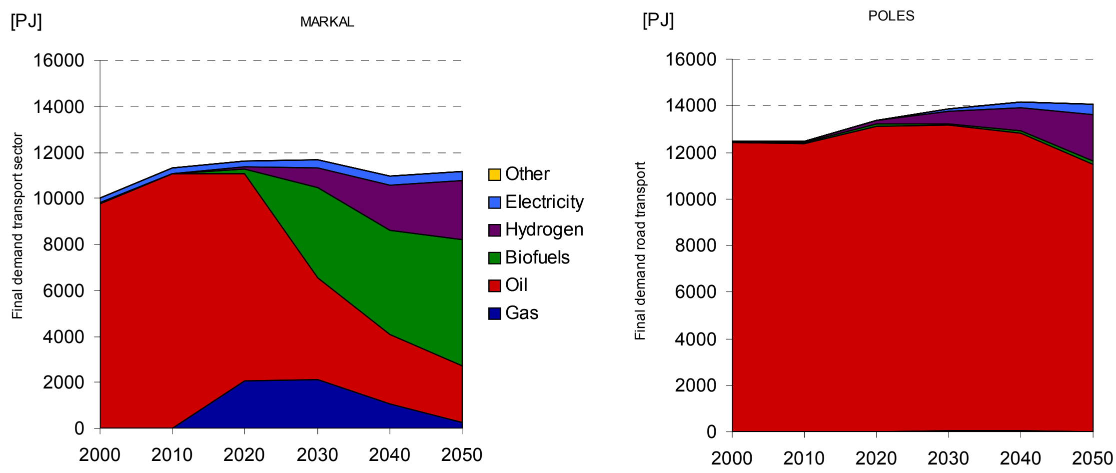

Figure 6.5 *Final demand in the European transport sector; case TP-CV (POLES: road transport only)*

Transport sector

A strong climate policy is particularly important for the transport sector, because its emissions are still strongly increasing, and technological developments are crucial to provide alternatives to the conventional technology, e.g. the internal combustion engine with petroleum based motor fuels. There are great differences in projections of the future mix of transportation fuels in the baseline, and these are reflected in the assessments of the impact of the carbon value, which may reduce oil consumption with 15-65% with respect to the baseline. Petroleum based fuels are substituted by biofuels (MARKAL, MESSAGE) or CNG (GMM, MARKAL), and demand reductions of some 5% are reported. Hydrogen has a moderate share according to most of the models, although this share may be considerably larger when the assumptions of enhanced technological progress are applied.

Emissions

The carbon policy does what it is intended for: a reduction of CO_2 emissions. At world level, the reduction ranges from a mere 40% according to MESSAGE to as much as 67% according to DNE21+, by 2050 and relative to the baseline. It is important to notice here that the baseline projections for CO_2 emissions in 2050 among models differ substantially, as illustrated in Figure 6.6, due to different estimates for the role of renewable technologies and in particular learning effects for wind energy and biomass. At European level, the shift to renewables, coal with CCS, and possibly nuclear power allows CO_2 emissions to be reduced with 21%-54% in 2050, with respect to the baseline. When the possibility of enhanced technological progress is added, the transport sector, thanks to the breakthrough of fuel cell cars, may contribute with up to 10% additional emission reduction.

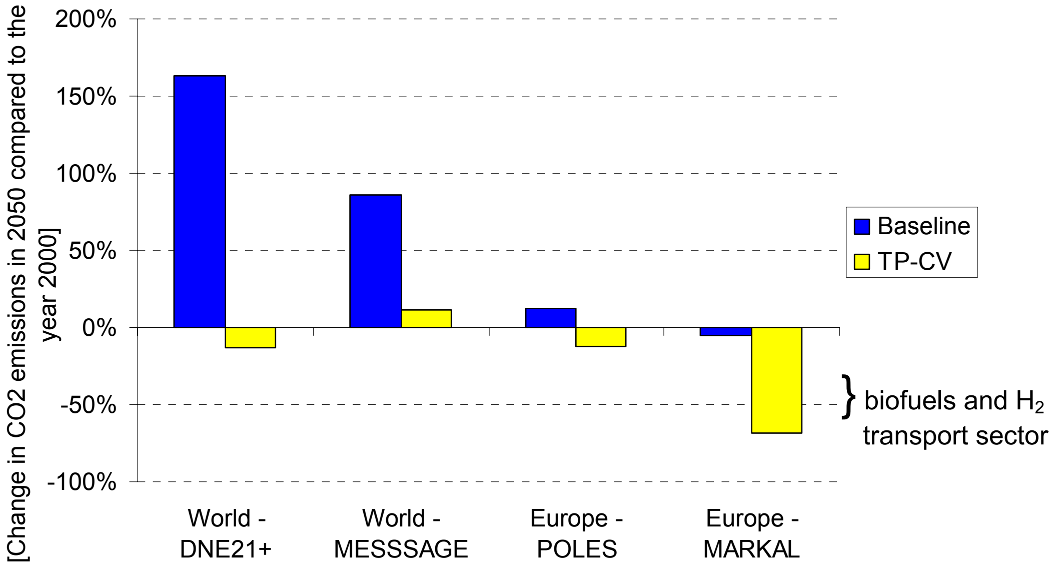

Figure 6.6 *Change in CO_2 emissions in 2050, relative to the year 2000, under baseline conditions and with ambitious climate policy combined with enhanced technological progress.*
Source: selected models.

Security of supply
For the energy dependence of regions with relatively few resources of their own, such as Europe and Japan, the introduction of a carbon tax does not necessarily provide a framework in which the dependence on critical resources, especially oil and gas, is reduced. As the DNE21+ model illustrates, a strong carbon policy may result in a substantial increase in natural gas consumption, leaving at the same time the consumption of oil almost unchanged, for a region like Japan that has few options for massive production from renewable resources.

Economic impacts of the carbon value
In the global general equilibrium model NEWAGE-W the carbon policy case has been studied in detail, differentiating between a combined action from Western Europe (WEU) and Pacific Asia and Oceania (PAO) and a single action by Europe. A direct effect is a decrease of exports of solid fuels from PAO in the case of a single action by Europe. This holds not only for exports to WEU, but also for exports to other world regions, because of negative GDP induced spill-over effects. At the same time, it results in higher imports of oil and gas into the PAO region.

In case of bilateral action by the WEU and PAO regions the impacts on welfare for these two regions are roughly of the same order of magnitude - a little over 2% for WEU against a little under 2% for PAO. Quite interesting is the small difference between the bilateral and unilateral policies for the welfare in Europe. This indicates that for the time period studied with the model, it matters little for Europe whether Pacific Asia and Oceania enters the carbon policy scheme. It does however raise the question what North America entering the scheme would bring, particularly regarding the welfare effects for the respective regions.

6.3 High oil and gas prices: the return to coal?

If the price of oil increases up to 110 $/barrel in 2050, and natural gas prices also rise substantially above the baseline level, as is projected in the high oil and gas price (OGP) scenario, the contribution of oil to the primary energy consumption is substantially reduced, as well as the consumption of natural gas, at least in the European models. The world models show less agreement on this, which is related to the presence of gas fields in several world regions. Once the import prices of gas reach a certain height, demand will drop and it becomes more attractive to use domestic gas resources. As a consequence, and according to two of the models, the gas consumption in production regions then may reach higher levels than in the baseline.

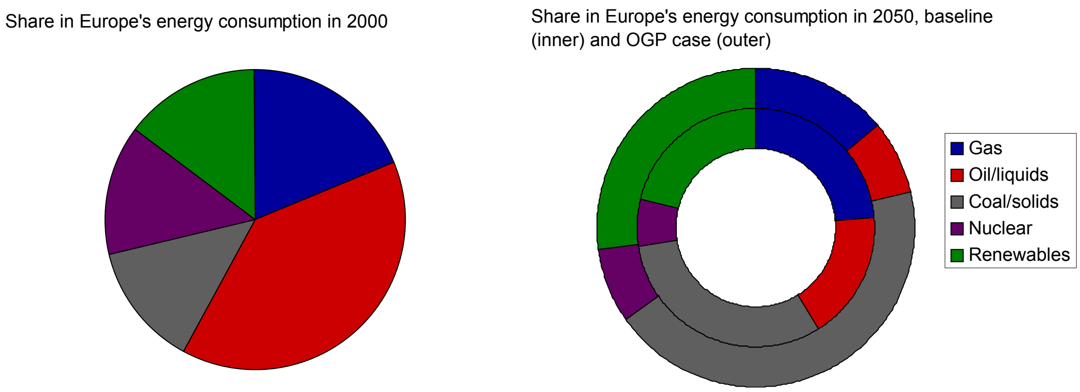

Figure 6.7 *Global energy consumption in 2000 and 2050, under baseline conditions and in a scenario with high oil and gas prices.*
Source: MARKAL.

Power sector
Again, the largest shifts are visible in the power sector and the transport sector. For other sectors, the high oil and gas prices merely induce a reduction of demand, and an enhanced deployment of biomass. In the power sector, the search is for alternatives to natural gas. Nearly all models expect drastic reductions in gas input for power generation, and generally, this is compensated by an increase in coal-based electricity production. In principle, nuclear power is a cost effective alternative to gas in the power sector, its expansion, however, depends on political decisions.

Transport sector
The transport sector is most sensitive to increases in oil prices, and to some extent, gas prices. In Europe, according to POLES, by 2050, the consumption of oil-based automotive fuels (diesel and gasoline) could be reduced by more than a quarter (compared to baseline developments) and substituted mainly by hydrogen. The MARKAL model expects an even faster adjustment of the transport sector and shows a large penetration of biofuels, which could replace virtually all oil in 2050. The passenger car fleet consists largely of ICE cars on biofuels and some 10% CNG cars. The enhanced technological progress gives momentum to the hydrogen based passenger cars, mainly fuel cells cars. Thus, in the TP-OGP case, models estimate 20-95% of the European passenger car fleet in 2050 to be based on hydrogen.

