The contribution of nuclear energy to a sustainable energy system

Volume 3 in the CASCADE MINTS project

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Preface

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- Energy research Centre of the Netherlands (ECN) (The Netherlands); coordination/MARKAL model.
- ICSS/NTUA - E3MLAB (Greece); PRIMES and PROMETHEUS models.
- The International Institute for Applied Systems Analysis (IIASA) (Austria); MESSAGE model
- IPTS (Institute for Prospective Technological Studies), Joint Research Centre, EC (Spain); POLES model.
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- The Centre for European Economic Research GmbH (ZEW) (Germany); PACE model.
- The Institute for Energy Economics and the Rational Use of Energy (IER) (Germany); TIMES-EE and NEWAGE-W models.
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- National Institute for Environmental Studies (Japan); AIM model.
- Natural Resources Canada (Canada); MAPLE model.

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Abstract

This report 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. 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 €/tonne CO_2 in 2030, nuclear power plants could somewhat reduce the import dependency of natural gas, and could contribute to up to 50% of Western Europe's power generation mix.

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Policy brief

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. Two contrasting scenarios have been analysed, comparing the impacts of a phase-out of nuclear capacities to a 'renaissance scenario' 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 €/tonne CO_2 in 2030, nuclear power plants could somewhat reduce the import dependency of natural gas, and could contribute to up to 50% of Western Europe's power generation mix.

Comparing a nuclear phase-out to a nuclear renaissance due to cost reduction and increased acceptance

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 €/tonne CO_2 in 2010, 2020 and 2030 respectively. In comparison, the current CO_2 price of over 20 €/tonne CO_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[1]. 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)[2]. 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 €/tonne CO_2 from the year 2012 onwards.

The policy brief reflects the consensus among modellers concerning the results presented and the main policy messages. 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

1 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.

2 This is in line with results of the WETO project, although it is relatively low in comparison to current prices. A forthcoming scenario in the Cascade Mints project will include higher oil price projections.

presented in this paper 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 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.

P.1 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. In the coming decades, Europe's energy system is facing a number of challenges. Most of these are related to the continuing, worldwide, reliance on fossil fuels, with still a 70-75% contribution to the primary energy mix in 2030.

Worldwide a doubling in CO_2 emissions in 2030 compared to 1990
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 of these emissions is expected to occur in the developing world, in particular in Asia.

CO_2 emissions continue to grow moderately despite climate policy
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 €/tonne CO_2, emissions are expected to continue their growth with ca. 0.4% per year.

Increased dependency on oil from the Middle East, and competition with emerging regions
Europe's dependence on oil from the Middle East is expected to increase up to 85%. As other world regions, such as Asia, also increasingly rely on oil from this region, this may lead to further oil price increases, which will particularly affect the transport sector.

Increased dependency on gas from Russia and Algeria
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. Additionally, the accession of the new Member States and their heavy reliance on supplies from Russia increases the risks related to gas supply security. On the other hand, enlargement is expected to reduce the risks associated with transit of gas across the new Member States towards the former EU-15 countries.

P.2 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[3] with 25% by 2020, and that improved safety characteristics lead to a larger social acceptance of nuclear power. This way, the

[3] 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).

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 P.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.

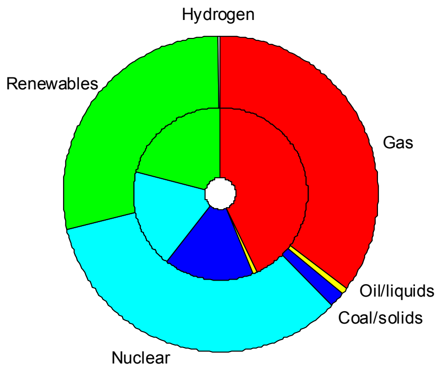

Figure P.1 *Electricity generation mix in the EU-25 in 2030; baseline (inner circle) compared to Renaissance & Carbon value case (outer circle)*
Source: PRIMES.

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 P.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.

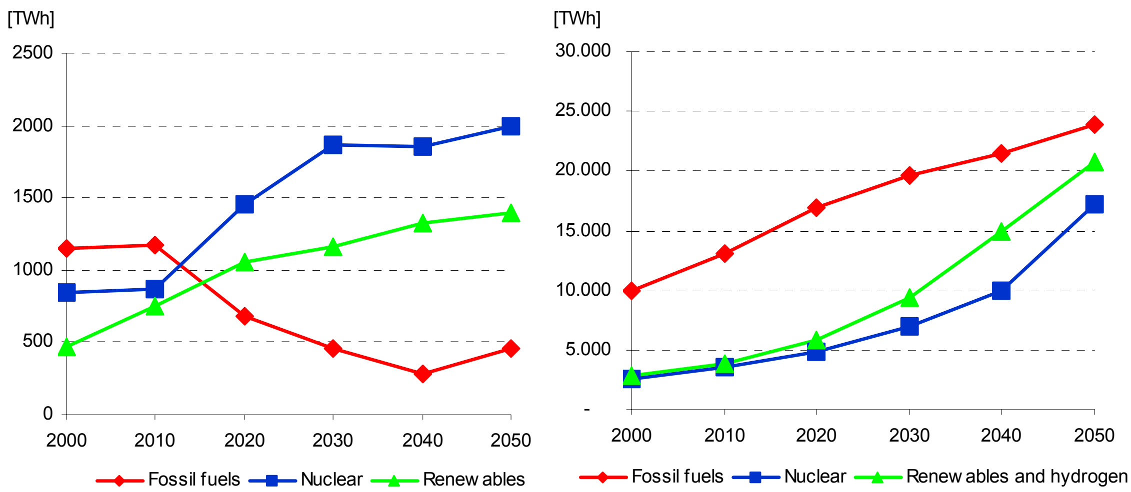

Figure P.2 *Electricity generation by fuel for Europe and the world for the Renaissance & Carbon value case*
Source: MARKAL and GMM.

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 tonnes 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[4] together amount to 8.3 million tonnes. A further 12.1 million tonnes 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.

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

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.

P.3 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 €/tonne CO_2 in 2020, increasing to 100 €/tonne CO_2 in 2030 and further.

The return to gas, renewables and clean coal
Figure P.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.

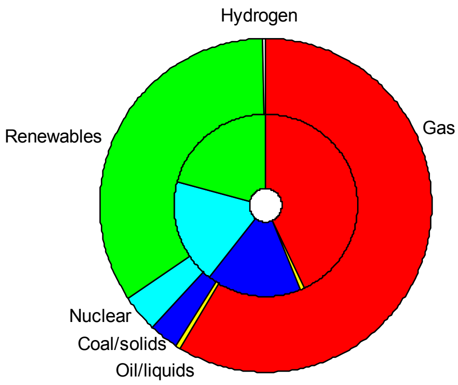

Figure P.3 *Electricity generation mix in the EU-25 in 2030; baseline (inner circle) compared to Phase-out & Carbon value case (outer circle)*
Source: PRIMES.

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 P.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.

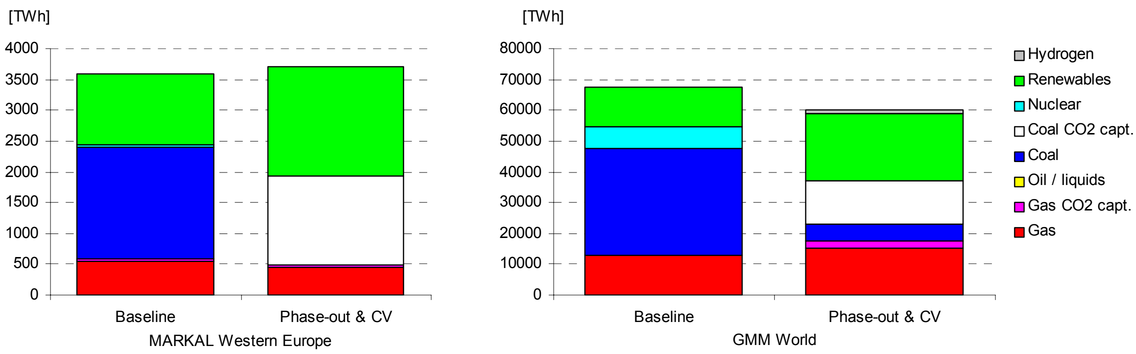

Figure P.4 *European and global power generation mix in 2050; Phase-out & CV case*
Source: MARKAL and GMM.

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.

P.4 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 P.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.

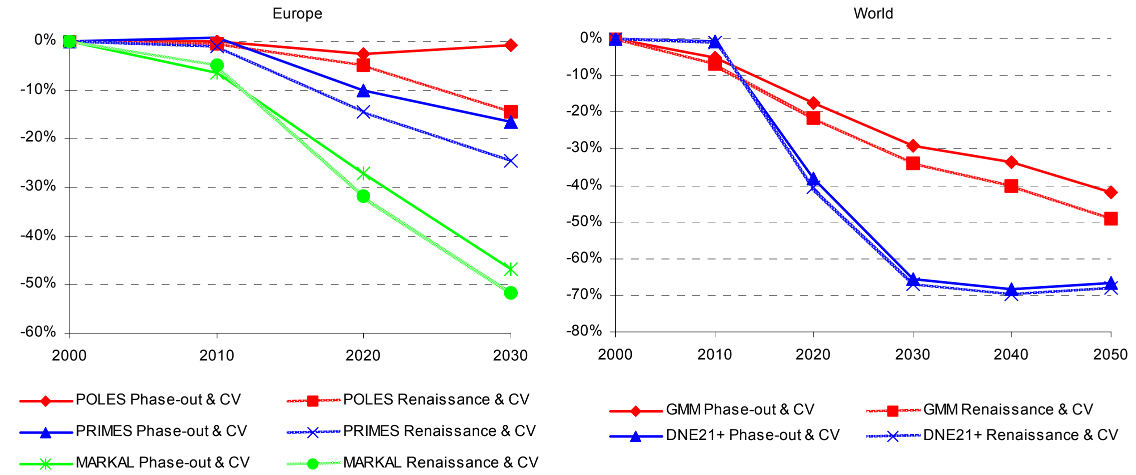

Figure P.5 *Change in CO_2 emissions relative to the Baseline*

The importance of nuclear energy as compared to other options within the carbon mitigation strategy is illustrated in Figure P.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).[5] 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.

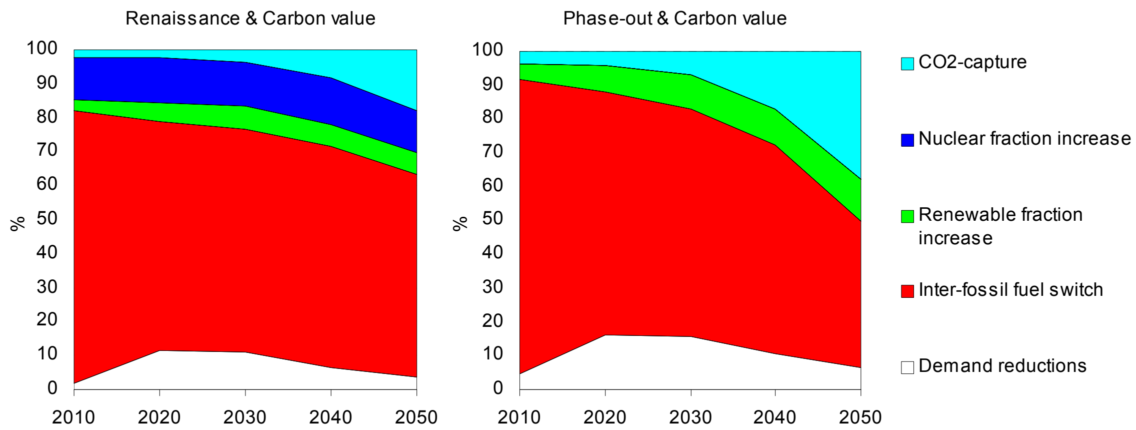

Figure P.6 *Breakdown of CO_2 reduction components*
Source: GMM.

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

P.5 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.

P.6 Economic impacts

Welfare

Overall welfare losses[6] for Europe are small and mainly due to the carbon value, see Table P.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.

Table P.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.

P.7 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

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

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.

1. Introduction

1.1 The CASCADE MINTS project

The current report presents results of Part 2 of the CASCADE MINTS project (CMP2). The CASCADE MINTS project is split into two distinct parts:

- Part 1 focuses on modelling, scenario evaluation and detailed analysis of the prospects of the hydrogen economy. It involves extensive development and use of detailed energy models that have received assistance from previous framework Programmes of DG Research. 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.
- Part 2 does not involve significant model development. Its main aim instead is to use a wide range of existing operational energy and energy/economy models in order to build analytical consensus (to the extent that this is possible) concerning the impacts of policies aimed at sustainable energy systems. This part builds on the experience obtained in the ACROPOLIS project (Das et al, 2003), funded by DG Research within the 5th Framework Programme and involves common exercises carried out using a wide variety of models. This part involves modelling teams from both inside and outside the EU. The emphasis is placed on evaluating the effects of policies influencing technological developments.

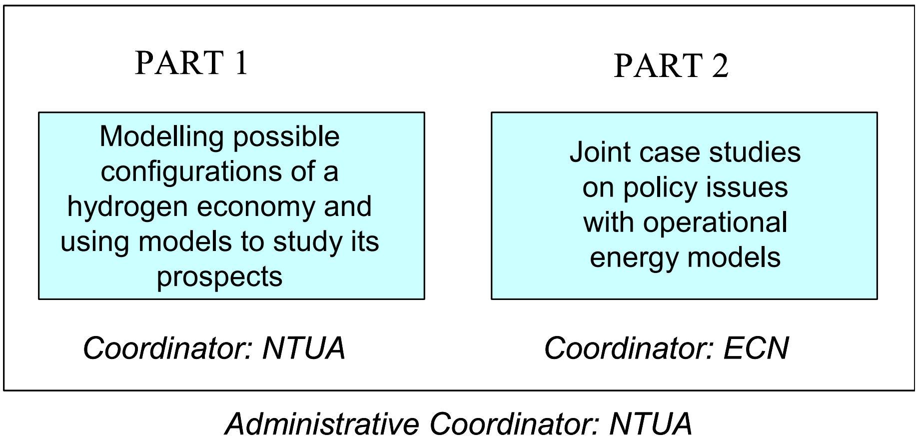

Figure 1.1 *Overview of the CASCADE MINTS project*

Part 2 of the project consists of six work packages. Five of these involve modelling work, and one work package is devoted to reporting and dissemination. In each of the work packages a set of common case studies is analysed with the participating modelling teams. The current report presents results of the third work package on nuclear energy/electricity. All work packages are briefly summarised below.