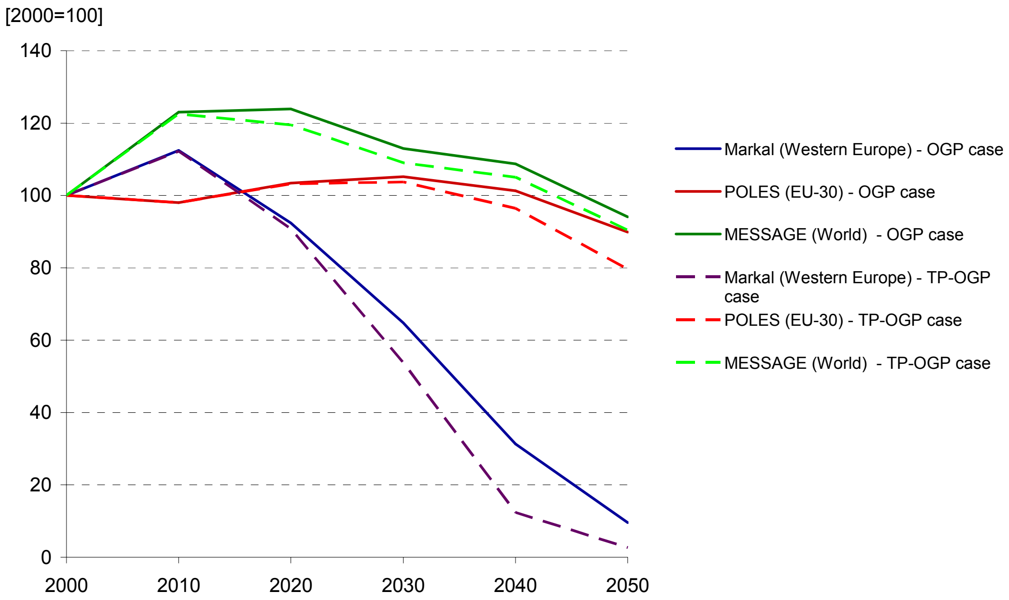

Figure 6.8 *Consumption of oil in the transport sector relative to the year 2000; cases OGP and TP-OGP*
Source: selected models.

The global picture gives additional insights. On world level the enhanced technological progress is more influential, and according to POLES results, it is not Europe where the highest increase in H_2 use takes place. It is rather concentrated in the North American and Asian regions. This is probably due to the fact that in 2040 and beyond the largest demand for new cars emerges outside Europe. The other world models, as well as PRIMES for Europe, show only marginal responses in the transport sector. An important determinant seems to be the existence of alternatives in the model. While hydrogen is an option in two out of three models, this substitution option plays only a modest role up until 2050 (see the discussion on hydrogen below).

Emissions
The impact of the high oil and gas prices on the global CO_2 emissions is to increase levels somewhat, which is reflected in all world models. The main reason for the increased emissions is a 'return to coal', particularly in the power sector. The European models show very moderate reductions, compared to the baselines, mainly due to the penetration of hydrogen in the transport sector.

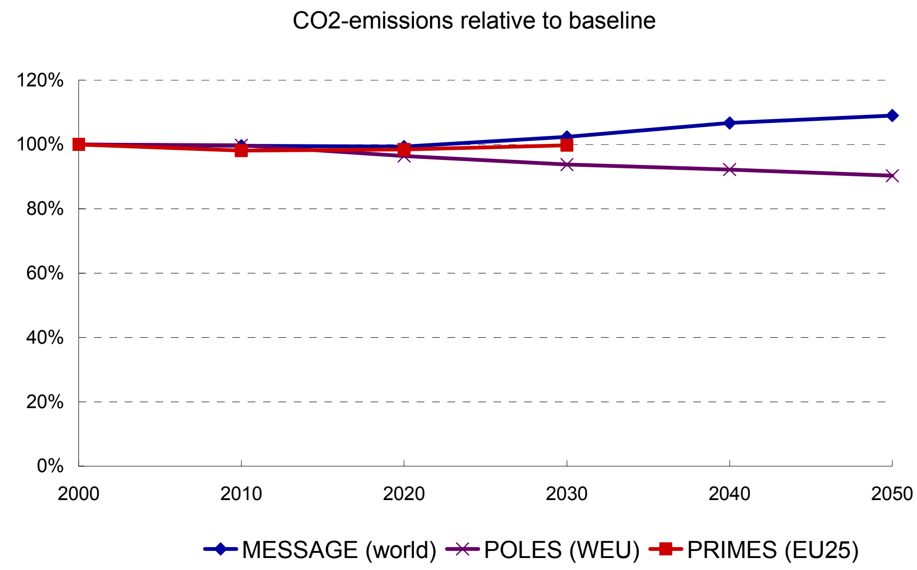

Figure 6.9 *Change in CO_2 emissions in the scenario with high oil and gas prices, relative to the baseline*

Security of supply

As far as security of supply is concerned, Europe's oil import dependence is generally reduced, although the assessments of the remaining dependency of Europe's transportation sector on oil strongly differ among models. For Japan the DNE21+ model indicates that as far as the 'strategic' fuels are concerned a considerable decrease in oil and gas consumption occurs so that in all the security of supply in Japan seems positively influenced by high oil and gas prices.

However, as most models indicate that the dependence on oil-based products remains strong in the transport sector, an important sector remains highly vulnerable, and possibly all the more so if one assumes that the high prices are an indication of strategic behavior of producers, or political turmoil, and thus a forebode of possible interruptions in supply.

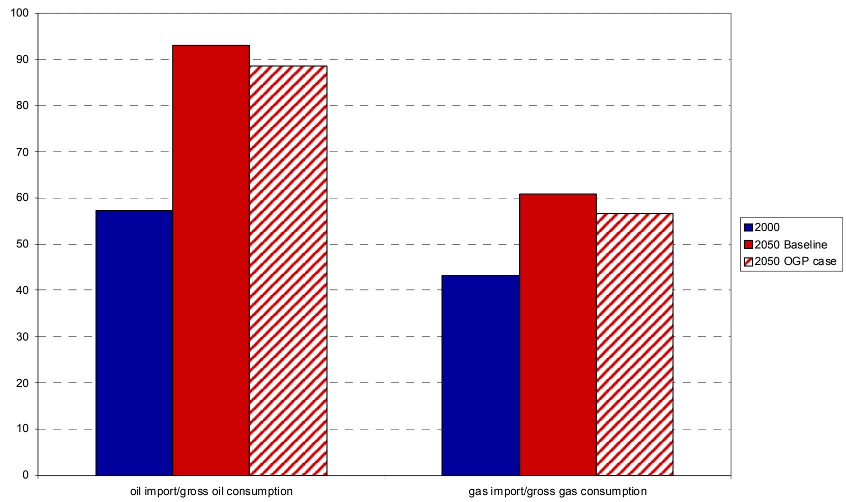

Figure 6.10 *Changes in Europe's import dependency for oil and gas under baseline conditions and in a scenario with high oil and gas prices.*

Source: POLES (EU-30)

6.4 Enhanced technological progress

The impact of enhanced technological progress by itself is quite limited, all models agree, particularly when looking at aggregated results such as primary fuel consumption, CO_2 emissions or security of supply. In itself this is not surprising, as the enhanced progress is assumed to come on top of the (substantial) technological improvements that occur in the baseline and policy cases. However, when looking at individual technologies, the enhanced progress may have a profound effect, such as a strong growth in use of wind energy, hydrogen, or solar PV. Such results are quite dependent on the specific assumptions for respective technologies, as is illustrated by the lack of consensus with regards to the technology-specific growth prospects.

In case of a combination of technological progress with a carbon policy, or high oil prices, or both, the impacts on the energy system are generally of the same order of magnitude as for the baseline case. Some of the models, however, indicate that for hydrogen, the additional technological progress - in combination with carbon policy or high oil prices - may be essential for a breakthrough in the transport sector. Additional cost decreases of not only fuel cells, but also of other components such as H_2 storage tanks appear to be necessary for fuel cell cars to become competitive. Another remarkable observation is that the enhanced progress may hamper the introduction of renewables, because other emission-free technologies become more cost-competitive. A striking example is provided by Japan, where low-cost wind energy sites are sparsely available, and progress of CCS technologies brings a cheap competitor in the market.

The macro-economic models (global NEWAGE-W, EU-specific PACE and NEMESIS) agree on the impact of technological progress by itself, even though the impact on the details of the power sector differs substantially. All models foresee a small positive effect on the Hicksian Equivalent Variation (HEV), of the order of a few tenth of a percent by 2030. However, the agreement totally disappears as soon as the enhanced progress is combined with a carbon policy. Here NEWAGE-W expects effects of the same order as in the baseline, while PACE foresees that the negative effects of the carbon policies are reduced by 1/3.

Another interesting outcome of the global NEWAGE-W model is that the impact of the technological progress is substantially more pronounced for the PAO region than for the North America (NAM) region, in all cases. This is due to the more pronounced growth in the electricity sector in the region, and particularly to the role that nuclear power production can play here.

The stochastic evaluation results derived from PROMETHEUS are in line with the individual outcomes of the various deterministic models. Indeed enhanced technological progress has a different effect on different technologies depending mainly on their maturity (new technologies are more probable to register additional improvements than mature technologies). In addition the synthetic probabilistic evaluation indicates that technological progress for the majority of technologies is more likely in the presence of high fuel prices.

6.5 Prospects for hydrogen

It is generally believed that a strong carbon policy could stimulate the introduction of hydrogen, it being a flexible fuel with high potential to replace oil-based products in the transport sector. As such, a high oil and gas price scenario could also favour hydrogen, and definitely a combination of the two drivers would seemingly provide a very strong case for hydrogen.

All models that include a description of the hydrogen sub-system (GMM, MESSAGE, MARKAL and POLES) reflect the strong reaction of hydrogen production and consumption to external drivers such as climate policy and oil prices. In all models, both the introduction of the carbon policy and the enhanced technological progress are stimuli for the deployment of hydrogen technologies. But this is about as far as the agreement goes.

On a global level, the level of hydrogen production in 2050 in the baseline ranges from a little over 3 EJ according to GMM, to almost 23 EJ according to MESSAGE, while the maximal production in 2050 ranges between almost 14 EJ in GMM to almost 34 EJ in MESSAGE. In GMM, the main consumption of hydrogen is in the transport sector, especially in the scenarios with high levels of production. The models provide different views on the major consumption sectors of hydrogen, with almost complete dominance of the transport sector to a share as high as 50% of all hydrogen consumed in stationary applications in residential, commercial and industry sectors according to POLES, or possibly even higher in case of strong competitors in the transport sector, as in MESSAGE.

Ranking of drivers
More in general, the ranking of the drivers is quite different between the models. According to GMM, the most important factor is climate policy, followed rather closely by the high resource prices. Technological progress compared to these is only a minor driver. Furthermore, the combined effect of climate policy and high prices is less than additive, while a combination of either or both of these drivers with enhanced technological progress gives rise to less favorable circumstances for hydrogen. In MESSAGE, also climate policy is the most important driver, but the order of enhanced technological progress and high oil and gas prices are reversed. What is more, due to the alternative transport fuels and natural gas being the preferred feedstock, high prices are even a negative driver for hydrogen. And like in GMM, the combination of technological progress and another driver does not lead to synergy effects, but quite contrary poses barriers for quick take-up of hydrogen. In POLES the major driver is technological progress, followed by resource prices. On a global scale the introduction of a climate policy is slightly negative for hydrogen, although on the scale of Europe the combination of any driver with another leads to increased penetration. In MARKAL, technological progress is the essential factor required to achieve a breakthrough of hydrogen, particularly in the transport sector.

Hydrogen production and consumption
There is as little agreement on the preferred feedstock for hydrogen, as there is on the overall production level or the importance of drivers. While GMM and MESSAGE agree on the importance of biomass and natural gas, they differ completely on the relative importance of the two. At the same time, POLES sees a more balanced production portfolio, with a slight preference for coal as feedstock.

6.6 Macro-economic impact of carbon policies and high resource prices

The impact on the economy as a whole of the various policy cases studied here has also been assessed using macro-economic models. In the global NEWAGE-W the carbon policy case has been studied in detail. In the EU-specific models PACE and NEMESIS both the carbon policy case as well as the high oil price case have been studied.

GDP and welfare
The models show quite some variance in the impact of the policy cases on the overall CO_2 emissions. The impact of the carbon policy on welfare shows a similar variation amongst the models, the model NEWAGE showing effects roughly twice as high as the European PACE model, as can be seen in Figure 6.11. The figure shows welfare measured in terms of Hicksian Equivalent Variation (HEV)[14].

[14] NEMESIS gives results only for GDP, but these are comparable to the effects on GDP in the two other models.

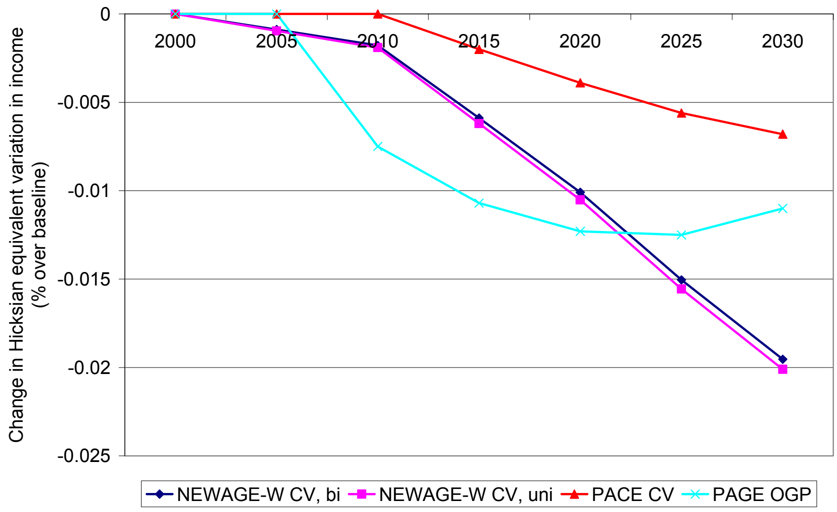

Figure 6.11 *Change in Hicksian Equivalent Variation in income over baseline value*[15]

Electricity price effects
With PACE an analysis of the introduction of a carbon policy as well as high resource prices on the generation costs for electricity has been made. Obviously, both will lead to increases in costs, and as such will lead to a diminished demand for electricity. A remarkable feature here is that although the carbon policy leads to relatively higher generation costs, the decrease in electricity demand is less than for the high oil and gas prices. This is due to a high increase in electricity imports. An essential assumption here of course is that the carbon policy is limited to Western Europe.

Variation over EU Member States
The results from NEMESIS show that there may be quite some differences between the various Member States. While the average impact on European GDP is close to -1.5% in 2020 according to this model, the individual countries show deviations of over plus or minus 1% compared to this value. This difference is strongly related to the importance of energy prices for an economy, as well as dependent on inflationary reactions in each Member State. As in the other macro-economical models, the combined case shows that the two cases are not just additive, as the European average lays around -2.5%, and the variation remains of the order of plus or minus 1%.

6.7 Conclusions

Enhanced technological progress
In this case study, *enhanced* technological progress in terms of investment cost reductions has been modelled to reflect the impact of additional R&D policies on top of the considerable technological progress already represented in the baseline and policy cases. It should be stressed that this case set-up does not cover all possibilities for progress in the techno-economic characteristics of technologies. Looking more closely at the role and contribution of the enhanced technological progress, it appears to have the most significant impacts on hydrogen production, storage and consumption and on the use of renewables (wind and solar PV) for power generation. This may lead to a reduction of Europe's dependence in electricity imports. All energy system models indicate that the enhanced technological progress leads to a decrease in overall costs of a few percent, both for the carbon policy as well as for the high oil and gas price scenario. While in itself such impacts may seem minute, it is important to realize that the assumed additional cost

[15] See text for an explanation of the model-specific scenarios.

reductions involve only a limited section of the energy system, and that from this perspective the cost savings may be substantial.

Furthermore, models with endogenous technological learning show the most sizeable impacts of technological progress, because the impacts of the other drivers (carbon value, high oil and gas prices) are reinforced by the stronger cost reductions as a result of higher volumes of carbon-free technologies. Since this reflects the effect of learning-by-doing, it indicates that the impact of enhanced technological progress may in reality be stronger than what has been shown by most of the models in this case study. However, it remains a challenge to design R&D policies that actually achieve these stronger cost reductions.

Hydrogen can play a significant role in meeting challenges posed by the introduction of climate policies or increasing oil and gas prices. Enhanced technological progress in general does not necessarily lower the barriers for hydrogen, as competitors may also profit from increased research efforts, but if the effort is aimed specifically at hydrogen technologies, technological progress will considerably speed up the uptake of hydrogen in the energy system.

Climate policy

The global energy system can meet the challenge of a strong climate policy, with carbon prices up to 100 €/tCO_2, through a mix of options. In the power sector, penetration of renewable and nuclear technologies up to 50% combined with the deployment of carbon capture and storage can result in emission reductions up to 40%. Similarly, in Europe, CO_2 emissions can be reduced with 21%-54% in 2050. The contribution of coal remains uncertain, as it depends on the estimates for costs and potential for CCS.

Regarding the setup of a climate policy, for Europe it seems to matter little if its current allies participate in the policy, as this will change the welfare effects by a few tenth of a percent at most. The main question remains what would happen in welfare terms if North America would join Europe in setting a carbon tax up to 100 €/tCO_2.

High oil and gas prices

The implications of high oil and gas prices are not necessarily environmentally favourable, as there is a tendency towards coal, even though renewables also benefit. The additional effect of technological progress again is strongest in the transport sector, where it can stimulate hydrogen, but also biofuels, to reduce the dominance of petroleum-based automotive fuels.

As illustrated, finally, by the ‘combined case’, a carbon value could counter the adverse environmental impacts of high oil and gas prices. This would specifically provide opportunities for renewable energy technologies, which have shown to possess a large potential for learning and associated cost reductions. Alternatively, the prices of oil and gas could be decoupled, to prevent the undesired shift to coal without CCS.

7. Overall conclusions from the models involved

7.1 MESSAGE: a global energy system model

The model used for the CASCADE MINTS study at IIASA, MESSAGE, is a ‘bottom-up’ systems-engineering optimisation model of the energy system that disaggregates the world in a number of regions. The model provides a framework for representing the global energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services. MESSAGE model was used in all work packages studied under the part 2 of the CASCADE MINTS project, except for the study on nuclear.

A common conclusion for several of the individual studies made is that holistic policy instruments are often much more effective in producing sustainable results; subsidies targeted only for renewable electricity generation proved to be much less efficient in reducing CO_2 emissions and increasing the share of renewable energy sources on the primary energy level than schemes where also other sectors, e.g. transport, would have renewable energy sources subsidized. Similarly, imposing strict standards for carbon capture technologies proved to be significantly more costly than a direct emission cap applied for all sectors and technologies. In both of these cases the asymmetrical use of policy instruments moves fossil fuels to the sectors where their use is not punished, therefore creating an inter-sector ‘carbon leak’.

Another interesting finding is that there exists a complicated interplay between the drivers of the energy system and when several of these drivers are changed simultaneously, interesting results can often observed. This was clearly observed in the case were fuel prices, carbon taxes and the speed of technological progress were studied. The results showed that the effect of several drivers altered together is clearly different from a sum of the effects of single drivers changed and with some combinations single drivers may even pull in different directions than when used alone.

As both of the general conclusions presented here suggest, a possibly fruitful area for future research may be in studying scenarios where the dynamics and interplay of several key drivers are studied simultaneously and exhaustively. Such an exercise may offer advice in defining the combinations of developments of individual drivers that may lead the energy system into directions deemed preferable - or to directions that are to be avoided.

7.2 GMM: a global energy system model

PSI used the GMM model for the CASCADE MINTS project. GMM (the Global MARKAL Model) is a ‘bottom-up’, partial equilibrium energy-systems model that provides a relatively detailed representation of energy supply technologies and a stylized representation of end-use devices. It addresses technology dynamics in the energy system by indigenizing learning-by-doing for selected electric and synthetic fuel technologies. Also, demands for energy are self-adjusted to increased marginal cost of energy services that results from the imposition of policy constraints.

Renewable technologies
Three levels of subsidies for renewables are introduced in GMM and a sensitivity analyses is performed assuming learning-by-doing for power generation systems including biomass and geothermal energy. The conclusion was that the design of subsidies should always take the regional resources and technology specific conditions into account and help to avoid lock-out of

systems like solar PV or to avoid support of systems that are already competitive, i.e., to avoid potential over- and under-subsidizing. Policies to design efficient subsidies measures should be further investigated and identified.

Nuclear Technologies
The study on nuclear technologies has quantified different scenarios related to nuclear breakthrough in combination with carbon taxes. The main conclusion is that nuclear energy is an important component of the portfolio for carbon mitigation strategies and for the security of supplies and needs to be supported by policies in favour of cost and performance improvements. Needed technology improvements for a nuclear breakthrough include: introduction of inherent safe reactor systems; standardization and modularity in plant construction; better utilisation of fissile materials in advanced fuel cycles; reduction of the amount of nuclear wastes for final disposal; reduction of proliferation risk by adopting appropriate fuel cycles and reactor designs. All these options require a detailed technology assessment model with specific software development for the representation of the advanced and generation IV reactor concepts.

Carbon Capture and Sequestration: CCS scenarios analyzed include CCS Standards, a carbon constraint without standards and a carbon constraint with subsidies. CCS standards for fossil-based power generation might be potentially a powerful policy instrument to reduce substantially CO_2 emissions but, technologies should first become matured, and a gradual adoption of such standards is needed to reduce the associated cost penalty. This smooth penetration will be better obtained if supporting policy are defined following market oriented principles instead of CCS standards.

Technological Progress (TP) synthesis study concluded as follows:
Hydrogen production is mainly based on biomass and gas as a primary source of energy at low gas prices and follows the regional resource availability. Hydrogen production gets its maximum level when high oil and gas prices together with an active climate policy are applied and is mainly used to substitute for oil in private transportation and less for decentralized power generation.

The combination of objectives related to climate policy and security of supplies, as obtained under the TP and Carbon policies, is very attractive. In that case, we realize not only a better response of consumers to price changes but also a technology portfolio consisting of renewables, nuclear and coal with CCS systems (while the captured CO_2 is disposed to geological sinks) together with biomass farming for the production of hydrogen to displace oil in the transport sector. Enhanced R&D should be always a function of the policy objective we are aiming for. Our analyses indicate that an enhanced benefit for each € spent on R&D could be obtained if the targets of climate policy and the security of supplies are simultaneously followed.