Baseline (WP 2.1)
The report on the first work package, on harmonisation of initial assumptions and evaluating a common baseline projection, has been published separately (Uyterlinde et al, 2004).

Renewable energy (WP 2.2)
The second work package has analysed the role of renewables in solving global and European energy and environmental issues. 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. The report has been published separately (Uyterlinde et al, 2005).

Nuclear energy (WP 2.3)
Nuclear power currently accounts for approximately one-third of the electricity generating capacity in the EU and is therefore a main topic in the current debate concerning security of energy supplies in the EU and the reduction of GHG emissions. Replacement of existing nuclear power plants puts even more stress on both policy issues. Important issues which will shape the future trends in the nuclear sector, are the problems of managing nuclear waste, the economic viability of the new generation of nuclear power plants, the safety of reactors in eastern Europe, in particular Candidate Countries and the policies to combat climate change and improve the security of supply. The main research question that will be addressed is under what conditions and by means of which policy instruments will investments in new nuclear power plants become environmentally and economically feasible? What will be the potential impact of nuclear energy in terms of GHG emission reduction and improving of supply security in 2020 and 2050?

CO_2 capture/storage (WP 2.4)
CO_2 capture and storage will always come with an additional cost to any power generation plant. This is true both for the conversion to electricity and the conversion to hydrogen, if hydrogen is used as an energy carrier. CO_2 capture and sequestration will therefore only be applied if future specific or general policies provide the necessary financial incentive. Under what conditions and by means of which policy instruments will CO_2 capture and storage in e.g. old gas and oil fields or aquifers become environmentally and economically feasible? Considering different possible policy strategies to intervene and to stimulate CO_2 capture and storage becoming a mature technology, what is the potential impact of CO_2 capture and storage in terms of GHG emission reduction in 2020 and 2050?

Trade offs and synergies (WP 2.5)
The final work package forms the link between Part 1 and Part 2 of the project. It integrates WP 2.2 (renewable energy), WP 2.3 (nuclear energy), WP 2.4 (CO_2 capture/storage) and WP 1.2 (hydrogen).

1.2 Comparing a nuclear phase-out to a nuclear breakthrough scenario

As stated above, the current report presents results of Work-package 2.3 on the policy issues related to the contribution from nuclear to the energy system, particularly in a world with a high carbon value. Two distinct, rather opposite scenarios have been considered, that 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 technology breakthrough. In the breakthrough 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 post-Kyoto target.

For this purpose, the models have been clustered according to their regional coverage and time horizon.

- Cluster 1: Medium term (2030) focusing on EU. The following models have participated in this cluster: PRIMES, MARKAL Western Europe, POLES, TIMES-EE, NEMESIS, NEWAGE-W, and PACE. NEMS and MAPLE also have a focus on one world region (US and Canada respectively) and therefore have also participated in Cluster 1.
- Cluster 2: Long term (2050), world coverage. This cluster should provide the long-term global perspective complementary to the European case. In this cluster, DNE21+ and GMM have participated.

Table 1.1 *Nuclear scenario assumptions*

	Cluster 1: European models	Cluster 2: Global models
Nuclear phase-out with a post-Kyoto target	*Carbon constraint*: CO_2 price imposed, with a path of 10-50-100 €/tCO_2 (2010, 2020, 2030) permit price, and constant thereafter.	*Carbon constraint*: CO_2 price imposed, with a path of 10-50-100 €/tCO_2 (2010, 2020, 2030) permit price, and constant thereafter. For the first Kyoto period only the Annex B countries pursue the permit price, as of 2020, the same CO_2 price is pursued for all countries.
	Technology assumptions: Nuclear capacity phase-out in Europe: No lifetime extension for existing capacities and no new capacities built in Europe. (See Appendix A for details).	*Technology assumptions*: Nuclear capacity phase-out in the Annex B countries. See Appendix A. For the Non-Annex B regions no new nuclear capacity is assumed (with the exception of those already started construction (see Appendix B for details).
Nuclear technology breakthrough[7] with a post-Kyoto target	*Carbon constraint*: similar to the phase-out case.	*Carbon constraint*: similar to the phase-out case.
	Technology assumptions: capital costs are reduced by 25% from the baseline costs of the cheapest nuclear option. This reduction takes effect between 2012-2020 reaching the full 25% cost reduction in 2020 and assuming linear trend.	*Technology assumptions*: capital costs are reduced by 25% from the baseline costs of the cheapest nuclear option. This reduction takes effect between 2012-2020 reaching the full 25% cost reduction in 2020 and assuming linear trend. This cost reduction is applied for all world regions.

Furthermore, some auxiliary scenarios have been calculated.

- In order to analyse the impacts of the cases, a scenario specific reference case - with the given carbon value path (10-50-100 €/tCO_2) - has been calculated and used in the analysis.
- Some models have investigated whether the nuclear breakthrough technology is likely to be competitive in the baseline. This scenario has used no additional carbon constraint except the CO_2 price of 10 €/tCO_2 as adopted in the baseline of the Cascade Mints Part 2 project.

1.3 Report overview

This report is structured as follows. First, Chapter 2 reviews some of the main issues concerning the long-term prospects for nuclear energy and some of the relevant sustainability arguments in this context. Next, Chapter 3 presents results of all models that have analysed the nuclear phase-out or breakthrough scenario for a specific world region, e.g. Europe, the US or Canada. A synthesis of these individual model results is provided in Chapter 4. In Chapter 5, the world models present a report of their analysis of the nuclear cases, while Chapter 6 again provides a synthesis of the global trends.

[7] In the policy brief, this scenario is referred to as Nuclear Renaissance & CV.

2. Issues regarding the long-term role and sustainability of nuclear energy

2.1 Introduction

Nuclear energy remains 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. Recent national policy directions in some countries show that such a potential comeback of nuclear energy is not just wishful thinking of the nuclear establishment. Because nuclear energy currently faces stagnation, it is unrealistic to consider it a serious option for significantly reducing carbon emissions in the short run. On the other hand, it seems a mistake to exclude at this time any of the available options, among which nuclear power, that could possibly contribute to decreasing emissions of greenhouse gases in the longer run. Whether or not nuclear energy will play a role of significance in the long-term future, all energy technologies - including nuclear ones - ought to be considered in terms of their potential to contribute to goals of sustainable development, including all aspects related to environmental, economic and social benefits, drawbacks and risks, and climate change prevention and supply security support in particular. This chapter briefly reviews some of the main issues concerning the long-term prospects for nuclear energy and some of the relevant sustainability arguments in this context.

2.2 Nuclear energy and sustainability

Sustainability indicators for any energy option are among three categories: environmental, economic and social. Addressing the role of nuclear energy in establishing sustainable energy paths involves aspects of radioactive waste, reactor accidents, nuclear proliferation, market competitiveness, resource availability, and public opinion (see Bruggink and van der Zwaan, 2002). Radioactive waste and reactor accidents mostly belong to *environmental* indicators for the sustainability of nuclear energy. Its market competitiveness and natural resource availability have a predominantly *economic* dimension. Its characteristics in terms of nuclear proliferation and public opinion are mainly *social* indicators. The three most technological ones of these aspects - radioactive waste, reactor accidents, and nuclear proliferation - are concisely examined here in terms of the potential risks they involve.

Radioactive waste

One can predominantly distinguish between two types of nuclear waste: spent fuel (in solid state) and radioactive emissions (in liquid or gaseous state), both produced by nuclear power plants in normal operation. These two forms of waste are dealt with in two opposite manners. The attitude to the former is that of ‘concentration and protection’: radioactive contamination of the external environment from spent fuel storage is minimised through several layers of physical containment. To the latter mostly the principle of ‘dilution and exposure’ is applied: the emissions of the nuclear industry may therefore lead to increases in ambient radiation levels. The emissions into the atmosphere or surrounding waters from nuclear power plants are typically much lower than those of reprocessing plants, and even for the latter, after dilution, the additional radiation doses generated can generally be neglected in comparison to natural levels of radioactivity.

Radioactive waste production occurs at basically every stage of the nuclear fuel cycle: uranium mining, uranium conversion and enrichment, fuel fabrication, reactor operation, spent fuel management and, if applicable, reprocessing. Spent fuel is the most problematic form of waste produced, since it generates heat during many years after having been de-loaded from the reactor core, while remaining highly radioactive for several hundred thousands of years. It is therefore referred to as high-level waste (HLW). Low-level waste (LLW) is generated at various other phases (in solid, liquid and gaseous states), such as the mining and fuel fabrication / reprocessing stages of the fuel cycle and at the stage of the decommissioning of nuclear power plants.[8] This waste is generally relatively large in volume, but with radioactivity levels only moderately exceeding natural levels. Solid LLW materials can be protected in straightforward ways and loose much of their radioactivity in short periods of time.

The most viable option today for managing high-level wastes is to store them in geological depositories, usually deep underground. Studies have been undertaken that demonstrate, in principle, the long-term reliability of such geological depositories. To this date, however, no country has yet implemented a permanent solution for final nuclear waste disposal and/or storage from the civil nuclear industry. For example, the Yucca Mountain repository in Nevada, U.S., is planned to open and receive its first nuclear waste not before 2010. On the basis of studies performed between 1991 and 2005, the French government will in 2006 initiate a debate with Parliament on which solution to choose for the long-term disposal of HLW.

The main issue concerning long-term storage is whether the isolation offered by underground geological formations will be sufficient. Among the reasons that governments delay on this issue are the uncertainties that remain about the integrity of spent fuel canisters, over a required period of (many) thousands of years. Over short time periods (e.g. centuries) no uncertainties on either geological or container integrity exist. A remaining fear though is that canisters, as a result of corrosion, may start to leak after thousands of years, and consequently contaminate ground water. The role of public opinion in governments' decisions on burying waste underground, in the form of local opposition (NIMBY)[9], is a determinant factor in this matter. The problem of nuclear waste, however, is dynamic, since solutions that contribute to mitigating the waste problem are being researched. At least two channels exist through which the nuclear waste problem could be mitigated: reducing the radioactive lifetime and, thereby, the radiotoxicity 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 above-ground) disposal facilities for high-level nuclear waste.

Reactor accidents

One of the intrinsic risks of nuclear energy is the occurrence of reactor incidents and accidents, such as those that occurred at Three Mile Island and Chernobyl. Apart from some of the reactors designed in the former Soviet Union, particularly those of the Chernobyl-type power plant, the present generation of nuclear reactors has had a good safety record when one takes the ratio of incident occurrence and operation-years achieved as reference. The fact, however, that severe accidents *can* still occur, provides insufficient safety guarantees for the future, as the consequences of a serious accident, if it occurs, can be large. The potentially pervasive scale of reactor meltdown accidents was experienced through the Chernobyl accident in 1986, involving some 40 immediate deaths and a radioactive contamination of large areas surrounding the reactor for long periods of time, as well as an estimated aggregate of many thousands of people who got or may develop a fatal cancer as a result of radiation exposure.

Since 1986, however, both regarding the probability for accidents to occur, and in terms of the control of potential consequences, a lot has changed. In addition to many improvements in the

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8 The terms 'radioactive emissions' and 'spent fuel' categorise the waste produced according to the state in which it is generated. On the other hand, the notions HLW and LLW form a categorisation according to the level of radioactivity of the waste. Note that the nuclear fuel cycle also generates liquid high-level waste that falls outside the first categorisation (as it is not emitted into the environment). The distinction between HLW and LLW is sometimes refined by adding ILW (intermediate-level waste).

9 Not In My Back Yard.

technologies and materials used for reactor operation worldwide, basically all power plants are today equipped with confinement domes. Such domes ascertain that, in the occurrence of an accident, the radioactive material is not released to the outside environment. Since the Chernobyl accident, man-machine interactions in reactor operation have also been considerably improved. One of the additional measures that have contributed to establishing a better safety culture is the creation of an international ‘early notification system’, involving the obligation to report any nuclear accident or incident on the International Nuclear Event Scale (INES).

Scope exists for further enhancing nuclear security and reactor safety through combined research and development on new reactor types. New designs for power plants, that make greater use of passive-safety features and build on the construction and operation experience gained in today’s plants, already exist. Examples are the European Pressurised water Reactor (EPR) and pebble-bed High Temperature Reactor (HTR). Like in the field of waste disposal, the EU is in the process of creating new directives in the field of reactor safety, in order to improve security in this matter and orchestrate this largely national issue on a European level. In particular, among the issues addressed are:

- the ascertaining of sufficient funds for decommissioning nuclear power plants,
- the exchanging of best practice in enhancing safety of nuclear installations, and
- the providing of greater transparency and information for citizens.

Nuclear 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. For nuclear power production, facilities are needed to enrich natural uranium, containing about 0.7% of fissile uranium-235, up to levels of 3-4% of this isotope. Civil-purpose enrichment technologies can be used for enriching to higher levels of uranium-235 (highly enriched uranium, HEU). HEU is the main component needed to fabricate an atomic explosive. Countries possessing enrichment technologies, or organised terrorists possessing HEU, may use these for military or terrorist purposes, respectively.

Every year more than 50 tonne of plutonium is produced by the current global nuclear capacity of over 400 reactors. Most of the plutonium isotopes contained in spent reactor fuel are fissile. This plutonium can, in principle, be used to construct nuclear explosive devices and therefore necessitates dedicated technical and institutional safeguarding efforts. Especially in the context of spent fuel reprocessing these problems become apparent. Whereas plutonium in the so-called ‘spent fuel standard’ (in which it remains or is purposefully encapsulated amidst the fission products and actinides generated during reactor operation) is reasonably safe against diversion for weapons use - because of the highly radioactive materials in which it is embedded - its separation in a reprocessing facility (or, more broadly, ‘reprocessing economy’) requires proper safeguarding to avoid it being diverted for non-civil purposes.

Reactors can be designed that are less prone to proliferation of nuclear weaponry technology and materials. Practical potential for the development and fabrication of such reactors, in particular the so-called Generation-IV reactors (see below), is available. All nuclear reactors, however newly designed and incorporating whatever progressive proliferation-beneficent techniques, will always involve some proliferation risks. It would be erroneous to assume that totally proliferation-resistant reactors can ever be built. 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.