7.3 DNE21: a global energy system model

The DNE21+ model is a linear programming model that employs a bottom-up approach for the technologies of the energy supply side and minimizes the total cost of world energy systems. The model considers a time range that covers the first half of the 21st century. The model disaggregates the whole world into 77 regions: US, UK, Germany, France, Japan, China, Russia, etc., in order to consider regional differences in energy resources, growth in energy demands, etc. Four case studies were carried out by using the DNE21+ model. The overall conclusions are as follows.

- *RES case*: The assumed subsidy in RES case is not enough for deep penetrations of renewables, because of their high costs and their unpromised supply capacities for instantaneous peak demands of electricity. As a result, the effect on CO_2 emission reduction is limited. The optimal technological portfolio can achieve the same amount of CO_2 emission reduction with a smaller energy system cost increase by 0.2 percentage points.

- *NUC case*: The influence of phase out of nuclear is negligibly small because the phase out is also observed in the case without the constraint for nuclear. For Breakthrough case, the relatively large use of nuclear power is achieved. When R&D costs for the breakthrough are not counted, the energy system cost increase is reduced by 0.6% relative to Phase out case.
- *CCS case*: The achieved CO_2 emission reduction in CCS case is 17.2 $GtCO_2$/yr in 2050; this standard has a large impact on the emission reduction. The optimal technological portfolio can achieve the same amount of CO_2 emission reduction with a smaller energy system cost increase by 1.6 percentage points. However, CCS contributes a large emission reduction also in the optimal technological portfolio and therefore this CCS standard policy would be effective when a large amount of emission reduction is required.
- *TP case*: Here, 'TP (technological progress)' means the acceleration of the cost reductions of wind power, PV and CCS technologies. The global impacts by the assumed TP are increase in the usage of wind power and PV and decrease in CCS usage. However, regional differences in the potentials of these technologies affect the results significantly and the opposite impacts are observed in such regions with small potentials of the renewables as Japan.

Generally, achieving bottom-up type targets of CO_2 emission reductions in specific sectors or technologies are more expensive than top-down type targets, e.g., a fixed amount of emission reduction. On the other hand, international agreements with respect to bottom-up type targets seem to be reached with smaller difficulty than top-down type targets. The trade-off relationship exists between bottom-up type and top-down type targets; this study represents quantitative evaluations of differences in the cost between the bottom-up type and top-down type targets in RES and CCS cases, and will support the policy decisions.

According to existing regional differences in energy resources, energy demands, technology potentials etc., optimal technology strategies and policy measures are different over regions for emission reductions, which justifies such models having high regional resolutions as DNE21+.

Currently, regional cooperation arguments for technology development, transfer and diffusion, e.g., Asia-Pacific Partnership of Clean Development and Climate (APP), are exploring energy efficiency improvement and CO_2 emission reductions in addition to the frameworks under the UNFCCC. This study will contribute also to such tasks orienting bottom-up type targets.

7.4 POLES: a global energy simulation model

The POLES (Prospective Outlook for Long-term Energy Systems) model is an Integrated Energy-System Simulation Model applying systems dynamics methodology. It is characterised by a detailed representation of both energy demand, and supply technologies (the latter includes end-use, conversion and production technologies). Demand sectors are disaggregated into industrial sub-sectors and processes, residential and service categories, and transport modes. Demand and technology developments are driven by exogenous scenario assumptions, mainly GDP and population growth rates.

The POLES model stands out with its global perspective of the world energy system with 47 regions. The model covers the whole demand and supply sides, which makes it well-fitted for modelling global and regional, highly interconnected energy markets. Typical example are the crude oil and natural gas markets, where prices are estimated through endogenous price setting mechanisms, generally a lacking feature in other (regional or country specific) models.

In summary the following main conclusions could be drawn from the performed model experiments:

1. An active renewable support policy (aiming at the target similar to the present long term EU targets of 12 to 20% renewable share in the primary energy consumption) requires signifi-

cant amount of subsidies, similar to the present base-load electricity prices in Europe. The model projections also indicate that this level of subsidisation should be maintained through the whole time-span (i.e. 2001-2030) in order to reach the proposed targets. According to the POLES results the power generation sector stands out with its contribution to the renewable base. In primary energy terms, around 40% of green electricity generation is projected by 2030. Both the carbon emission reduction potential and the impact on the security of supply indicators are significant and very positive for this policy instrument.

2. Various levels of carbon emissions constraints were modelled in the different case studies - through exogenous carbon value paths representing the existing and planned trading schemes - and all of them showed the efficient functioning of the instrument. Interestingly the impact on the security of supply indicators is ambiguous, depending on the influence on the natural gas markets. Through increasing natural gas consumption, the final effect of this policy instrument could be slightly negative. Carbon capture and sequestration (CCS) technologies could significantly contribute to carbon reductions. However the model indicates that maintaining their capacities in the long term requires continuous support for them (stable supporting mechanisms or obligations).
3. The technological progress (TP), carbon capture and sequestration and nuclear case studies in combination with the carbon constraint scenarios show that nuclear based energy technologies could play an important role in the future energy system. They could offer a solution to many problems coming from the development of the global energy system, but require the fulfilment of two conditions: the new nuclear designed (NND) technology will be available in the foreseen future, and secondly this technology will be accepted by the nest generations. The nuclear phase-out scenario shows that a carefully planned capacity phase-out is also feasible, but as a consequence the climate change and security of supply issues become even more challenging. Technical aspects (availability of the NND technology) and non-technical aspects (inherent social values, perception and attitude toward the use of nuclear power) make the future of the nuclear energy highly uncertain.
4. Policies aiming exclusively at the power generation and energy intensive industrial sectors show their limitations in achieving the serious commitments of the EU for the sustainable future developments of its energy system (with global consequences). From this point of view the expected development of the transport sector (both personal and freight) is a key issue. Policy portfolios that fall short to regulate this sector are deemed to failure. In this context hydrogen does not offer a quick solution in the near future. The model results suggest that significant amount of hydrogen use could be expected only after 2030.

7.5 PROMETHEUS: a global stochastic model

This is a summary of the conclusions derived using the PROMETHEUS stochastic model to assess the case studies analysed within Part 2 of the CASCADE MINTS project.

The output of PROMETHEUS consists of a massive Monte Carlo set representing at least 1000 alternative scenarios; it can thus be considered that the different case study assumptions, to the extent that they are probable at all, are incorporated in the 'baseline' results. Moreover, the introduction of specific values for given stochastic variables or even the calibration of the model to reproduce such values as means, is contrary to the philosophy of the model.

On the other hand, PROMETHEUS being a stochastic model can be used to perform uncertainty analysis regarding the assumptions and the evolution of exogenous variables of the Case Studies. The uncertainty analysis was performed in order to:

- Provide assessments on the likelihood of the different assumptions one by one.
- Provide evidence of joint variance of the different variables in order to identify possible stochastic dependence.
- Provide joint probability assessment by evaluating the assumptions synthetically in order to assess the likelihood of their occurrence at the same time.

Using PROMETHEUS three case studies were examined assessing the effects of different technology policies on greenhouse gases, the security of supply and cost and investigating the trade-offs and synergies of alternative technology policies.

PROMETHEUS is capable of refined *security of supply* analysis in that it can measure impacts in terms of changes in probability of an adverse event, which corresponds closer to the notion of security than more traditional measures such as import dependence and diversity indices. The usual supply concerns relate to oil price shocks. In this direction, the uncertainty analysis suggests that under the baseline assumptions, there is a substantial probability (almost 50%) that a sudden price hike of more than 15 $95 in the oil price will occur by 2030.

However given the low penetration of oil in the power generation sector (especially in Europe), it was deemed more appropriate to also address the question of security of gas supply, since gas is projected to take a substantial share in power generation in the next two decades. The measure of security retained was the highest increase in imported gas prices over any 3-year period to the year 2030. According to the results the probability that the highest increase in gas price will exceed 50 $€_{2000}$/toe is 64% for the baseline scenario and 58% for the combined policy (doubling R&D spending on renewables and introducing 2.5 $€ct_{2000}$/kWh direct support) of the renewables case study. The same probability for the threshold value of the 100 $€_{2000}$/toe is about 10% and 8% respectively.

Baseline results indicate that the probability that energy related CO_2 emissions worldwide more than double between 1990 and 2030 is nearly 85%. By evaluating the outcomes of the *Renewables Case Study* it was found that the 1cent/kWh direct support policy and the R&D on renewable policy are about equivalent in meeting the renewable targets (target levels: 28% and 37%).The R&D scenario implies a certain cost which is 20% higher than the mean cost of the direct support scenario. However, when the costs are expressed in terms of avoided CO_2 emissions, the direct support policy is substantially more expensive. Looking at the CO_2 effectiveness of the stronger policies it is worth noting that the combined case (doubling R&D spending on renewables and introducing 2.5Ec00/kWh direct support) compared to its almost equivalent in terms of achieving the target direct support policy case (of 4Ec00/kWh) is much cheaper on average. Moreover, the probability to achieve the 28% target is ~87% while the same probability as regards 37% target is ~59%.

The *CCS Case Study* results indicate that the introduction of stringent requirements for CCS with fossil fuel plants improves the chances of penetration considerably but the policy risks being costly. However, the prospects of renewables and nuclear are just as likely to improve from such requirements therefore the main element determining the chances of CCS making major inroads is the possibility of intensive climate policy in general. Subsidies work equivalently but to the extent that they enable lower overall policy intensity the effect tends to be neutralized. The probabilities in cases 2[16] and 3[16] of the CCS Case Study are much higher than in case 1[16] and the reference case due to the higher (on average) carbon value imposed, since the higher the carbon value level the faster the convergence of the production costs. However, in case 1 the higher probabilities (compared to the reference case) are attributed to the learning by doing effect. Biomass gasification combined with CCS offers prospects for negative costs in cases of very high carbon values but in probability terms, it is the least likely option for major CCS introduction because of considerable risks of high capital cost.

[16] Case 1: All fossil based fuel plants (excluded CHP, peaking devices, biomass gasification) had to be equipped with a capture facility (2015 developed counties, 2025 LDCs)
Case 2: The cumulative CO_2 emissions of Case 1 was used as a constraint on average
Case 3: The cumulative CO_2 emissions of Case 1 was used as a constraint on average and the capital cost of CO_2 capture and storage facilities was subsidized

In the Case Study '*Trade-offs and synergies* for renewables, nuclear, CCS and hydrogen' technological improvement (50% additional reduction in the capital cost difference between 2000 and 2030) was assumed to a selection of technologies (renewable, biomass, nuclear, carbon capture, hydrogen related). The evaluation of PROMETHEUS correlation matrix indicates that clustering among technologies, climate policy intensity and fossil fuel prices affect the technological progress of the technologies. More specifically, the cost improvement of biomass based technologies are strongly correlated since they share common components as members of the same cluster matrix (i.e. biomass handling). The cost improvement of Renewable based technologies are strongly correlated as well. These technologies are influenced by the same conditions since their learning by doing induced technological progress is affected by climate policy intensity and high fossil fuel prices. The same conditions influence the technological progress of the CO_2 capture group of technologies the cost improvement of which is also strongly correlated. The cost of H_2 Internal Combustion Engine and On Board Hydrogen Storage are also highly correlated with Gas Steam Reforming. The improvements in these technologies depend partially on learning by experience (technology take-up) which in its turn depends on the availability of reasonably priced hydrogen and Gas Steam Reforming is the most likely option in the medium term. However, hydrogen production technologies since on the one hand do not belong to a specific cluster and on the other they consume different fuels, do not appear to co-vary with regard to technological progress.