2.3 Nuclear energy and climate change

An important reason for developing a domestic nuclear energy capacity in the past was its potential to greatly enhance national energy independence, mainly since nuclear fuel (uranium) is widely available, cheaply acquirable and easily storable. Arguments of energy supply security will continue to motivate countries to maintain, expand and/or develop domestic nuclear power facilities, not only in the industrialised world (among which notably counties in the EU, the ex-Soviet Republics, Japan, and the U.S.), but including those in the developing world with presently modest or absent shares of nuclear energy in electricity production (among which China and India). Since the subject of climate change mitigation has been recognised as one of the largest present global challenges, nuclear energy has received renewed consideration (Sailor et al., 2000). If it is decided that nuclear power is not left out of the current energy mix, however, it can only somewhat address the problem of climate change when it is significantly expanded on a global scale. Note that in some countries (like Belgium, France, and Sweden) the contribution of nuclear energy to avoiding CO_2 emissions is already relatively large.

If, for example, nuclear energy were expanded 10-fold, it could contribute substantially to reducing carbon dioxide emissions: such an expansion could avoid about 20% of cumulative CO_2 emissions over the period 2000-2075, while annual emissions in 2075 are reduced by about 30% (van der Zwaan, 2002). Still, it is evident that nuclear energy can constitute no panacea to the problem of global warming. Even with a massive 10-fold 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, in order to attain a CO_2 emissions reduction down to a third of the present level during the second half of the 21st century (and to lower values after that). Such a carbon emission profile would preclude reaching over a doubling of the carbon dioxide concentration in the atmosphere. A doubling of this concentration corresponds to an increase of the average atmospheric temperature on Earth of a few degrees Celsius.

2.4 Sustainability of the Light Water Reactor

Many reactor types exist, the differences between which may be large. The sustainability of each distinct nuclear power technology should therefore be evaluated separately (Bruggink and van der Zwaan, 2002). While reactor types such as the Soviet graphite-moderated reactor, the Canadian heavy-water reactor, the older UK gas-cooled reactor, the newer pebble-bed reactor, or liquid-metal reactors have either been deployed in the past or are presently receiving increased interest, the most conventional reactor is the light water reactor (LWR). There are two LWR energy systems: pressurized water reactors (PWRs) and boiling water reactors (BWRs). There are also two types of LWR fuel cycles: the once-through cycle, in which enriched uranium fuels the nuclear reactor and is processed for long-term disposal after its use, and the closed cycle, in which uranium and plutonium are recovered from spent nuclear fuel and subsequently re-used again. As LWRs today dominate the commercial nuclear power industry - while not holding a monopoly - LWRs mostly determine whether currently nuclear energy is sustainable or not.

Under the assumption of an appropriate operational definition of (weak, intermediate, strong) sustainability and proper criteria by which to judge the sustainability of any (nuclear, or other) energy technology, LWR energy systems do probably not violate sustainability over the foreseeable future for environmental externalities or the social externalities associated with health and safety, including accidental releases of radioactivity (Rothwell and van der Zwaan, 2003).[10] However, they fail to meet at least three criteria:

[10] The criteria proposed by these authors are: non-renewable resource depletion, environmental externalities (related to both waste disposal and reactor accidents), social externalities (related to both health/safety issues and nuclear weapons proliferation), and economics.

- *Non-renewable resource depletion*: like fossil-based power plants, LWR technology uses a depletable resource, uranium.[11]
- *Social externalities*: LWR technology requires extrinsic social institutions to restrict the proliferation of materials and techniques on which it relies.
- *Economics*: the LWR industry cannot maintain its capital stock at the current high costs of power plant construction.

Therefore, while maintaining safety and properly managing its wastes, LWR technologies must be more fuel-efficient, more proliferation resistant, and cheaper in capital costs. If LWR technology cannot meet these challenges, nuclear energy must switch to technologies other than LWRs in order to qualify as sustainable. The U.S. Department of Energy (DoE) has engaged governments, industry and the research community in a worldwide discussion on the development of a next generation of nuclear energy systems, known as Generation-IV. The purpose of this discussion is to assess which of a set of 6 selected nuclear power technologies best meet the above sustainability challenges.

2.5 Concluding remarks

Only recently nuclear energy has been subjected to studies in terms of its potential contribution to establishing sustainable development. Most analysts confirm that nuclear energy does at present not meet some essential requirements for constituting a sustainable energy resource, and that, in particular, the current use of light water reactor (LWR) technology cannot be qualified sustainable. Arguments concerning radioactive waste, reactor accidents, nuclear proliferation and terrorism, economic competitiveness, and public opinion all play a role in the discussion regarding the sustainability of nuclear energy. Likewise, however, it has been pointed out that it is hard to claim that any of the present ‘renewable’ energy technologies meet all criteria of sustainability. One of the major reasons is that renewables have so far not been applied on a large global scale, so that the risks involved with their usage - however different in nature from those associated with nuclear energy - cannot yet be fully apparent. Fundamental issues determining the (un)sustainability of renewables relate to land usage, materials use, waste production and environmental impact.

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. Whereas changes in energy infrastructures, including nuclear ones in particular, occur generally relatively slowly, nuclear energy should still be viewed in a dynamic way. During a transitional phase with some role for nuclear power, some of the more problematic aspects of nuclear energy might be rendered more sustainable. Technological developments in the nuclear field over the past few decades have been considerable, demonstrated for example by the substantially declining likelihood, since the Chernobyl catastrophe in 1986, of experiencing another serious reactor accident with large consequences for the external environment. These technological advancements are likely to continue, not only with respect to increasing reactor safety, but also in view of ascertaining containment integrity of radioactive waste storage, or building more proliferation- and terrorism-resistant reactors and spent-fuel storage. This could give nuclear energy a potential role beyond a sustainability-transition period. To some extent, depending on perspectives of both time and location, nuclear energy could therefore contribute to realising paths towards the establishment of sustainable energy systems and thereby to achieving sustainable development.

[11] Still, uranium resources may last for centuries, even under a significant expansion of nuclear energy. Hence, while LWR energy systems may fail on this criterion in the long term (many centuries), for the near term (century, or longer) uranium resources are abundant.

3. Europe

3.1 PRIMES

3.1.1 Introduction

In the context of the nuclear case four scenarios were examined so as to address the impact that different developments of the nuclear sector would have in the evolution of the EU-25 energy system and the achievement of post-Kyoto CO_2 emission reduction targets.

- The 'Nuclear phase-out with carbon value' scenario (PO-CV case) assumes that there is no lifetime extension for existing capacities and no new capacities are built in the EU-25. Furthermore, stricter policies towards reducing CO_2 emissions are assumed with permit prices for CO_2 emissions rising from 10 $€_{2000}$/t of CO_2 in 2010 (as in the Baseline scenario – constant over the projection period) to 50 $€_{2000}$/t of CO_2 in 2020 and 100 $€_{2000}$/t of CO_2 in 2030
- The 'Nuclear technology breakthrough with carbon value' scenario (BT-CV case) reflects a contrasting development for nuclear energy in EU-25 with investment costs for new nuclear technology design becoming 25% lower than in the Baseline scenario beyond 2010. In addition, the improved safety characteristics of this technology compared to conventional nuclear technology are assumed to lead to the re-evaluation of declared nuclear phase-out policies in EU-25 Member States and the acceptance of nuclear energy as an option for non-nuclear EU-25 Member States. Permit prices for CO_2 emissions are assumed the same as in the PO-CV case.
- The 'Nuclear technology breakthrough in Baseline scenario' (BT case) exploits the role that a nuclear breakthrough as in the BT-CV case would play in the absence of additional incentives towards reducing CO_2 emissions (i.e. permit prices are kept constant at 10 €2000/t of CO_2 over the projection period as in the Baseline scenario).
- The 'Baseline scenario with carbon value' (CV case) examines the effect that stricter CO_2 emissions reduction targets (with permit prices as in the PO-CV and BT-CV cases) would have on the evolution of the EU-25 energy system while technology developments for nuclear energy are assumed unchanged from the Baseline scenario.

3.1.2 Results

Primary energy consumption

The evolution of primary energy needs and changes in comparison to the Baseline scenario for the four cases examined are illustrated in Table 3.1.

In the PO-CV case primary energy needs decline over the projection period reaching -12.8% from Baseline levels in 2030 as a result of the higher permit prices introduced in the long run, but also the lower exploitation of nuclear energy (with an efficiency of some 33% in the EU-25 energy system) in the presence of nuclear phase-out policies. The most pronounced decline in percentage terms occurs for nuclear energy (-81.5% from Baseline levels in 2030), followed by solid fuels (-68.6%), and liquid fuels (-8.0%). On the contrary demand for renewable energy forms is projected to grow well above Baseline levels reaching +36.3% in 2030 from Baseline levels whereas a less pronounced increase is also projected for natural gas (+3.6% in 2030).

The BT-CV case is also characterized by a decline of overall energy requirements (-4.4% from Baseline levels in 2030), which is, however, significantly less pronounced than in the PO-CV case as the higher use of nuclear energy (+85% from Baseline levels in 2030) involves an increase of primary energy requirements that partly counterbalances the effect of higher permit prices. Demand for solid fuels and liquids (-72.8% and -8.3% from Baseline levels in 2030) exhibits similar trends to those observed in the PO-CV case. This is not the case for natural gas demand of which declines by -14.8% from Baseline levels in 2030, as the assumed nuclear technology breakthrough acts to the detriment of the use of natural gas in the power sector. In the same content primary energy demand for renewable energy forms exhibits a less pronounced growth than in the PO-CV case (+28% from Baseline levels compared to +36.3%).

Table 3.1 *Evolution of primary energy needs in the EU-25 energy system*

PO-CV case	Mtoe				% change from baseline		
	2000	**2010**	**2020**	**2030**	**2010**	**2020**	**2030**
Solid Fuels	303.2	218.9	112.0	62.7	1.2	-41.4	-68.6
Liquid Fuels	635.6	647.6	633.6	610.6	0.4	-4.2	-8.0
Natural Gas	376.0	510.4	618.8	688.9	0.7	1.3	3.6
Nuclear	237.7	237.1	184.0	35.9	-3.3	-13.7	-81.5
Renewable energy forms	96.1	139.8	204.7	267.4	0.2	22.2	41.7
Total	**1651**	**1757**	**1756**	**1669**	**0.1**	**-4.9**	**-12.8**
EU-15	**1453**	**1553**	**1547**	**1461**	**0.1**	**-4.6**	**-13.2**
NMS	**198**	**203**	**208**	**208**	**0.0**	**-6.9**	**-9.7**
BT-CV case	**Mtoe**				***% change from baseline***		
	2000	**2010**	**2020**	**2030**	**2010**	**2020**	**2030**
Solid Fuels	303.2	212.1	94.0	54.4	-2.0	-50.8	-72.8
Liquid Fuels	635.6	641.2	631.1	608.4	-0.6	-4.5	-8.3
Natural Gas	376.0	504.8	579.2	566.5	-0.4	-5.2	-14.8
Nuclear	237.7	251.9	288.2	359.1	2.7	35.2	85.0
Renewable energy forms	96.1	139.2	200.4	241.5	-0.2	19.6	28.0
Total	**1651**	**1751**	**1793**	**1830**	**-0.2**	**-2.9**	**-4.4**
EU-15	**1453**	**1550**	**1584**	**1611**	**-0.1**	**-2.3**	**-4.3**
NMS	**198**	**201**	**209**	**219**	**-0.8**	**-6.7**	**-5.2**
BT case	**Mtoe**				***% change from baseline***		
	2000	**2010**	**2020**	**2030**	**2010**	**2020**	**2030**
Solid Fuels	303.2	212.1	165.4	146.5	-2.0	-13.5	-26.7
Liquid Fuels	635.6	641.2	660.5	660.9	-0.6	-0.1	-0.4
Natural Gas	376.0	504.8	594.7	630.0	-0.4	-2.7	-5.2
Nuclear	237.7	251.9	294.6	374.3	2.7	38.2	92.8
Renewable energy forms	96.1	139.2	161.2	183.5	-0.2	-3.7	-2.7
Total	**1651**	**1751**	**1876**	**1995**	**-0.2**	**1.6**	**4.3**
EU-15	**1453**	**1550**	**1655**	**1756**	**-0.1**	**2.0**	**4.4**
NMS	**198**	**201**	**222**	**239**	**-0.8**	**-1.0**	**3.6**
CV case	**Mtoe**				***% change from baseline***		
	2000	**2010**	**2020**	**2030**	**2010**	**2020**	**2030**
Solid Fuels	303.2	216.3	104.1	57.3	0.0	-45.5	-71.3
Liquid Fuels	635.6	644.8	631.9	609.3	0.0	-4.4	-8.2
Natural Gas	376.0	506.8	608.0	613.7	0.0	-0.5	-7.7
Nuclear	237.7	245.3	209.8	220.9	0.0	-1.6	13.8
Renewable energy forms	96.1	139.5	207.6	252.8	0.0	24.0	34.0
Total	**1651**	**1755**	**1764**	**1756**	**0.0**	**-4.5**	**-8.2**
EU-15	**1453**	**1552**	**1554**	**1543**	**0.0**	**-4.2**	**-8.3**
NMS	**198**	**203**	**209**	**214**	**0.0**	**-6.5**	**-7.4**

Source: PRIMES

The BT case is the only one of the cases examined in which the energy intensity of the EU-25 energy system is projected to exhibit a worsening in comparison to the Baseline scenario (+4.3%, equivalent to the projected change in primary energy requirements as the macroeconomic development of the EU-25 energy system is assumed to remain unchanged from Baseline levels – this is also valid for all the other cases examined). The projected growth in overall primary energy needs is due to the much higher exploitation of nuclear energy (+92.8% from Baseline levels in 2030) occurring to the detriment of solid fuels (-26.7% in 2030), and to a less extent natural gas (-5.2%) and renewable energy forms (-2.7%). Demand for liquid fuels remains almost unchanged from Baseline levels (-0.4% in 2030) clearly reflecting the insignificant role of this energy form in power generation, especially in the long run.

A significant decline in primary energy needs is also projected to occur in the CV case (-8.2% from Baseline levels in 2030) as the introduction of higher permit prices in comparison to the Baseline scenario leads to adjustments both in the demand and the supply side. Primary energy demand for solid fuels and liquids (-71.3% and -8.2% respectively from Baseline levels in 2030) exhibits a decline similar to that observed in the PO-CV and BT-CV cases, whereas demand for nuclear energy, even in the absence of a technological breakthrough, increases by +13.8%. However, the most pronounced increase is projected for renewable energy forms primary energy demand of which reaches at +34% from Baseline levels in 2030.