Finally an attempt is made to consider the Case Study assumptions synthetically in order to address the issue of their overall likelihood. In this context four scenarios were evaluated namely: 'high technological progress', 'high technological progress and high oil/gas prices', 'high technological progress and high carbon value' and 'high technological progress, high oil/gas prices and high carbon value'. The analysis was performed for each technology separately.

PROMETHEUS synthetic analysis results indicate that the technological progress for the majority of technologies is more probable to happen with high fuel prices than without them. For example the New Nuclear (4^{th} gen.) displays 35.3% on the probability proximity index to achieve high technological progress with high fuel prices while the same value without high fuel prices falls to the level of 16.6%. Analogous conclusions can be drawn regarding the technological progress of hydrogen internal combustion engine passenger car (index with high prices: 69.5%- index without high prices: 29.2%), fuel cells (index with high prices: 28.8%- index without high prices: 10.4%), Pre-combustion CO_2 capture for electricity production (index with high prices: 17.8%- index without high prices: 33.5%), etc.

7.6 PRIMES: a partial equilibrium model for Europe

This report summarises the key findings of the case studies examined in the context of Part 2 of the CASCADE MINTS project using the PRIMES energy model. PRIMES is a partial equilibrium model for the European Union energy system developed in the context and with the financial assistance of a series of research programmes of the European Commission. In its present version it covers all EU-25 Member States, the remaining EU candidate countries, Norway and Switzerland. The present analysis is based on a new baseline energy scenario for Europe which has been constructed in late 2005 and published in 2006 by the European Commission. This scenario has been harmonised to the assumptions underlying the analysis within Part 2 of the CASCADE MINTS project. The case studies have been built as a result of assumptions varying from baseline with the aim to provide insights on the effects of different technology policies on promoting sustainable development.

In this context two renewables cases ('Low' and 'High' target cases setting 12% and 20% target shares for renewables in the EU-25 primary energy consumption for the year 2020) have been examined using PRIMES. Additional runs have been performed to estimate the subsidies required to achieve these targets. The results indicate that in both cases biomass/waste play the most significant role in achieving the targets, whereas the contribution of hydro, wind and solar energy is less significant. Promoting renewable energy forms results in substantially reduced emissions and lower import dependence relative to the baseline for the EU-25 energy system. However the need for additional policies towards improving energy efficiency in the EU-25 energy system has been identified in order to achieve high shares of renewable energy forms since available options - especially on the demand side - are highly exploited.

In the context of the nuclear case PRIMES has been applied to examine four scenarios designed to assess the potential role of nuclear energy in the evolution of the EU-25 energy system. The nuclear phase out scenario results in substantial reduction (81.5%) of electricity generation from nuclear power plants. The gap generated is covered by an increase in electricity production from natural gas, intermittent renewable energy forms and biomass-waste. In the higher carbon value case the EU-25 power generation sector adjusts to the introduction of stricter emission reduction constraints showing a continuing trend away from solid fuels towards production from nuclear and renewables. The nuclear technology breakthrough leads to substantially increased electricity generation from nuclear plants relative to the baseline which again occurs mainly to the detriment of solid fuels. As a result of energy intensity gains and changes in the fuel mix towards less carbon intensive energy forms CO_2 emissions in the EU-25 energy system are substantially reduced relative to the baseline, ending up in 2030 at lower than 1990 levels in all cases considered. Changes in the fuel mix towards the use of indigenous energy forms (such as nuclear and renewable energy forms) lead to lower import dependency in the nuclear breakthrough cases. The reverse trend is projected for the nuclear phase out with stricter CO_2 emissions reduction targets case (mainly affecting solid fuels, one of the main indigenous energy forms in the EU-25) which leads to increased import dependency.

All scenarios examined in the context of the 'Technological progress' (TP) case produce higher than baseline demand for nuclear and renewable energy forms; the opposite outcome emerged for oil and natural gas energy requirements. Demand for solid fuels varies with the intensity of the climate policy: in the cases assuming the implementation of a higher carbon value demand for solids declines substantially from baseline levels whereas higher oil and gas price assumptions lead to a higher deployment of solid fuels in the EU-25 energy system. The role of renewable energy forms but also nuclear energy in satisfying electricity requirements becomes even more pronounced in the presence of stricter policies towards reducing CO_2 emissions. Hydrogen is projected to make some - albeit limited - inroads in electricity generation on the assumption of higher oil and gas prices. On the other hand Fuel Cells are particularly influenced by the scenarios involving faster technical progress which produce shares in total installed capacity of up to 5.8% by 2030 for this technology.

In all TP scenarios examined CO_2 emissions grow at a slower than baseline rate. Although high oil and gas prices encourage the use of solid fuels and increase the carbon intensity of the system, CO_2 emissions in 2030 are slightly lower than baseline levels mostly due to energy intensity improvements emerging from higher energy import prices. The assumption of stricter carbon emissions constraints and faster technical progress gives rise to a stronger reduction of CO_2 emissions for the EU-25 energy system (-22.1% from Baseline levels in 2030) which is even sharper when higher oil and gas prices are combined (-24.6%). These scenarios are the only ones producing lower than 1990 emissions in 2030. Finally, improvements in import dependency of the EU-25 energy system emerge from all TP cases examined, on account of both energy intensity improvements and changes in the fuel mix towards the use of indigenous energy forms (such as nuclear and renewable energy forms).

7.7 MARKAL: an energy system model for Europe

One of the models used in the CASCADE MINTS scenario studies was the MARKAL-WEU model describing the energy system for Western Europe (EU15 plus Norway, Switzerland and

Iceland). The MARKAL-WEU is a bottom-up model that optimises the total system cost for the whole time period at once. This perfect foresight feature of the model makes it possible to treat endogenously cost decreases through capacity build-up (learning by doing). Below the main results on the two key-issues of this study are given.

Climate change
Several policy measures to reduce CO_2 emissions have been analysed, some direct measures like imposing a tax on the use of carbon (carbon containing fuels), but also indirect measures on stimulating less carbon intensive technologies. It turned out that stimulation of renewable electricity by a 33% target in 2020 has hardly any impact on the overall CO_2 emissions. In the transport sector, taxation of conventional fuels such as diesel and gasoline, equivalent to 100 €/tCO_2, on the other hand, can lead to a significant decrease of CO_2 emissions. The effect of CO_2 capture facilities as a standard on new power plants will in the long run be limited to a 10% CO_2 reduction in 2050 compared to the 2000 level. Moreover, it turned out that this emission reduction could be reached in a much cheaper way by defining an overall CO_2 reduction target, thus involving more sectors. Taxing directly the use of CO_2 showed to be a very effective tool. With an increasing CO_2 tax to 100 €/tCO_2 the emissions in 2050 will be half that of 2000. In all, one can conclude that for significant reduction of CO_2 emissions direct measures in the form of taxing carbon are most efficient.

The results described above were all derived under moderate oil and gas prices. Some analyses have also been done with high fuel price assumptions. High fuel prices will lead to less CO_2 emissions. This is mainly a consequence of a shift in transport fuels from gasoline and conventional diesel to biodiesel and hydrogen. However, hydrogen is used only when optimistic assumptions on the (cost) improvement of hydrogen technologies are made. Combining high oil and gas prices, high taxation of CO_2 and assuming an increased technological progress of less carbon intensive or carbon free technologies leads to a reduction of 60% of CO_2 emissions in 2050 with respect to 2000.

In many of the scenario studies the role of nuclear was modest at best, but to a large part this was due to the assumption that it can not grow beyond its current capacity. This assumption was introduced to reflect current and assumed future political preference in the Member States, where some may allow for a growing contribution, but such a growth is compensated by the phase-out in others. Even under such a constraint, the contribution generally decreased, except for the cases with intense carbon policies or high oil and gas prices, in which case the maximum on the installed capacity was indeed a limiting factor. Only in the break-through case, nuclear attained a substantially larger share in electricity production, to a level where one might even question the realism of the outcome because of the required abrupt capacity build-up. However, a general conclusion that can be drawn from the scenario studies is that nuclear power could play a role in meeting strong climate policy target, but that its role will only significantly increase when there is a change in the political landscape.

Security of supply
Although security of supply was the other key-issue in this project, it was less stressed out and often more seen as a side benefit. Clearly, all cases under investigation tended towards a high penetration of renewables, be it introduced through a specific target or by replacing fossil fuels under high carbon taxes, and resulted in increases in Europe's security of supply and contributed to a higher diversification.

Recommendations for future research
For future research it would be interesting to combine and study policies and measures other than a carbon tax under different fuel prices assumptions. With regards to high oil prices, it would be interesting to investigate the impact on the price of oil of synthetic fuels produced from coal, and of shifts to more renewables. Finally, it would be interesting to study the impact

of enhanced energy saving, and in particular whether higher fuel prices due to policy measures could help to reduce final energy demand.

7.8 TIMES-EG: an energy system model for Europe's electricity and gas markets

A liberalized electricity market with the option of free choice regarding the electricity generation technologies is a basic requirement for a cost efficient electricity market. If GHG reduction is an energy policy objective, specific policies such as renewable quotas, standards or subsidies for CCS technologies are less cost efficient than absolute GHG reduction targets or CO_2 certifcate prices. A common European solution for the electricity market without a one-sided focusing on a single technology group appears to be more favourable compared to national targets as it achieves similar CO_2 emissions reductions with lower costs.

The target for a given national or EU-25 quota of 33% RES-E in 2020 will only be reached, if it is possible to double the wind power generation and the use of biomass. In order to achieve this significant increase the wind offshore technology will have to reach its technical maturity concerning the supply system and its integration into the electrical grid.

The role of nuclear does not only depend on technology progress, but also on the acceptance and possibility of investment. Until 2010 the nuclear phase out will not have a large influence on the CO_2 emissions from the European electricity generation. In case of a CO_2 price development with a linear path of 10 €/tCO_2 in the year 2010 and 100 €/tCO_2 in 2030 combined with a nuclear phase out, the total amount of natural gas consumption in all sectors (including the end use sectors) will increase by 80% compared to the consumption in 2000. This is 20% point higher than in the scenario with the steady use of nuclear. Additionally the gas consumption can only be covered by a significant share of over 25% of LNG. If nuclear remains an option it plays an important role in the electricity market regardless of the further cost reductions, climate policies or higher oil and gas prices.