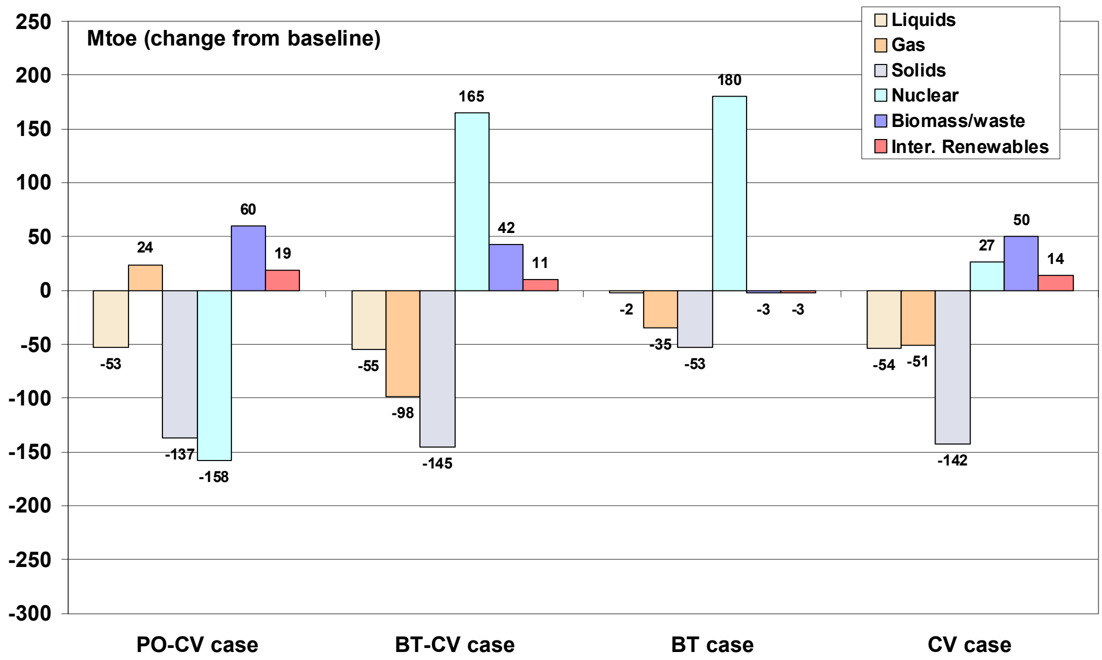

Figure 3.1 *Changes of primary energy needs in 2030 for the EU-25 energy system*
Source: PRIMES

Figure 3.1 illustrates the projected changes of primary energy needs in absolute terms in comparison to the Baseline scenario for the four cases examined. It is interesting to note that demand for solids and liquid fuels exhibits similar levels of decline in comparison to the Baseline for all the cases that involve the introduction of higher permit prices in the EU-25 energy system whereas fluctuations in the demand for natural gas and renewable energy forms are closely linked to the prevailing assumptions as regards the use of nuclear energy.

3.1.3 Share of renewables

The introduction of a CO_2 tax in the EU-25 energy system leads to an increase of the share of renewable energy forms ranging from +6.2 percentage points in 2030 under the PO-CV case assumptions to +3.3 percentage points in the BT-CV case (see Table 3.2). Furthermore, in the BT case the assumed nuclear technology breakthrough has only a limited effect on the role of renewable energy forms in the EU-25 energy system with their share declining from 9.9% in 2030 under Baseline assumptions to 9.2%.

Table 3.2 *Share of renewable energy forms in primary energy needs of the EU-25 energy system*

	% of primary energy needs				percentage points change from baseline		
	2000	2010	2020	2030	2010	2020	2030
PO-CV case	5.8	8.0	11.7	16.0	0.01	2.59	6.16
BT-CV case	5.8	7.9	11.2	13.2	0.00	2.10	3.34
BT case	5.8	7.9	8.6	9.2	0.00	-0.48	-0.66
CV case	5.8	7.9	11.8	14.4	0.00	2.70	4.53

Source: PRIMES.

Final energy demand

Changes in final energy demand are driven by the introduction of stricter CO_2 emissions reduction targets whereas the differentiation of assumptions as regards the evolution of nuclear energy in the EU-25 has only a limited impact on the demand side (see Table 3.3). This is clearly illustrated in the BT case, in which final energy demand exhibits an increase of just 0.1% from Baseline levels in 2030. In the three other cases, that involves higher permit prices faced by consumers, the decline of energy requirements in the demand side ranges from -9.0% in the PO-CV case to -8.7% in the BT-CV case. The response of the different sectors in the demand side also exhibits the same trends for the different scenarios examined.

Table 3.3 *Final energy demand in the EU-25 energy system*

PO-CV case	**Mtoe**				***% change from baseline***		
	2000	**2010**	**2020**	**2030**	**2010**	**2020**	**2030**
Industry	309.1	335.4	348.6	359.4	0.2	-3.4	-6.0
Tertiary	154.2	169.0	177.4	185.7	0.4	-6.4	-13.0
Households	279.1	304.9	307.6	298.1	0.1	-5.0	-10.8
Transport	332.0	384.4	403.3	403.8	0.0	-4.0	-8.5
Total	**1074**	**1194**	**1237**	**1247**	**0.2**	**-4.4**	**-9.0**
EU-15	**955**	**1063**	**1094**	**1099**	**0.1**	**-4.4**	**-9.1**
NMS	**119**	**130**	**142**	**147**	**0.0**	**-5.1**	**-9.0**
BT-CV case	**Mtoe**				***% change from baseline***		
	2000	**2010**	**2020**	**2030**	**2010**	**2020**	**2030**
Industry	309.1	334.7	348.4	361.5	0.0	-3.5	-5.5
Tertiary	154.2	168.4	177.3	186.9	0.0	-6.4	-12.4
Households	279.1	304.5	308.0	300.5	0.0	-4.9	-10.1
Transport	332.0	384.3	403.2	403.7	0.0	-4.0	-8.5
Total	**1074**	**1192**	**1237**	**1252**	**0.0**	**-4.4**	**-8.7**
EU-15	**955**	**1062**	**1094**	**1105**	**0.0**	**-4.4**	**-8.7**
NMS	**119**	**130**	**143**	**148**	**0.0**	**-5.0**	**-8.6**
BT case	**Mtoe**				***% change from baseline***		
	2000	**2010**	**2020**	**2030**	**2010**	**2020**	**2030**
Industry	309.1	334.7	361.4	383.4	0.0	0.1	0.3
Tertiary	154.2	168.4	189.9	213.9	0.0	0.2	0.2
Households	279.1	304.5	324.2	334.6	0.0	0.1	0.1
Transport	332.0	384.3	420.0	441.1	0.0	0.0	0.0
Total	**1074**	**1192**	**1295**	**1373**	**0.0**	**0.1**	**0.1**
EU-15	**955**	**1062**	**1145**	**1211**	**0.0**	**0.1**	**0.2**
NMS	**119**	**130**	**150**	**162**	**0.0**	**0.0**	**0.0**
CV case	**Mtoe**				***% change from baseline***		
	2000	**2010**	**2020**	**2030**	**2010**	**2020**	**2030**
Industry	309.1	334.7	347.8	360.4	0.0	-3.6	-5.8
Tertiary	154.2	168.4	176.9	185.9	0.0	-6.7	-12.9
Households	279.1	304.5	307.4	299.3	0.0	-5.1	-10.4
Transport	332.0	384.3	403.2	403.6	0.0	-4.0	-8.5
Total	**1074**	**1192**	**1235**	**1249**	**0.0**	**-4.6**	**-8.9**
EU-15	**955**	**1062**	**1093**	**1102**	**0.0**	**-4.5**	**-8.9**
NMS	**119**	**130**	**142**	**148**	**0.0**	**-5.1**	**-8.8**

Source: PRIMES.

Similar are the findings and as regards changes in the fuel mix with demand for liquid fuels and natural gas declining at similar rates for the different cases examined with higher CO_2 emissions reduction constraints involved (see Figure 3.2). However, as regards electricity demand the decline from Baseline levels is to some extent affected by the prevailing nuclear policy assumptions ranging from -7.0% from Baseline levels in 2030 in the PO-CV case to -4.2% in the BT-CV case.

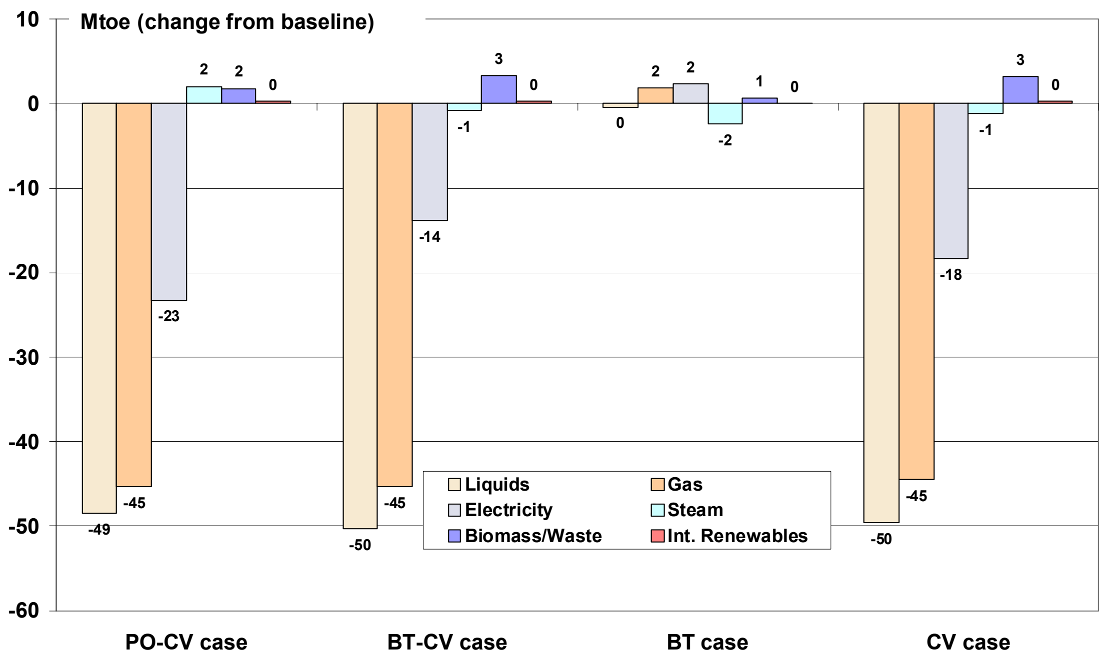

Figure 3.2 *Changes of final energy demand by fuel in 2030 for the EU-25 energy system*
Source: PRIMES.

Electricity and steam generation
Significant changes are projected to occur in the electricity and steam generation sector under the different nuclear cases examined (see Figure 3.3). In the PO-CV case, combining stricter policies towards reducing CO_2 emissions with a gradual phase-out of nuclear power plants, overall electricity generation declines by -7.9% from Baseline levels in 2030. Generation from solid fuels is limited by 2030 to just 16% of that in the Baseline scenario with the decline in electricity generation from nuclear power plants reaching at -82.4% from Baseline levels. The gap generated is covered by an increase in electricity production from natural gas (+25.1% from Baseline levels in 2030), intermittent renewable energy forms (+26.3%) and biomass-waste (+183.7%). As a result of the above changes the share of renewable energy forms in electricity generation reaches 34.2% in 2030 (including waste), i.e. an increase of 13.4 percentage points compared to the Baseline scenario. In contrast the share of nuclear energy in overall electricity generation declines from 31.8% in 2000 and 18.4% in 2030 under Baseline assumptions to just 3.5%.

In the BT-CV case, the assumed nuclear technological breakthrough leads to an increase of electricity generation from nuclear power plants by +75% in 2030 when compared to the Baseline scenario while overall electricity generation declines by -4.7% due to the introduction of higher permit prices. A growth on top of Baseline levels is also projected for renewable electricity (+14.8% for electricity generated from intermittent renewable energy forms, +111.5% for electricity generated from biomass-waste). In the contrary, electricity generation from solid fuels declines by -89.3% in 2030 whereas that from natural gas is limited to 77.9% of the projected electricity production in 2030 under Baseline assumptions. The strong shift away from fossil fuels in the power sector is clearly reflected in the share of non fossil fuels in overall electricity generation that reaches 62.3% in 2030 (33.8% for nuclear energy and 28.5% for renewable energy forms), some 23 percentage points higher than in the Baseline scenario.

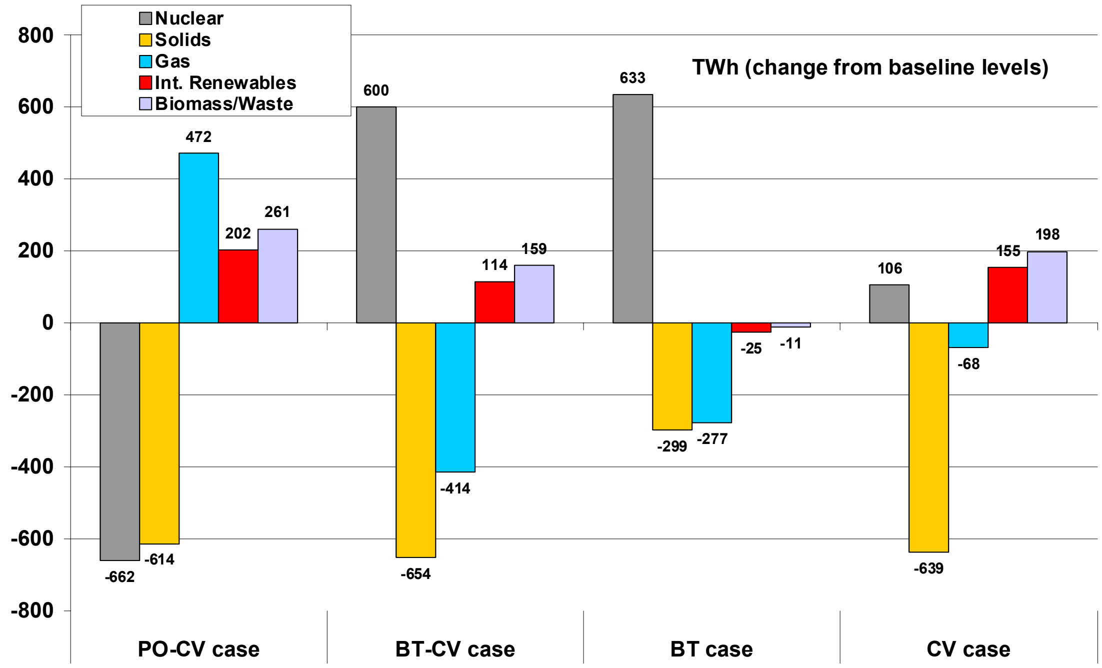

Figure 3.3 *Changes in electricity generation in 2030 for the EU-25 energy system*
Source: PRIMES.