In general, the enhanced technology progress has less influence on GHG-emission reduction in the future than policy measures. If no substantial cost reduction of the technology for electricity production from renewables will be realized, it would result into a significant increase of costs for the final consumers and/or the entire electricity production.

A combination between higher oil and gas prices and climate policy promote the share of bioenergy plants and CHP within the total electricity generation. The effects of high oil and gas prices do not automatically lead to a GHG-emission reduction, due to a shift to coal-based power generation. The share of coal fired power plants already increases without additional policy measures.

CCS technologies, mainly combined with coal fired power plants, only enter the market under the conditions of high carbon value prices or if CCS standard will be given as a policy measure. Subsidies for CCS of 35% of the investment cost for power plants with CCS technology will not be enough to reduce the costs and efficiency handicaps of power plants with integrated CCS technology. Until 2030 the CO_2 storage capacity of all EU-25 countries is not the limiting restriction for CCS.

7.9 NEWAGE-W; a global general equilibrium model

In order to reach national and international emission targets, various technological options for CO_2 mitigation have been analyzed within the CASCADE MINTS project using the CGE-model NEWAGE-W. The most striking results regarding the deployment of electricity generation technologies based on renewable energy sources, nuclear power plants, the use of carbon capture and storage technologies as well as the implementation of a carbon value will be briefly discussed in the following.

In the analyzed renewable energy scenario the share of renewable electricity generation in Western Europe that has to be achieved is 22% in 2010, 33% in 2020 and 40% in 2030. The greater penetration of renewables leads to a decrease in CO_2 emissions of approximately 27 million ton of CO_2 in 2010, 68 million ton in 2020 and 117 million ton in 2030. Regarding the economic impact, a decrease in GDP due to rising generation costs is observed. The GDP in Western Europe decreases by approximately € 46 billion, i.e. 0.3% compared to the baseline scenario in 2010, € 137 billion (0.8%) in 2020 and € 325 billion (1.7%) in 2030.

The renaissance of nuclear energy in Western Europe, e.g. induced by a decline in specific investment costs due technological progress or state-run subsidies, has a positive impact on CO_2 emissions, GDP and welfare. The CO_2 emissions from electricity generation decrease by 46% in the year 2030 compared to the baseline in which a premature nuclear phase-out in some European countries is assumed.

Regarding an increase in the deployment on carbon capture and storage technologies for electricity generation, it can be observed that, given the very low initial capacity in the regarded base year 2001, only slight environmental and economic impacts occur. Focusing on the overall economic impact in Europe, the carbon capture and storage induced effects can be disregarded.

Implementing a carbon value to lower overall CO_2 emissions in Western Europe has a strong impact on the environmental and economic development. CO_2 emissions decline by 43.5% in 2030 compared to the baseline. Combining the carbon value with an increase in technological progress leads to slightly enhanced emission reductions of 44.2%. However, given the emission reductions in Western Europe, leakage effects increase CO_2 emissions in North America by 3.8% in 2030. Regarding Pacific OECD and Asia, leakage effects result in increased CO_2 emissions by 2.8% and 3.0%, respectively. The decrease in Europe's CO_2 emissions is mainly caused by lower consumption of fossil fuels. Concerning coal, energy use is reduced by 85% in 2030 compared to the baseline. Moreover, the consumption of gas is reduced by 20%, whereas oil consumption is reduced by 24%. Along with the lower fossil fuel consumption, region specific exports of the various energy carriers face significant changes. Regarding coal exports from Pacific OECD to Europe, a nearly complete decrease in 2030 can be observed. Gas exports from Former Soviet Union to Western Europe decrease by 13%. Regarding the carbon value induced impact on macroeconomic parameters, it is projected that GDP in Western Europe will decline by 2.5% in 2030 compared to the baseline. The negative impact on GDP can partly be mitigated if an increase in technological progress is assumed. In this case the expected GDP loss is 2.3%. Due to trade related spill over effects, GDP in North America decreases by 0.2%.

Further research
The model-based analyses of the economic impact of energy-related policy measures as well as technological progress would benefit from a more detailed representation of the energy technologies and a better understanding of the interaction within innovation processes.

7.10 PACE: a general equilibrium model for Europe

The scenario analysis in Part 2 of the CASCADE MINTS project is carried out within the framework of a recursive-dynamic version of the computable general equilibrium (CGE) model PACE for the EU-15. The model features a bottom-up description of different power generation technologies for the electricity sector. These technologies are characterized by their specific cost structure based on techno-economic data, their physical capacity constraints, and their output shares in the benchmark equilibrium. The model is calibrated on the European Commission's assumptions on non-uniform growth rates for GDP and projections on fossil fuel production and use. Similar to energy system models, CGE models allow to determine the effects of alternative policies on electricity production and technology mix. It furthermore quantifies macroeconomic repercussion effects due to behavioural changes, which are neglected in energy system models.

The analysis with PACE focused on three issues: renewable energy, nuclear energy, and technological progress. The findings are multifaceted and depend on the detailed implementation of the different policies. For example, encouraging renewable energy by subsidies increases overall electricity production by 5% in 2020 and triggers a major shift from conventional technologies to wind and biomass (production increase of more than 170%). From the sectoral viewpoint this development induces large employment shifts from conventional to renewable technologies. Due to the subsidies, electricity production costs slightly decrease and thus electricity demand and supply is positively affected. The results also reveal a small decline in economic welfare.

Not surprisingly, a nuclear phase-out reduces electricity production while it increases in the case of a nuclear phase-in. Consequently, a phase out (phase in) leads to lower (increased) electricity production from the nuclear technology, increases (decreases) production costs and electricity imports, and reduces (increases) electricity supply. Welfare is slightly lowered in both scenarios mostly because of the additional introduction of the carbon value.

Technological progress that reduces the technology specific costs of nuclear, wind and biomass by 50 percent more than through the baseline leads to major increases in electricity production and especially in the production from those technologies (wind, biomass) that are favored the most. This lowers production costs and thus raises electricity supply and demand. Economic welfare is slightly improved from stand-alone technological progress due to the cost advantages but is lowered if technological progress is combined with a carbon value, higher oil and gas prices or both.

All three scenario results suggest reduced carbon emissions. The decrease is very modest in the renewable scenario where emissions are reduced by 2.6% in 2020. Both a nuclear phase-out as well as a phase-in when combined with a carbon value lead to larger reductions in carbon emissions by 13-16% (a phase-out alone would increase carbon emission). Stand-alone technological progress also implies modest decreases in carbon emissions which is simply due to the rising electricity production. Technological progress in a carbon constraint world or with higher gas and oil prices leads to a much larger reduction in carbon emissions of 25-30% in 2020. Combining technological progress with a carbon value and higher oil and gas prices has the most favorable effect on CO_2 emissions which decline by more than 40%.

There are two recommendations drawn from the analysis. First, future research could focus on a further development of the integration of CGE models with energy system models (e.g. distinguish between peak and base load). Second, technological progress in the current analysis is implemented as exogenous cost advantage. Interesting enhancements would be to allow for endogenous technological change.

7.11 NEMESIS: an econometric model for Europe

The NEMESIS model (New Econometric Model for Environmental and Sustainable development and Implementation Strategies) is a macro-sectorial econometric model aimed at developing tools for decision making in the fields of energy, environment and economic policies.

The contribution of renewable to a sustainable energy system
Using a subsidy of 2.4 $€_{2000}$ct/kWh in 2005-2020 leads mainly to a sharp rise for renewables at the expense of a gas, coals and solids. The most significant renewable sources come from hydro power, biomass and wind. They represent in 2020 respectively 7% of total energy consumption

for hydro, 4.1% for biomass and only 3.3% for wind. The electricity production slightly decreases by almost 25% for gas and by 18% for coal/solids. The development of renewables has a positive impact on Europe dependency on imported fuels, as described by an increase of the Shannon diversity index.

The contribution of nuclear to a sustainable energy system
In the context of nuclear case with a carbon value equal to 50 $€_{2000}/tCO_2$, the 'phase-out' case leads to a reduction of primary energy consumption from nuclear with an increase of renewables, whereas in the 'break-through' scenario nuclear sources mainly increase at the expense of gas and coal/solid. The nuclear case leads gradually to an increase in security supply in the 'break-through' scenario, which means that the reliance on few primary energy sources decreases as nuclear capacities are unconstrained.

Several policy cases
In 2020, the different policy case scenario implemented in NEMESIS on the Carbon value, Oil/gas price (OGP.) and Technological progress (TP.) leads to more efficient energy consumption due to increasing use of energy-efficient technologies, a substantial shift in the structure of energy consumption away from gas, coal/solids, oil/liquids towards renewable energy. This implies a further decline in the importance of energy-intensive sectors, in favour of less energy-intensive production.

Macroeconomics consequences
The impacts of various policy scenario obtained with NEMESIS are shown in Table 7.1. The macroeconomic effects in 2020 are significant and comparable for all scenarios expect for the development of renewable sources. The inflationary trends in all scenarios, due to the higher energy prices, induce a negative on European competitiveness, resulting in a rise of imports and a fall of exports. The policy case studied also lead to a sharp change for employment explained mainly by an increase in the nominal wage and due to competitiveness losses. However, the fall on employment level is limited by the reduction of the real wage.

Table 7.1 *Macroeconomic impacts of alternative cases in 2020 (w.r.t. the baseline)*

	Renewable low target scenario	**Renewable high target scenario**	**Nuclear case with the post-Kyoto scenario**	**OGP scenario**	**CV scenario**	**OGP+CV scenario**
GDP	-0,03%	-0,18%	-1,25%	-1,42%	-1,45%	-2,42%
Private consumption	-0,02%	-0,18%	-1,34%	-1,56%	-1,65%	-2,66%
Price index	0,21%	0,83%	3,49%	2,25%	2,86%	4,16%
Employment	-0,03%	-0,15%	-1,00%	-0,86%	-1,08%	-1,62%
Exports	-0,07%	-0,28%	-2,30%	-1,66%	-1,97%	-3,07%
Imports	0,05%	0,11%	0,87%	2,25%	2,86%	4,16%

The combination of C.V. and O.G.P. is less recessive than the sum of results on GDP of each separate shock. This is contrary to the pure energy results for which the energy costs of the combination are more important than the sum of the costs of the separate shocks. It is easily explained by the labour market functioning that lowers the wages with recession and limits the decrease of GDP, such as this latest effect is more than proportional and then the compound scenarios are less recessive than the sum. The directions of the macroeconomic impacts are different in each European country, as a consequence of different energy system for consumption and production added to different labour market structure.

Environmental consequences
The table below shows the evolution of energy-related CO_2 emissions in 2020 with respect to the baseline in the different scenario implemented in NEMESIS. The expected evolution of final

energy consumption shows significant sectoral reduction in CO_2 emissions, excepted for the ‘phase-out’ nuclear case. This is due to the shift in energy production and consumption towards less polluting sources (renewable, gas, nuclear). Relatively high prices for energy consumption in the scenario will encourage industry to make further investments in energy-friendly technologies with a view to more efficient energy consumption and the development of renewable sources. The change in industrial energy consumption is confirmed during the simulation as the consumption from solid and liquid fuels shift downward. The market penetration of renewable sources contributes to increase the reduction of CO_2 emissions. Nuclear sources also contribute to a reduction of CO_2 emissions. Technological progress has a very slight effect reduction of CO_2 emissions as it induces no change in production and consumption.

Table 7.2 *Impacts of alternative policy scenario on CO_2 emissions in 2020 (w.r.t. the baseline)*

	Renewable low target scenario	Renewable high target scenario	Nuclear case scenario Phase-out	Nuclear case scenario Break-through	TP scenario	OGP scenario	CV scenario	TPOGP scenario	TPCV scenario	TPCVOGP scenario
Total from energy sector	-0,72%	-5,12%	0,83%	-1,93%	-0,18%	-9,18%	-14,32%	-9,43%	-14,62%	-22,13%
Power sector	-2,87%	-20,23%	3,33%	-7,81%	-0,63%	-2,02%	-22,04%	-2,94%	-23,15%	-30,51%
(other) conservation	-0,24%	-2,03%	0,37%	-0,81%	0,00%	-1,71%	0,18%	-1,71%	0,18%	-1,64%
Industry	0,09%	0,47%	0,18%	-0,43%	-0,02%	-24,82%	-30,08%	-24,85%	30,11%	-43,31%
Residential, commercial and service sector	0,04%	0,25%	0,02%	-0,04%	0,00%	-15,01%	-13,21%	-15,01%	-13,22%	-23,89%

Emissions caused by the power sector are expected to decline sharply in 2020 in all case with respect to the baseline. The evolution of power generators in the simulation anticipates the carbon value implemented in NEMESIS, which leads to a significant progress of less polluting sources replacing solid and liquid fuels by renewables and nuclear. Emissions caused by households and services should rise slowly in the renewable scenarios whereas it decrease in the other context. In addition to CO_2 emissions caused by industry remains constant in the renewables scenario due to a structural shift in energy consumption away from solid and liquid fuels and towards gas and electricity.

8. Overall conclusions

The transition towards a more sustainable energy system requires a portfolio of technological options. The problems faced by Europe and the world are of a magnitude for which no single technology is the solution. Some of the options benefit both the climate problem and security of supply, and thus provide synergies, while others represent trade-offs for the policymaker.

8.1 Trade-offs

Solid fuels

The case studies have shown that high oil and gas prices induce a shift towards solid fuels, as coal is a cheaper and more abundant alternative to other fossil fuels (oil and gas), with more and more applications, not only for power generation, but through a gasification process also for synthetic fuels that can be used for transportation. Given the fact that coal resources are relatively abundant and well spread over different world regions, European security of supply definitely improves with an increased share of coal. However, the use of coal potentially is a threat to the environment, and it needs clean technologies such as CCS to prevent environmental drawbacks. Furthermore, coal mining is also not always done in a sustainable way and is a source for non-CO_2 greenhouse gas emissions.

Nuclear power

The role of nuclear power largely depends on the public and political acceptance of this option. The scenarios analysed in this report have shown that, when this acceptance is no limiting factor, and investment costs drop with 25%, nuclear energy could have a share up to 50% in the European power generation mix, and 30% in the global power mix, as it is attractive in terms of costs and hardly generates polluting emissions. Europe's security of supply would benefit from a larger penetration of nuclear, as uranium resources are mainly found in Australia, Canada and Kazakhstan. However, the trade-off with other options here involves questions of safety, proliferation, and nuclear waste storage for many centuries to come. Conditions for increased acceptance would therefore comprise the development of inherent safe reactor systems, better utilisation of fissile material and shortening of waste lifetime. The scenarios also show that a nuclear phase-out is feasible, even under a strong climate policy, but does increase dependency on natural gas, CCS, and renewables.

Hydrogen

Hydrogen in transport can certainly play a role in meeting challenges posed by climate change and scarcity of fossil fuels. Hydrogen is mainly used to substitute oil in private transportation, where the main competitors for fuel cell cars are biofuels (in case of climate policy) and fossil methanol or CtL (in case of high oil prices). The models have shown considerably different penetration speeds. To some extent, this is due to the difference between simulation and optimisation models, and this illustrates the difference between incremental and radical innovation. For hydrogen, which needs strong cost reductions of the drive train, and imposes new infrastructure requirements, strong hydrogen specific policies with a long-term vision will be particularly important, because general policies supporting incremental innovation will probably not be sufficient to lower these initial barriers. High oil and gas prices seem to provide a stronger incentive for hydrogen use in the transportation sector than ambitious climate policy, while the application of CCS is essential for successful market introduction of fossil-based hydrogen in a carbon constrained world. However, the introduction of hydrogen is most strongly influenced by assumptions on technology learning.

Biomass
In many of the scenarios analysed, particularly those on renewables, the key role of biomass has become clear. An increasingly important trade-off will be where to apply the scarce biomass resources, in view of competing applications in the power, transport and heating sectors, apart from the non-energy uses such as food production. Security of supply might be a stronger driver than greenhouse gas emission reduction, because of the lack of alternatives for oil in transport sector, and because biomass is not carbon-free but rather carbon neutral. Other sustainability issues, such as land use, biodiversity, emissions due to fertiliser use, and water requirements are also becoming increasingly important. It is expected that in the future, most biomass will be used in gasification processes with many different applications.

Natural gas
From the range of fossil fuels, natural gas fits best in a carbon constrained world. Although in the baseline, gas demand grows faster than total consumption, this level is usually not achieved in the policy scenarios, where its prospects depend on the success of competitors such as renewables or nuclear in the power sector, or biofuels in the transport sector. Natural gas has a key role when it comes to security of supply. A strong climate policy may induce an increasing role for natural gas, which can further increase Europe's dependency on gas imports which is already very high. However, in case of higher CO_2 prices than the 100 €/tCO_2 assumed in this project, the role of natural gas will probably become more marginal.

CO_2 capture and storage
Finally, as already alluded to, CO_2 capture and storage (CCS) appears to be an important technology for the perspectives of hydrogen in a carbon-constrained world, while it is also vital for the prospects of coal. According to the scenarios assessed in this project, CCS on coal-based power plants, notably IGCC, is preferred over gas-fired plants. This implies that especially for countries with a booming demand for cheap (often coal-based) energy, CCS could still allow for a low-carbon energy supply. The application of CCS could lead to an increased reliance on coal, thus increasing security of energy supply.

However, there is still a large uncertainty on the potential for CCS and when it will become available, while legal issues, risks and public acceptance also play a role. The only incentive for CCS is in climate policy, but here it can complement other technologies in a useful way. Moreover, if the world is moving towards a more coal-intensive energy system, it is crucial to stimulate the timely development of affordable CCS technologies in order to counter the climate effects.

8.2 Synergies

Energy efficiency
One of the most robust options is energy efficiency as it provides a significant contribution to reducing both import dependency and mitigation of CO_2 emissions at negative or low cost. None of the policy cases in the CASCADE MINTS project has specifically focused on the possible contribution of energy efficiency. There are indications (Uyterlinde et al., 2007) that high oil and gas prices may induce energy intensity improvements that counterbalance the increase in carbon intensity resulting from the expected shift to solid fuels.

Renewable energy
Another apparent option for a sustainable energy system is renewable energy, as most renewable sources - with the exception of biomass - are both indigenous and emission-free, thereby benefiting both climate objectives and security of supply. The main barriers are in terms of high costs and limited potentials. For most technologies, large cost reductions are still possible. The case study has shown that enhanced technological progress, which can be operationalised through R&D and increased deployment, can make a difference for wind and solar PV. Fur-

thermore, a combination of high prices for oil and gas, and ambitious climate policy provides a strong incentive for renewable energy, although coal with CCS can be a serious competitor. A high penetration of renewables imposes additional challenges due to their intermittent nature, and may take time. The introduction of hydrogen produced by means of electrolysis may increase the potential share of intermittent renewable options.

Transport sector
Finally, a synergy can be found in policies targeting at the transport sector, as these can achieve both emission reduction and increased security of supply, when the dependence on oil is significantly reduced. The case studies have shown that major shifts in the structure of the transport sector are technically possible, up to completely phasing out petroleum based fuels in Europe by 2050. However, is conditional on the success of the 2nd generation of biofuels, as these have a larger energy density per hectare of land, and on a strong cost reduction of the drive train of hydrogen vehicles.

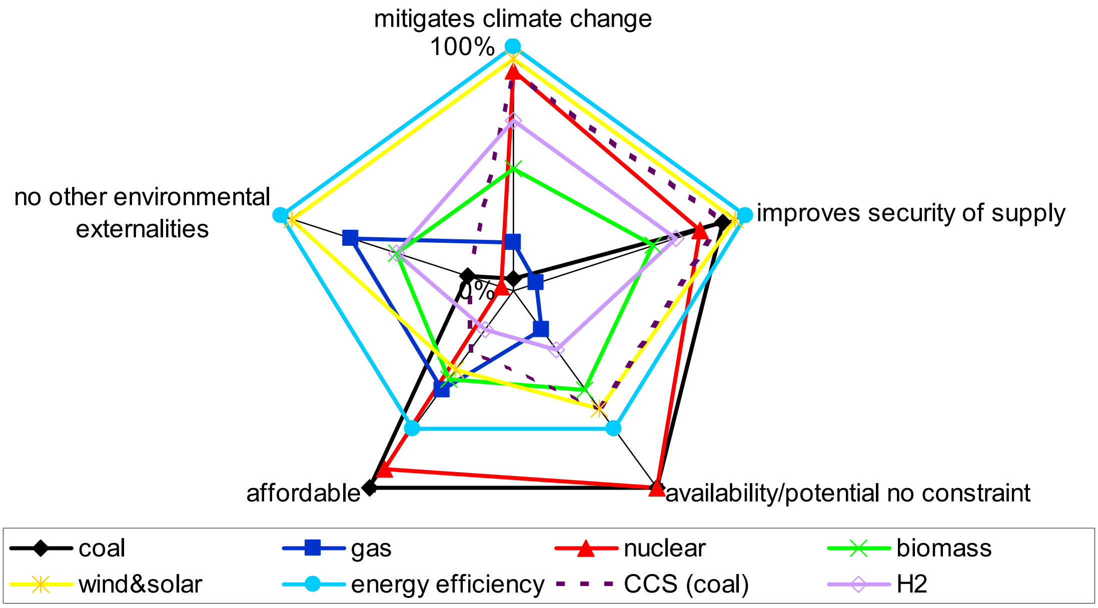

Figure 8.1 *Illustration of trade-offs and synergies*

Finally, Figure 8.1 provides an overview how the different technological options perform against the most important policy objectives and criteria. Options should ideally mitigate climate change and improve security of supply, while being affordable, available, and without other environmental externalities. It demonstrates that while energy efficiency, intermittent renewable resources, nuclear and CCS (with coal) are robust in that they serve both objectives, they are no 'silver bullet', and a portfolio approach should be used to employ mixes of options, also depending on regional potentials and preferences.