An even higher increase in the use of nuclear energy is projected in the BT case (+78.8% from Baseline levels in 2030), in which however electricity generation remains rather stable at Baseline levels (+0.2% in 2030). This increase occurs mainly to the detriment of solid fuels (-40.8% in 2030) and natural gas (-14.8%). A limited decline is also projected for intermittent renewable energy forms (-3.2%) as well as electricity generation from biomass-waste (-7.9%). In this case the share of nuclear energy in overall electricity generation in 2030 is projected to reach at 32.9% (14.5 percentage points above Baseline levels) while that of renewable energy forms declines to 20.0% from 20.9% in the Baseline scenario.

Finally, in the CV case the EU-25 power generation sector adjusts to the introduction of higher CO_2 emission reduction constraints through the abandonment of solid fuels and a limited decline in the use of natural gas (with electricity production from these energy forms declining by -87.3% and -3.6% respectively in 2030), occurring in favour of non-fossil energy forms. Electricity production from nuclear energy increases by 13.2% that from intermittent energy forms by 20.2% and that from biomass-waste by 139.3%. With overall electricity production declining by -5.8% from Baseline levels in 2030, the share of renewable energy forms in electricity generation reaches 30.8% in 2030 with nuclear energy accounting for 22.2% of electricity production.

CO_2 emissions and concluding remarks
As a result of energy intensity gains and changes in the fuel mix towards less carbon intensive energy forms the evolution of CO_2 emissions in the EU-25 energy system under the four cases examined is projected to be significantly more favourable than in the Baseline scenario (see Table 3.4). For all cases CO_2 emissions in 2030 are projected to remain below 1990 levels over the projection period. A nuclear technology breakthrough under Baseline assumptions (BT case) limits CO_2 emissions in 2030 to 97% of those observed in 1990 (a reduction of -7.6% or -301 Mt CO_2 from Baseline levels in 2030).

Table 3.4 *Evolution of CO_2 emissions in the EU-25 energy system*

	Mt of CO2				% change from baseline		
	2000	**2010**	**2020**	**2030**	**2010**	**2020**	**2030**
PO-CV case	3665	3647	3413	3308	0.8	-10.1	-16.4
BT-CV case	3665	3586	3240	2985	-0.9	-14.6	-24.6
BT case	3665	3586	3650	3657	-0.9	-3.8	-7.6
CV case	3665	3619	3350	3109	0.0	-11.7	-21.5
	Index (1990=100)						
	2000	**2010**	**2020**	**2030**			
PO-CV case	97.2	96.7	90.5	87.8			
BT-CV case	97.2	95.1	86.0	79.2			
BT case	97.2	95.1	96.8	97.0			
CV case	97.2	96.0	88.9	82.5			

Source: PRIMES.

The assumptions of stricter policies towards reducing CO_2 emissions without a differentiation of policies as regards nuclear energy compared to the Baseline scenario (CV case) gives rise to a significantly more pronounced decline (-21.5% or -849 Mt CO_2 from Baseline levels in 2030). Combining these policies with a nuclear technology breakthrough (BT-CV case) leads to a further decline of CO_2 emissions (-24.6% or -974 Mt CO_2 from Baseline levels in 2030) whereas in the case of a nuclear phase-out in the EU-25 (PO-CV case) the reduction in CO_2 emissions is limited to -16.4% or -650 Mt CO_2 from Baseline levels in 2030.

The results obtained clearly illustrate that the role of a nuclear technology breakthrough is significantly more pronounced in reducing CO_2 emissions of the EU-25 energy system in the absence of strict policies towards reducing CO_2 emissions than when such policies are present. This is explained by the fact that in the second case action is undertaken not only in the power generation sector but also in the demand side and in addition that higher incentives are provided towards exploiting other carbon-free options in power generation (i.e. renewable energy forms). Thus, when comparing the results of the PO-CV and BT-CV cases to those of the CV case, in the first one the nuclear phase-out leads to an increase of emissions by 6.4% (or +199 Mt CO_2) in 2030, whereas in the second the nuclear technology breakthrough leads to a decline of CO_2 emissions by -4% (or -124 Mt CO_2) in 2030.

A side effect of the policies examined relates to the improvement of import dependency for the EU-25 energy system both as a result of energy intensity improvements but also because of changes in the fuel mix towards the use of indigenous energy forms (such as nuclear and renewable energy forms). Thus, compared to an import dependency of 65.8% in 2030 under Baseline assumptions, in the CV case import dependency is limited to 61%, in the BT case to 59.1% and in the BT-CV case to 56% (close to 10 percentage points lower than in the Baseline scenario). However, the reverse trend is projected for the PO-CV case, in which the combined effect of a nuclear phase-out with stronger CO_2 emissions reduction incentives (mainly affecting solid fuels, one of the main indigenous energy forms in the EU-25) leads to a worsening of import dependency which reaches in 2030 at 68.8% (+3 percentage points from Baseline levels.

3.2 MARKAL Western Europe

3.2.1 Introduction

After the oil crises in the nineteen seventies, nuclear power plants were seen as a cheap, clean way to reduce the dependency on fossil fuels from the Middle East. The number of nuclear plants has increased till the nineties of the last century. More and more the risks of nuclear power, related to reactor safety, nuclear waste and the cost of waste reprocessing and storage became clear. Nevertheless, nowadays almost a third of the power production in Western Europe is based on fission power.

In this chapter, two scenarios will be used to analyse the position of nuclear energy in a future where CO_2 emission reduction will have priority. The first scenario expects that the disadvantages of nuclear be not accepted anymore. The lifetime of existing nuclear plants will not be extended and no new plants are built. In the second scenario it is assumed that the safety risks and waste management problems are accepted and that a new cheaper nuclear technology is available.

Nuclear sector in MARKAL-WEU
In Western Europe the dominant reactor type is Light Water Reactors (LWR). The nuclear fission technologies in MARKAL-WEU are a 'classic' LWR and a MOX based LWR. From 2030 also two fusion power plants are available, this however is beyond the scope of this study.

The classic Light Water Reactor (LWR) uses enriched uranium as fuel input. For the spent fuel and the spent core of the reactor a cooling down period of ten years is assumed. After this period it can be stored further or reprocessed into low and high radioactive components. One of the reprocessed components is depleted uranium. Depleted uranium is also a by-product of uranium enrichment and can be up-graded and used in the MOX type of fission reactor.

This second type of LWR type reactor (MOX based LWR) uses mixed uranium oxide (MOX) instead of uranium. MOX is a derived fuel obtained by upgrading plutonium from spent nuclear fuel and low-grade uranium. The MOX based LWR has been built since the nineteen eighties and now Western Europe has about 20% of its current reactors fitted to run on MOX. The spent fuel of the MOX based LWR reactor also has to be stored for ten years before it can be stored further or can be reprocessed. No further use of these rest products is assumed.

Both type of reactors have the same investment cost structure, given in Table 3.5 although fuel costs differ, as outlined above. In these cost data the decommissioning cost are included.

Table 3.5 *Characteristics of nuclear power plants*

		LWR and MOX based LWR
Reactor cost	[€/kW$_e$]	1430
Steam turbine cost	[€/kW$_e$]	300
Balance of system cost	[€/kW$_e$]	253
Fixed O&M cost	[€/kW$_e$]	36.9
Variable O&M	[€/MWh$_e$]	4.14
Discount rate	[%]	8
Start year		1990
Lifetime	[yr]	40
Progress ratio of reactor only, not of overall plant	[%]	0.99

Storage costs for temporal and long storage of nuclear fuels and spent are € 247.9 kg/year. The cost for reprocessing of uranium oxide and MOX are assumed to be 800 €/kg.

3.2.2 Characterisation of the scenarios

Baseline
In the Baseline the strong increase of nuclear power plants in the nineteen seventies and eighties after its introduction will not be continued. The installed capacity will be used till the end of their lifetime, but will not be rebuilt. Consequentially the capacity of fission power plants decreases after 2010, where in 2030 the capacity is 15% of its 2000 level. In 2040 when the old plants are closed down only a small capacity (6 GW) of the MOX based LWR will be built, this is less then 5% of the level in 2000. The MOX used in this plant is fully imported. Till 2030 a

reprocessing percentage of the fuel spent is forced into the model to approach the situation of 1990 and 2000. The depleted uranium and plutonium produced by these reprocessing processes are used for MOX production. From 2030 on the fuel spent will be stored, this implies that reprocessing is too expensive.

Phase-out with post-Kyoto policy
Besides a forced phase-out of nuclear capacity this scenario also has an increasing tax on CO_2 emissions. Since in the Baseline the nuclear capacity decreases already considerably, the influence of the phase-out will not be that significant. But what will be the consequences of an increasing CO_2 taxation? In this scenario, Western Europe applies a tax of 10 €/tCO_2 (2010), 50 €/tCO_2 (2020), 100 €/tCO_2 (2030-2050). Note that fusion power plants are not included in the phase-out constraint.

Nuclear technology breakthrough with post-Kyoto policy
The assumptions on nuclear capacities in this scenario are opposite to the Phase-out scenario. Instead of a forced phase-out, there will be new opportunities for nuclear power with the introduction of cheap fission power plants. Moreover, the same CO_2 tax is applied as in the Phase-out scenario.

These new power plants will be a cheaper version of the existing ones, LWR-NEW and MOX based LWR-NEW. Both new types have an investment cost of 75% of the initial investment cost of LWR and MOX based LWR. The technologies will be available from 2020 and it is expected that future reactors additionally will have a longer lifetime of 60 years.

The nuclear scenarios will be compared to a case where the carbon tax is applied to the Baseline. This ‘Baseline with post-Kyoto policy’ is useful to determine which impacts are due to the assumptions regarding nuclear power, and which impacts are merely the result of the increasing CO_2 tax.

3.2.3 Results

Fossil fuels in primary energy consumption decrease

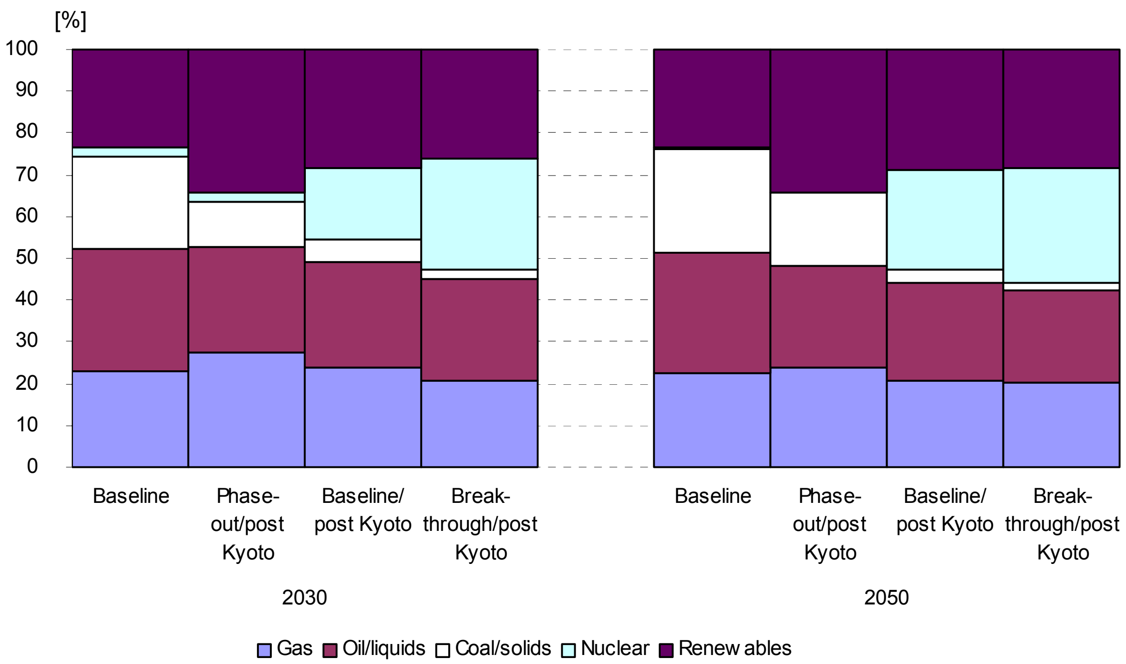

Figure 3.4 *Primary energy consumption*

The implementation of the higher carbon tax in the Phase-out and the Breakthrough scenario has no significant effect on the level of total primary energy consumption. In 2030 the differences between the Baseline and the alternative scenarios are less than 6%. By 2050 the scenarios differ even less. More interesting is the shift in the energy mix.

Whereas in both years coal, oil and gas have a share of almost 75% in the energy mix in the Baseline, their share in the Phase-out scenario is just 63% in 2030 and 66% in 2050. With the introduction of the cheaper nuclear power plants the share of fossils is even lower with 48% in 2030 and just 44% in 2050. Comparison to the Baseline post-Kyoto scenario shows that the carbon value already provides a big stimulus for nuclear power. In this scenario the share of fossil fuels is 54% (2030) and 47% in 2050. Although the effect of the carbon tax on the consumption of gas and oil is small, the coal consumption decreases substantially compared to the Baseline. This is related to the different applications of each energy carrier over the sectors and the possibilities to reduce emissions in the different sectors.

In the Phase-out case, obviously coal and oil are substituted mainly by renewables. In 2030 as well as in 2050 the total energy from renewables is 40% higher than in the Baseline. In addition, a large share of coal remains, but due to the carbon tax coal combustion is combined with CO_2 capture and storage.

In the Breakthrough scenario, due to the availability of cheap nuclear power plants, nuclear has become a competitive option for emissions reduction, and its share is still higher than in the Baseline/post-Kyoto case. In addition, renewables become more attractive in a post-Kyoto world, and have a 20% higher contribution than in the Baseline.

Electricity generation - over 50% nuclear in 2050

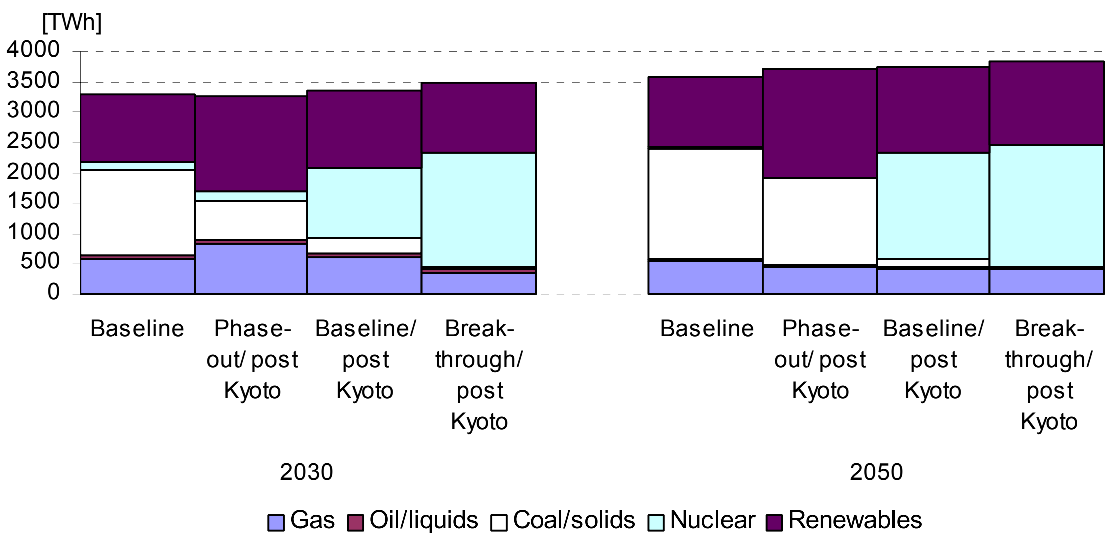

Figure 3.5 *Electricity generation mix*

Since it is relatively easy to reduce CO_2 emissions in the electricity sector, the impact of CO_2 reducing measures is even more visible here. With a percentage of more than 60% fossil fuels in the power generation mix in the Baseline, the share of fossils in the Phase-out scenario is just 50% in both years; while it drops to 13% in the Breakthrough scenario. In the year 2030, the impact of cheaper nuclear plants in the Breakthrough case is clear, compared to the Baseline with post-Kyoto policy. However in 2050 the difference between the latter two is much smaller, indicating that in a world where the risks related to nuclear power are accepted (or reduced), a high carbon tax can induce a large share of nuclear in the power generation mix.

In 2030 the amount of nuclear electricity in the Breakthrough scenario is almost 13 times the electricity from nuclear power plants in the Baseline. By 2050 this factor even has increased to 40, corresponding to a share of 52% of the total electricity production.

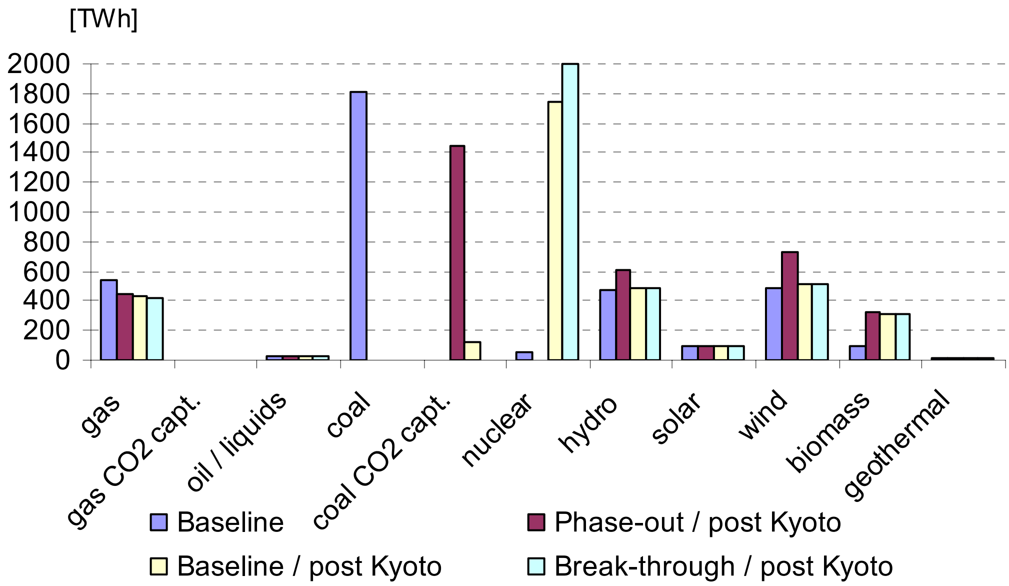

Figure 3.6 *Detailed technology mix in the power sector in 2050*

The fact that the amount of gas used in 2050 for electricity production is lower in the two nuclear scenarios compared to the Baseline, can mean that gas can be used more cost effectively to reduce CO_2 emissions in other sectors. In the Phase-out scenario the electricity produced from coal in 2030 is half of that in the Baseline. The difference in electricity produced by coal power plants, between the Phase-out and the Baseline in 2050 is much smaller. This is an effect of the increasing availability of new coal power plants with CO_2 capture by then. These carbon capture technologies are economically less interesting if the possibility of cheap nuclear electricity is available. Furthermore, compared to the baseline, wind and biomass increase in all Post-Kyoto cases, indicating that these options can reduce carbon emissions at lower costs than nuclear power plants.

3.2.4 Consequences of a nuclear phase-out or a breakthrough

Changes in carbon emissions

Obviously the increasing carbon tax leads to lower CO_2 emissions than in the Baseline, as illustrated in Figure 3.7. The impact depends on the options for emissions reduction available at a given cost. The nuclear phase-out leads to less emission reduction than the other two cases, while the additional effect of the breakthrough case is strongest in 2030.

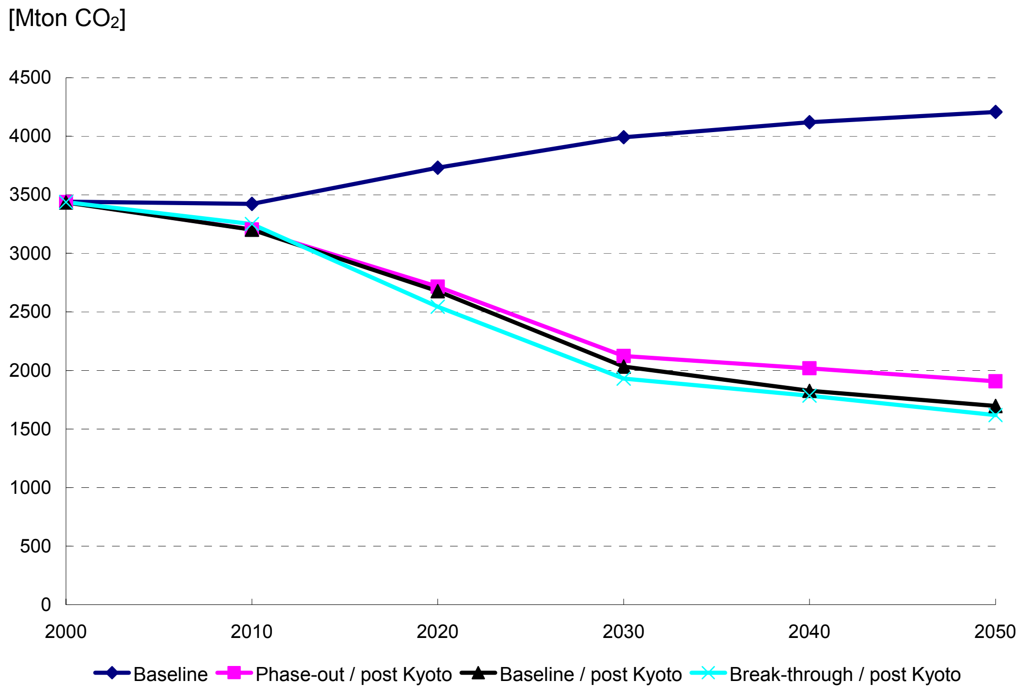

Figure 3.7 *CO_2 emissions (without CO_2 up take in biological sinks)*

In 2030 the emissions in the Phase-out scenario are half the emissions in the Baseline. Moreover, the increasing tax results in a decrease of CO_2 emissions over the time. In 2030 the emission are 60% of the emission level in 1990. Moreover if the emission tax is kept constant after 2030, the CO_2 emissions continue to decrease.

Figure 3.8 illustrates the fact that it is cheaper to reduce CO_2 emissions in some sectors than in others. So are the emissions in 2030, in spite of the high tax, of the residential and services, the commercial and the agricultural sector almost the same in the three scenarios as in the Baseline. The largest impact of the carbon tax and the largest differences between the three scenarios can be seen in the power sector. In the Phase-out scenario the reduction of CO_2 emissions is 70% with respect to the Baseline and accounts for half of the total reduction. With the cheaper nuclear power plants the emissions in the power sector are just 10% of their Baseline value and this reduction accounts for 60% of the total reduction. As seen in the technology mix of the power sector the decrease of CO_2 emissions in the Breakthrough is not only due to the new nuclear plants but a result of more carbon capture and renewable technologies as well. In all scenarios the emissions in the industry and other conversions processes can be reduced respectively about 50% and 60% with respect to the Baseline. For the transport sector this percentage is 30% and counts for 15% of the total emissions reduction. This is due to the increased penetration of biodiesel and decreased final demand in the transport sector under influence of the carbon tax.

For 2050 the picture of CO_2 reduction is similar to that in 2030 described above, be it that the reduction in the power sector is still higher. Interesting to see is a reduction of CO_2 emissions in the commercial and service sector due to a shift from coal boilers to electric heat pumps.

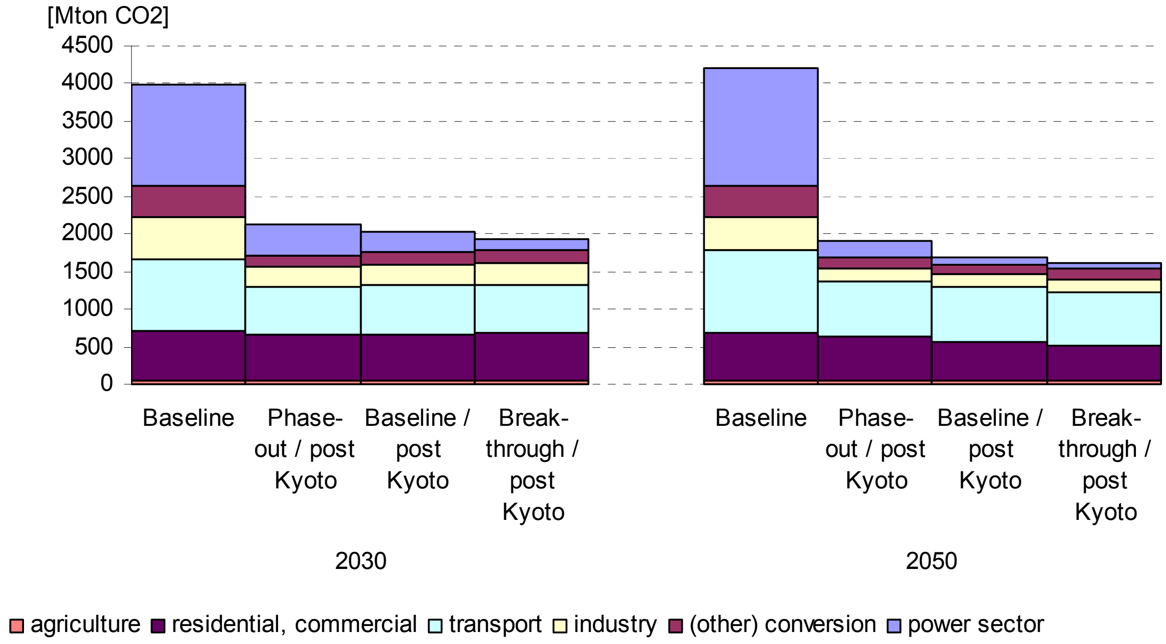

Figure 3.8 *CO_2 emissions by sector*

Costs of implementing the policies

As seen in the previous section the increasing CO_2 tax leads to a decrease of the overall CO_2 emissions. The power production sector is the major contributor to this reduction, as this sector has a substantial potential for reduction of CO_2 emissions at relatively low costs. The actual technologies deployed to meet the reduction differ between the scenarios, as the Phase-out sees enhanced deployment of carbon capture and renewables, whereas the Breakthrough sees a clear growth of nuclear technologies. The investments in alternative power generation are considerable, as a comparison to the Baseline illustrates: in the Phase-out, investments in the period 2020-2050 are on average 1.7 times that in the Baseline, and in the Breakthrough these are even 2.5 times higher.

Although investments in the power sector are substantially above Baseline levels, the differences in total system cost without taxes between the three scenarios are very small. In the Phase-out and the Breakthrough scenario the total system cost are maximal 2% and 3% respectively higher than in the Baseline. The small difference between Phase-out and Baseline is likely to be due to the choice of technologies. By the increasing capacity of CO_2 storage facilities, which are implemented as learning technologies, the investment cost of these technologies may decline enough to prevent a large increase in the total system cost. What is more, there are additional benefits from storage of CO_2 by enhanced coal-bed methane recovery (ECBM), since it has gas as a by-product, decreasing the add-on costs for CO_2 capture and sequestration. Finally, the increased deployment of renewables in the Phase-out scenario reduces the total fuel cost, as these technologies have zero fuel cost.

Impact on waste management

In the sections above, the influences of the new cheaper nuclear power plants on the energy system were discussed. Here the focus will be on the nuclear power sector itself in the Breakthrough scenario. First the increasing capacity of power plants is put in a broader perspective. Followed by a more precise look at the reprocessing and storage of nuclear waste.