8.3 Policy instruments

A common conclusion for several of the policy case studies is that generic policy instruments are often more effective in producing sustainable results. Subsidies targeted only to renewable electricity generation proved to be much less efficient in reducing CO_2 emissions and increasing the share of renewable energy sources on the primary energy level than schemes where also other sectors, e.g. transport, would have renewable energy sources subsidized. Similarly, imposing strict standards for carbon capture technologies proved to be significantly more costly than a direct emission cap applied for all sectors and technologies. In both of these cases the asymmetrical use of policy instruments moves fossil fuels to the sectors where their use is not punished, therefore creating an inter-sector ‘carbon leak’.

However, this conclusion mainly holds for proven technologies. In the stage of market introduction, there must be sufficient technology-specific incentives. Generic policy instruments may lead to lock-in situations where only the more mature technologies are supported, whereas the innovative alternatives may not be developed in time. The models used in this project usually assume perfect markets and therefore these mechanisms are less highlighted in the case studies.

Targets for renewables
For Europe, 20% renewables in 2020 will require strong policies, and it is recommended to pursue energy demand reductions simultaneously. Implementation of renewables is currently most straightforward in the power and transport sector, but to achieve further growth towards 2020, applications should involve other end-use sectors. For instance the potential in the building sector, including renewable heating and cooling options, such as solar thermal water heaters or biomass-based district heating should be further exploited. Bio-energy is one of the key renewable options because of its large potential and its different possible applications. A strong growth of biomass deployment is required for achieving ambitious renewables and climate targets. Policies in different areas such as energy, agriculture, and environment should be further streamlined in order to overcome current barriers.

A variety of policies have been implemented in the different models in order to achieve a 20% penetration of renewable energy sources in Europe. Most of the models have incorporated a separate target for the power sector of 33% renewable electricity consumption. There seems to be some consensus on a subsidy level up to 40 €/MWh, a level that would be comparable to the electricity commodity price. However, the design of the policy instrument differs, ranging from feed-in tariffs to quota/certificate systems. Moreover, a well-designed policy should differentiate support instead of providing a flat rate for all technologies, implying that the average subsidy would probably be lower. A comparison of a scenario of certificate trade in the EU-15 to a scenario where all 15 Member States achieve their targets domestically shows that trade leads to cost reductions for most of the countries, whereas expensive technologies, such as PV, experience a larger growth when the targets are met without trade.

Policies to stimulate CO_2 capture and storage
The main policy instrument analysed, which obliges new fossil power plants to install CCS technologies as of 2015, shows that 16% to 30% of global CO_2 emissions could be captured in 2050, while for Europe, due to a more limited growth of the power sector than in some other world regions, this would amount to some 20%-25% of total CO_2 emissions. These amounts could be regarded indicative of the maximal CCS penetration achievable by 2050, as the more flexible global CO_2 emissions cap induces a much lower CCS uptake, while at the same time there are several mechanisms limiting the effectiveness of any policy focusing exclusively on CCS.

A larger penetration is limited by several factors. First, the inertia in the power sector will slow down the penetration of CCS technologies, as retrofitting is expensive, existing plants will probably operate without CCS until the end of their lifetime. Secondly, imposing a strict standard requirement on one sector alone may lead to adverse effects such as moving the carbon intensive fuels to sectors where no such requirements are imposed. Third, it is difficult to target such a policy well, as it may easily provide an incentive for fossil-based technologies not covered by the standard, such as peak-load gas plants. Finally, the introduction of a CCS standards policy is often much more costly than imposing a CO_2 cap that reaches the same emission reduction. Therefore, a prerequisite for the implementation of this type of regulatory measure is that CCS technologies are both available and affordable for large-scale application. It is recommended to gradually adopt such a policy, in order to reduce the associated cost penalty. In the meantime, new power plants could already be built 'capture ready'.

Technological progress
In this case study, *enhanced* technological progress in terms of investment cost reductions has been modelled to reflect the impact of additional R&D policies on top of the considerable technological progress already represented in the baseline and policy cases. It should be stressed that this case set-up does not cover all possibilities for progress in the techno-economic characteristics of technologies. Looking more closely at the role and contribution of this enhanced progress, it appears to have the most significant impacts on hydrogen production, storage and consumption and on the use of renewables (wind and solar PV) for power generation. This may lead to a reduction of Europe's dependence in electricity imports. All energy system models indicate that the enhanced technological progress leads to a decrease in overall costs of a few percent, both for the carbon policy as well as for the high oil and gas price scenario.

Furthermore, models with endogenous technological learning show the most sizeable impacts of enhanced technological progress, because the impacts of the other drivers (carbon value, high oil and gas prices) are reinforced by the stronger cost reductions as a result of higher volumes of carbon-free technologies. Since this reflects the effect of learning-by-doing, it indicates that the impact of enhanced technological progress may in reality be stronger than what has been shown by most of the models in this case study. However, it remains a challenge to design R&D policies that actually achieve these stronger cost reductions.

Hydrogen in transport can play a significant role in meeting challenges posed by the introduction of climate policies or increasing oil and gas prices. Enhanced technological progress in general does not necessarily lower the barriers for hydrogen, as competitors may also profit from increased research efforts, but if the effort is aimed specifically at hydrogen technologies, enhanced technological progress will considerably speed up the uptake of hydrogen in the energy system.

Different policy objectives
Climate policies do not necessarily result in increased security of supply - depending on the role of natural gas. When Europe's energy system faces carbon prices of up to 100 €/tCO_2, it will respond mainly with a shift to renewables, natural gas and possibly nuclear power, allowing CO_2 emissions to be reduced with 21% to 54% in 2050, compared to the baseline. The changes largely take place in the power sector, where the contribution of coal remains uncertain, as it depends on the estimates for costs and potential of CCS. On the global level, the trends are similar, as the models are unanimous about the decreasing share of oil and particularly coal, while there is some uncertainty over to the role of natural gas, ranging from an increasing contribution in two of the models to a decreasing contribution in another model. In all, the potential role for natural gas in a world with a strong carbon policy is strongly linked to the success of its competitors.

Security of supply policies do not automatically lead to CO_2 emission reductions. The implications of high oil and gas prices for Europe are not necessarily environmentally favourable, as there is a tendency towards coal, even though renewables also benefit. In principle, nuclear power is an alternative to gas in the power sector, its expansion, however, depends on political decisions.

The combination of a strong climate policy and high oil and gas prices is a strong incentive in a sustainable direction. As illustrated by the 'combined case', Europe could introduce a carbon value to counter the adverse environmental impacts of high oil and gas prices. This would specifically provide opportunities for renewable energy technologies, which have shown to possess a large potential for learning and associated cost reductions. Alternatively, the prices of oil and gas could be decoupled, to prevent the undesired shift to coal without CCS.

References

Das, A., P. Russ, U. Fahl and A Voss (2003): *Assessing Climate Response Options: POLIcy Simulations - Insights from using national and international models - ACROPOLIS*. Publishable report, Stuttgart, September 2003.

Ragwitz et al. (2004): *European energy and transport - scenarios on key drivers*[17]

Uyterlinde, M.A., G.H. Martinus, E. van Thuijl, N. Kouvaritakis, L. Mantzos, V. Panos, M. Zeka-Paschou, K. Riahi, G. Totsching, I. Keppo, P. Russ, L. Szabo, S. Kypreos, P. Rafaj, C. Böhringer, A. Löschel, I. Ellersdorfer, M. Blesl, P. Le Mouël, A.S. Kydes, K. Akimoto, F. Sano, T. Homma and T. Tomoda (2004): Energy trends for Europe in a global perspective: Baseline projections by twelve E3-models in the CASCADE MINTS project. ECN-C--04-094, December 2004.

Uyterlinde, M.A., G.H. Martinus, H. Rosler, N. Kouvaritakis, V. Panos, L. Mantzos, M. Zeka-Paschou, S. Kypreos, P. Rafaj, P. M. Blesl, I. Ellersdorfer, U. Fahl, I. Keppo, K. Riahi, C. Böhringer, A. Löschel, F. Sano, K. Akimoto, T. Homma, T. Tomada, F. Pratlong, P. Le Mouel, L. Szabo, P. Russ, A. Kydes (2005): The contribution of renewable energy to a sustainable energy system; Volume 2 in the CASCADE MINTS project. ECN-C--05-034, July 2005.

Uyterlinde, M.A., G.H. Martinus, H. Rösler, B.C.C. van der Zwaan, L. Szabo, P. Russ, L. Mantzos, M. Zeka-Paschou, M. Blesl, I. Ellersdorfer, U. Fahl, C. Böhringer, A. Löschel, F. Pratlong, P. Le Mouel, I. Hayhow, A.S. Kydes, L. Martin, P. Rafaj, S. Kypreos, F. Sano, K. Akimoto, T. Homma, T. Tomoda (2006a): The contribution of nuclear energy to a sustainable energy system; Volume 3 in the CASCADE MINTS project. ECN-C--05-085, March 2006.

Uyterlinde, M.A., H. Rösler, H.C. de Coninck, B.C.C. van der Zwaan, I. Keppo, N. Kouvaritakis, V. Panos, L. Szabó, P. Russ, W. Suwala, P. Rafaj, S. Kypreos, M. Blesl, I. Ellersdorfer, M. Zürn, U. Fahl, A. Kydes, L. Martin, F. Sano, K. Akimoto, T. Homma, T. Tomoda, D. Gielen (2006b): The contribution of CO2 capture and storage to a sustainable energy system. Volume 4 in the CASCADE MINTS project. ECN-C--06-009, September 2006.

Uyterlinde, M.A., G.H. Martinus, H. Rösler, N. Kouvaritakis, L. Mantzos, V. Panos, M. Zeka-Paschou, I. Keppo, L. Szabó, P. Russ, W. Suwala, S. Kypreos, S. Jokisch, M. Blesl, I. Ellersdorfer, M. Zürn, U. Fahl, F. Pratlong, P. Le Mouel, F. Sano, K. Akimoto, T. Homma, T. Tomoda (2007): Trade-offs and synergies in a world moving towards a more sustainable energy system. Volume 5 in the CASCADE MINTS project. ECN-E-06-052, April 2007.

WETO-H2 (2006): World energy technology outlook - 2050. WETO-H2. European Commission publication 22038. Brussels.

[17] http://europa.eu.int/comm/dgs/energy_transport/figures/scenarios/index_en.htm.