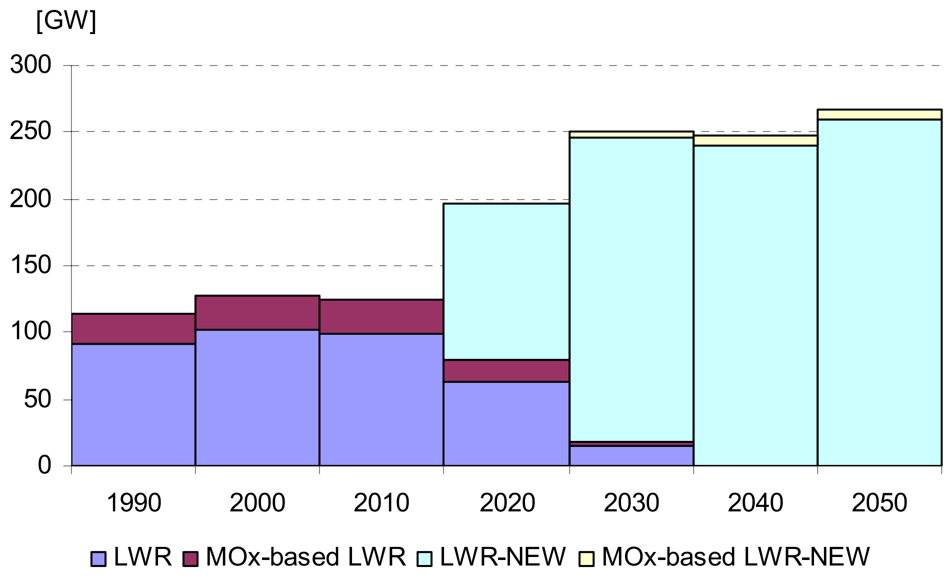

Figure 3.9 *Nuclear power plants by type in Breakthrough scenario*

Figure 3.9 presents the development of the nuclear power generating capacity in the Breakthrough post-Kyoto scenario. In the period 2010-2030 a total increase of 230 GW of new nuclear power plants can be seen. Assuming a capacity of 1200 MW for each plant, it means that in this period each year ten new plants are built in Western Europe. Comparatively, in the period 1980 till 1990 the nuclear capacity increased from approximately 42 GW to 115 GW.

Towards 2050 an amount of 187 kton uranium will be used. With the current assumptions on known reserves in Europe and Eurasia, it is not implausible that this amount of uranium can be used in Western Europe. This is different with the MOX use. The import of MOX is on its upper bound, which is based on the actual capacity for MOX production outside Europe.

Assuming a liberalized electricity market, with low governmental influence and a high risk for market actors, leads to very different picture. In this competitive environment lower investment costs are imaginable, but investors would use a higher discount rate. Despite the fact that the investments cost are lower a discount rate of 12% will imply 25% less investments in nuclear than in the Breakthrough scenario.

Reprocessing and storage

Currently, a number of reprocessing facilities in Europe are operational, implying that the model should include reprocessing as a relevant part of the nuclear cycle. As it turned out, under current market conditions reprocessing is not a cost-effective technology, and apparently other arguments for reprocessing played a deciding role in the decision to build reprocessing facilities. To reflect these non-economic considerations, and to reproduce the current practice, a bound has been included prescribing a minimal use of reprocessing facilities until 2020. From then onwards, it is assumed that existing facilities are phased out, and investment in new capacity will solely be based on economic grounds.

In the baseline, reprocessing disappears completely once the constraint is relaxed. Only when the demand for fuel increases considerably beyond the Baseline level, reprocessing seems to be able to play some role in the nuclear cycle. This is illustrated by the Breakthrough case, which however at the same time shows that its role is marginal at best. The underlying reason seems to be that the 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.

Figure 3.10 shows the development of the nuclear waste for which storage is needed. Here uranium oxide and MOX are the spent fuels of respectively the classic LWR and the MOX based LWR. Since both are not reprocessed yet, they should be seen as high radioactive. The other high radioactive part contains the high radioactive components after reprocessing. Most nuclear waste however will be low radioactive. This low radioactive is mainly depleted uranium, which is a by-product of the enrichment of uranium.

The depleted uranium could be up-graded to MOX and used for electricity production with the MOX based LWR and the MOX based LWR-NEW. One problem however, is that plutonium is needed for the up-grade and there is not enough plutonium available in Western Europe. Plutonium import is not modeled as it is assumed that plutonium is of too strategic value to be traded between world regions. Therefore, the number of MOX based LWR is limited to the import capacity of MOX. Furthermore, using the up-graded depleted uranium does not lead to a lower amount of waste, but to a shift from depleted uranium to spent MOX. Or when reprocessing the spent MOX, a shift to high radioactive components (90%) and other low radioactive components.

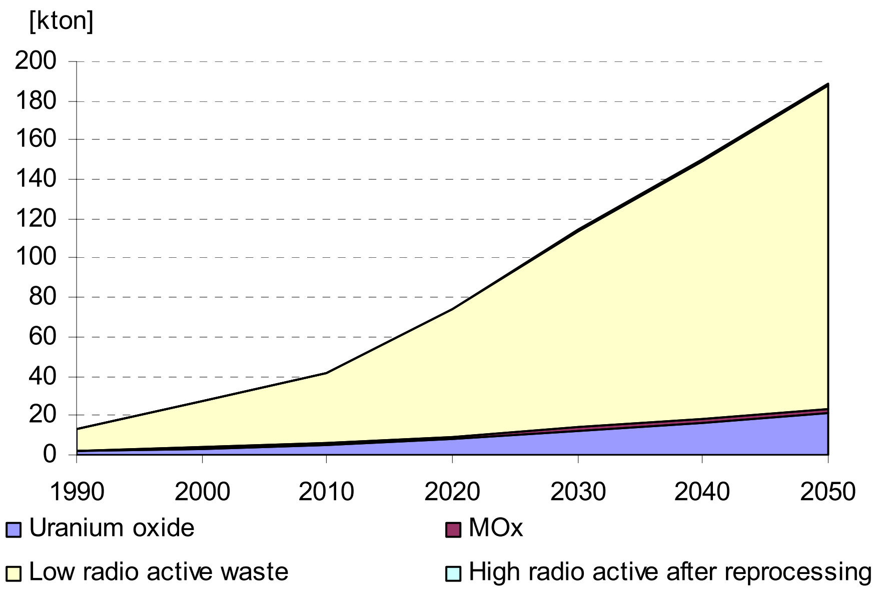

Figure 3.10 *Storage of nuclear waste in the Breakthrough/post-Kyoto scenario*

The increasing amount of nuclear waste induces high storage cost. In 2050 the annual cost for the nuclear storage is € 47 million[12]. Whereas the cumulative storage costs (1990-2050) is € 1.5 billion, and these costs will increase further as they continue beyond the end of the model horizon.

Security of supply

Due to an increase of renewables thanks to the carbon constraint, Western Europe will be less dependent of the rest of the world than in the Baseline. However the overall import dependency will grow over the years. Also the import dependency for each fossil fuel increases over time in all scenarios. Most interesting is the lower import dependency of coal. In the Phase-out and the Baseline post-Kyoto scenarios the domestic coal production equals the Baseline value while the total primary consumption is lower. Leading to a decrease of import dependency of coal compared to the Baseline. With the introduction of a cheap nuclear power plant the domestic coal that is only used in the electricity sector is phased out, as a result of that the import dependency of coal in the Breakthrough scenario is 100%.

[12] Based on estimated storage cost of 250 €/kg waste, from (Kolb, Martinsen, 2003).

By this and the fact that the uranium and MOX used by the power plants are mainly imported, the overall import dependency in the Breakthrough scenario is higher than in the situation where the fission plants are phased-out.

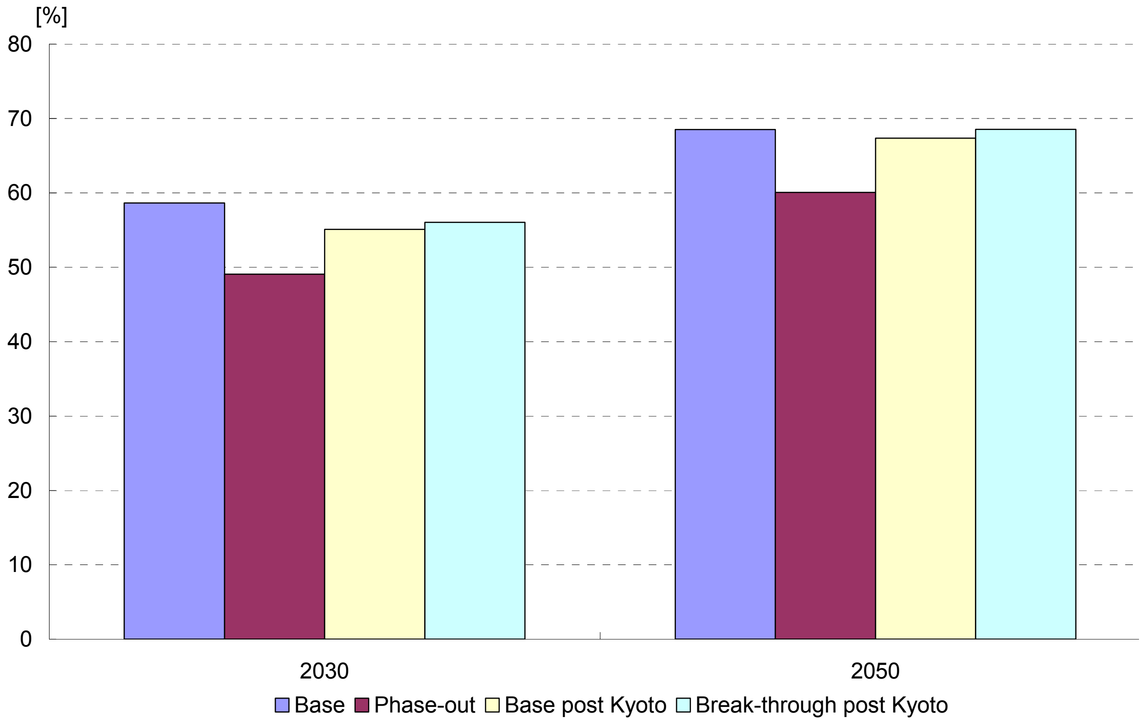

Figure 3.11 *Overall import dependency in Western Europe*

The variety and balance of the primary energy sources are reflected by the Shannon diversity index. An increase of the index means less dependency on only a few energy sources. In the Baseline the Shannon diversity index is stable round 72% from 2020 on. An increasing carbon tax leads to a more diverse and balanced energy system, mainly by the increase of biomass and nuclear in the nuclear cases. On the other hand the disappearance of coal in the Breakthrough scenario and the forced phase-out of nuclear in the Phase-out scenario cause that the Shannon index increases just a little to 74% in both scenarios. In the baseline with post-Kyoto policies these effects accounts less, leading to a Shannon diversity index of 76%. In all scenarios the index is more or less stable after 2020.

3.2.5 Conclusions and recommendations

This chapter has provided some insights into the contribution of nuclear power in a future where Post-Kyoto targets are pursued. Under the assumption of a carbon tax in Western Europe, increasing up to 100 €/tCO_2 in 2030, we compared a scenario where existing nuclear power is phased out to a scenario where a technology breakthrough reduces the investment costs of nuclear power plants with 25%. This leads to the following conclusions.

- The carbon tax induces a shift in primary energy mix towards renewables and nuclear power. The breakthrough scenario achieves the lowest share of fossil fuels with some 45% in 2050, compared to 75% in the baseline. In the scenario where nuclear power is phased out, it is more difficult to substitute fossil fuels, which remain at some 65%, while the emissions reduction is achieved with renewables and solid fuels combined with CO_2 capture and storage.

- In the year 2030, the lower investment costs in the Breakthrough scenario leads to a 60% higher electricity generation from nuclear compared to the scenario where only the carbon tax is applied. However in 2050 the difference between the two is only 15%, indicating that in a world where the risks related to nuclear power are accepted (or dealt with), a high carbon tax can induce a large share of nuclear in the power generation mix.
- The carbon tax leads to significant CO_2 emissions reductions, showing reductions of over 50% compared to the baseline in 2030. The impact depends on the options for emissions reduction available at a given cost. The nuclear phase-out leads to less emission reduction than the other two cases, while the additional effect of the breakthrough case is strongest in 2030. Moreover, the increasing tax involves a decrease of CO_2 emissions over the time. In 2030 the emission are 60% of the emission level in 1990.
- A large growth of the nuclear power generating capacity such as in the Breakthrough case implies that in Western Europe in the period 2010-2030, each year ten new plants are built, leading to a nuclear share of 52% in the total electricity production in 2050. This requires an amount of 187 kton uranium. With the current assumptions on proven reserves in Europe and Eurasia, this is not implausible.
- In the Breakthrough case, the amount of waste for which storage is required increases from 30 kton in 2000 to 190 kton in 2050. The annual storage costs in 2050 are 47 mln €, and will continue for an indefinite period of time.
- As regards security of supply, the phase-out case shows the best results, due to the highest increase in renewables. On the other hand, the import of uranium and MOX for nuclear power comes from other regions than the main suppliers of gas and oil. The diversity of Europe's energy mix improves most in the Baseline with post-Kyoto policies.

3.3 POLES

3.3.1 Introduction

POLES differentiates two types of nuclear capacities: conventional light-water nuclear reactors (NUC) and new nuclear design reactors (NND). Their techno-economic characterization of these technologies was made in the framework of JOULE III program. Their short description is the following:

- Standard Large Light-Water Reactor (NUC). This is the presently available nuclear reactor technology. In the reference case this plant type is supposed to exhibit capital costs slightly increasing over time due to increased investment in security measures.
- New Evolutionary Nuclear Design (NND). This technology is assumed to be introduced gradually after 2010 in the reference run and costs about 30% less to construct than the LWR by 2030 thanks primarily to its inherent safety characteristics. In the reference run it gains a considerable share of the total nuclear market (approx. 12%).

Table 3.6 *Cost characterisation of nuclear technologies in POLES (Europe)*

Investment cost		2000 [%]	2010 [%]	2020 [%]
Reference	NUC	100	100	100
	NND	195	189	98
Breakthrough case	NUC	100	100	100
	NND	195	189	74

Note: Relative to the investment cost of the standard reactor (NUC) in the reference.

Both the nuclear phase-out and the technological breakthrough cases were analysed with POLES. The scenario assumptions were translated to model assumptions in the following way:

1) Nuclear phase-out case:
   a) POLES followed the capacity path for the Annex-B regions (EU-30, Japan, USA, Canada, CIS and Ukraine) as defined for this the scenario within the Cascade-Mints project. For the Non-Annex B regions the nuclear capacity was limited to the existing capacities, and only the planned extensions were allowed. This determined the nuclear power capacities available for dispatching.
   b) From the capacity planning module both the conventional and new nuclear design were removed. This ensured that no new nuclear capacity was planned to be built.
   c) The given carbon value (CV) path was applied.

2) Nuclear breakthrough case:
   a) The investment cost for the new nuclear design type (NND) was changed, 25% reduction was applied to the reference investment cost. It must be underlined, that a significant reduction in the investment costs was assumed for the NND technology already in the reference case. Consequently the 25% reduction is an additional cost decline compared to the reference.
   b) The characterisation of conventional technology (NUC) remains unchanged.
   c) The agreed carbon value path was applied.

In addition to the two base scenarios three additional cases were implemented, in order to facilitate the analysis and decompose the effects of the nuclear policies and the carbon taxation. These supplementary scenarios were:

1. Nuclear phase-out without carbon value (‘Phase-out without CV’). This case is the same as the original phase-out scenario, with the only difference, that there is no CV applied.
2. Nuclear breakthrough without carbon value (‘Breakthrough without CV’). This is the same scenario as the original breakthrough case without applied CV values.
3. Only CV is applied (‘Only CV’). The reference case was modified with the pre-set CV values.

A further important fact has to be highlighted here. In POLES the nuclear fuel market is not modelled. The nuclear fuel is provided at an exogenously given cost (without domestic and import price differentiation), and no source of supply is identified. Consequently there is no export and import of this fuel. For ‘accounting’ reasons in the CM project, in order to achieve equilibrium in the energy balances, all nuclear fuel is assumed to be imported. This is certainly not accurate, although fuel cost are still relatively low and uniform amongst the different regions. This simplification will have a significant influence on some of the indicators analysed later.

3.3.2 Results

Effects on the primary energy consumption

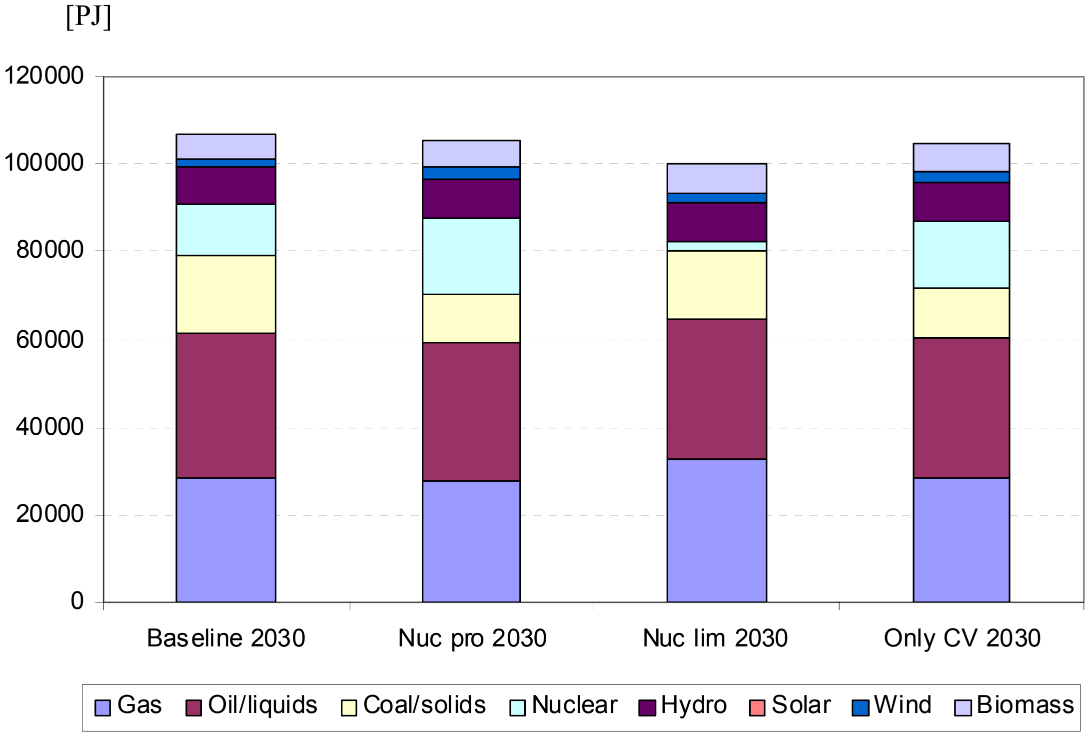

Figure 3.12 *Effects on the Primary energy consumption (EU-30, 2030)*

The effects of the two nuclear policy cases could be summarized in the following main points. All results refer to the POLES EU-30[13] region and to 2030 in this section.

The effects on the total primary energy production are relatively small. It is most significant in the case of the phase-out case, where the primary energy consumption of the EU-30 declines by 6%. However, it should be considered that the scenario includes relatively high carbon taxes and the share of nuclear primary energy consumption in the total consumption falls from 10% to 2%. The carbon tax explains 2% reduction in the total consumption, consequently more than half of the nuclear cutback is compensated by an increase in other energy carriers. Natural gas gains 5% higher share, followed by 3% increase in renewables and 1% increase in oil use. Coal is negatively affected, it loses 1% in the total share. However, the CV in itself would cut coal consumption by 5%, which means the nuclear phase-out alone gives a significant push to coal use.

In the nuclear breakthrough case, the reduction in total primary consumption is 1,5%, which is slightly above the total primary consumption when only the carbon value applied (-2%).

As already mentioned earlier, the assumed CV has significant effect on primary consumption. Column 4 of Figure 3.12 shows this effect and illustrates a further point. The CV would significantly increase the consumption of nuclear energy, but in the phase-out case, the constraint on nuclear capacities precludes this option. The response of the system is twofold: significant reduction in total consumption on the one hand, changes in the fossil fuel mix in the other. The carbon and the nuclear constraints together have higher impact on the total consumption, than what they reach separately. Thus this impact is more than additive.

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13 Poles EU-30 region applied in the CM project consist of the EU 25, Norway, Switzerland, Iceland, Romania, Bulgaria and Turkey. Because of model nomenclature the Baltic countries are not included in this region, while the former Yugoslavian countries are integrated.

The renewable energy is amongst the winners in the nuclear scenarios. Its total share goes up by 2.5-3% in the total primary energy consumption depending on the scenario. All sources (wind, biomass, hydro and solar) gain higher shares, but similarly to the earlier impacts only a smaller part (around one third) of this change could be attributed to the nuclear phase-out and breakthrough respectively.

In the nuclear breakthrough case a very direct substitution process takes place. While the nuclear share goes up by 6%, it substitutes almost exclusively coal, which has a 6% reduction in the total share. The 'impact pathway' is more straightforward than in the phase-out case: both the nuclear policy and the CV move the system to the same direction - reduction of coal use.

Finally, there are significant international trade effects on the fuel markets. In the case of nuclear phase-out total import reduces, but this is mainly due to the reduction of nuclear fuel import[14]. In the breakthrough case import is less affected, the increasing import of nuclear fuel replaces the declining import of coal.

Effects on the electricity generation
Similar tendencies could be followed in electricity generation as highlighted in the primary energy consumption. While the breakthrough scenario results in similar total fuel input as in the reference, the phase-out case shows significant reductions in fuel input in electricity generation (-13%), mainly due to the differences in efficiency. While the efficiency of the traditional nuclear plants is around 34% in the model, the substituting new gas technologies could reach much higher values (over 43%). In this second case the nuclear fuel is mainly substituted by natural gas. Coal use remains almost unchanged compared to the baseline, as a result of two opposite impacts: while the CV would reduce its use, the nuclear phase-out compensates for this decline. In the breakthrough case nuclear mainly replaces coal, while other fuels remain unchanged. In this case both the CV and the nuclear technological development have a parallel impact, moving the electricity system into the same direction: reducing coal use. The range of this change is illustrated by column 2 and 4 of Figure 3.13.

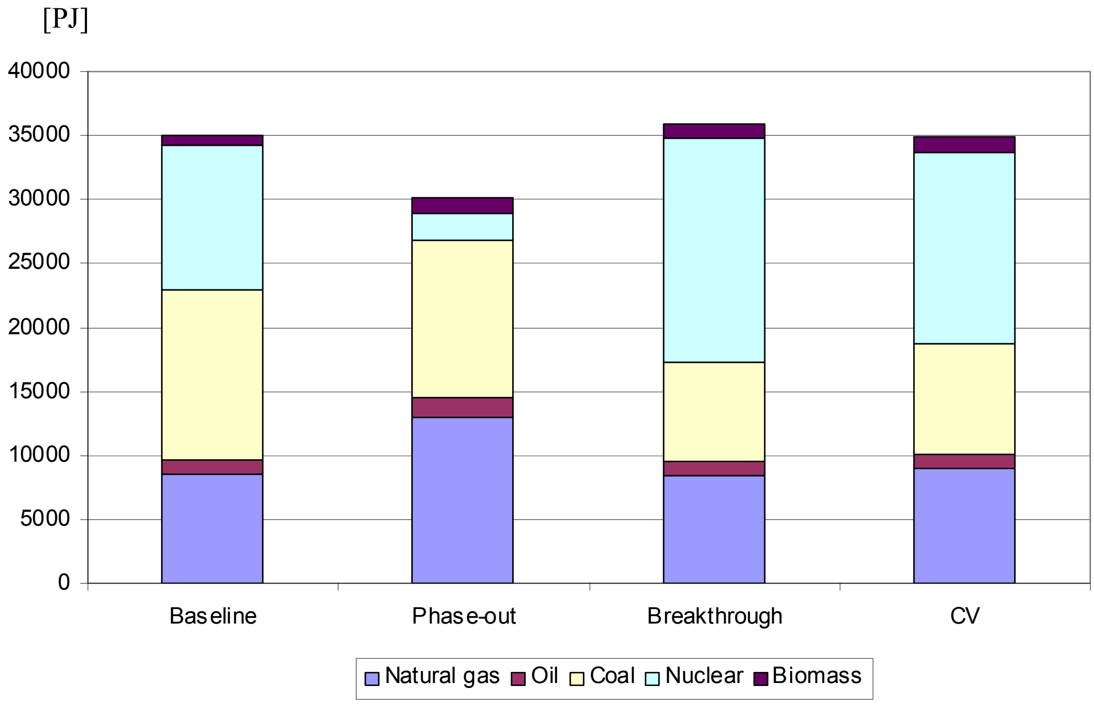

Figure 3.13 *Fuel input for electricity generation (EU-30, 2030)*

[14] In POLES the origin of nuclear fuel is not modelled, so in the CM project it is counted as import for energy balance reasons.

Considering renewable electricity generation, the policies have significant impacts. The reference 20% contribution to total electricity generation increases to almost 23% in both cases, mainly due to the imposed CV. In the breakthrough case the increase is slightly less. Electricity from wind and biomass sources are the winning technologies within the renewable category.

Effects on the fuel and electricity prices

Table 3.7 *Fuel price changes in the nuclear scenarios (Europe, 2030)*

	GAS [%]	OIL [%]	COAL [%]
Reference	100	100	100
Breakthrough	97	95	85
Phase-out	103	96	90
Only CV	98	95	86

Both the nuclear breakthrough and the phase-out case have a small effect on the oil and natural gas prices, the changes are within the +/- 5% range. The breakthrough case reduces the price of liquid fuels. This is a consequence of the reduced demand for fossil fuels. The phase-out case has mixed effect, the oil price decreases while the gas price increases, as a response to the growing demand for this latter fuel.

One important reason behind the limited impact on prices is that these fuels are traded on global markets. By 2030 the demand from the developing word (e.g. China, India and Brazil) is a significant driver of the global demand, which reduces the impact of a policy mainly focusing on the Annex B. In addition, the decreasing prices can induce further demand for the fossil fuels in the developing regions.

In the case of the coal markets[15], which are modelled in POLES as national markets, the price changes are more significant. E.g. in the breakthrough case the price change in Europe reaches -15%. Logically, the technology breakthrough has a higher impact on the coal price, as in the phase-out case the nuclear policy diminishes the impact of the CV on coal use. The table also illustrates, that the CV plays more significant role than the nuclear policies, as most effects already take place in the 'only CV' scenario.

Concerning the electricity prices, the changes are more difficult to summarise, as the prices are calculated on a country-by-country base, leading to diverse price ranges. Additionally, the effects of the policies are very different according to what type of capacity mix is available in a given region. E.g. a country that had less nuclear capacities in the beginning and an electricity system mainly based on hydro (example: Austria), will be less affected. In contrary a country with high nuclear ratio and dominant coal based system will be seriously affected (example: UK). The following table illustrates this point on five European countries.

Table 3.8 *Electricity price changes in industry, 2030*

[%]	Germany	Great Britain	Spain	Austria	The Netherlands
Reference	100	100	100	100	100
Breakthrough	106	120	106	103	107
Phase-out	117	129	112	103	114
Only CV	110	124	107	103	109

Great Britain confronts with the highest electricity price increase, which reaches as much as +29% by 2030 in the phase-out case, while in the same situation Austria faces only 3% increase.

[15] In the table an average European coal market price is reported.

The data also show, that in the phase-out scenario both the CV and the nuclear policy play an essential role in the price increase. This is also apparent in the nuclear breakthrough case.

3.3.3 Consequences of a nuclear phase-out or breakthrough

Effects on the security of supply indicators

Table 3.9 *Security of supply indicator (EU-30, 2030)*

	Shannon diversity index	Shannon diversity index incl. import dependency
Reference	70.1	32.0
Breakthrough	71.3	32.5
Phase-out	66.1	33.8
Only CV	71.3	32.9

The security of supply indicators show minor changes in the nuclear policy cases. Concerning the Shannon diversity index[16] calculated in CM, the effects are mixed. While the breakthrough case slightly increased the diversity (a tendency, which is already present in the 'only CV' case), the phase-out more significantly reduces it. It reflects the fact, that nuclear energy almost disappears from the primary sources and natural gas and oil further increase their shares. If the index includes import dependency, the picture is different. These indicators deteriorate in all policy cases. It is a common tendency in carbon constraint scenarios, where the intensified natural gas import deteriorates import dependency. The progress in renewables has the potential to reverse this trend, but not in these actual scenarios. The index in the breakthrough case also deteriorates, which requires a further note. The solution for POLES - to account the nuclear fuel as import - makes the index more biased toward import dependency than in reality. Most probably, if the nuclear fuel export and import had been accounted for, the index in this case would show an improving situation for the import dependency.

Changes in carbon emissions

Both the nuclear policies and the applied CV have significant impact on carbon emissions. In order to fully capture the effects of the different policies, all the individual scenario emissions (including the analytical ones) are depicted in the following figure.

[16] The Shannon index in Cascade Mints is defined as:

$$\left(\sum_i (-X_i / PEC_{total}) * \ln(X_i / PEC_{total})\right) / -\ln(1/N_{Xi})$$

where Xi: energy consumption by fuel type, PEC_{total}: Primary Energy Consumption, N_{Xi} : number of energy carrier considered.

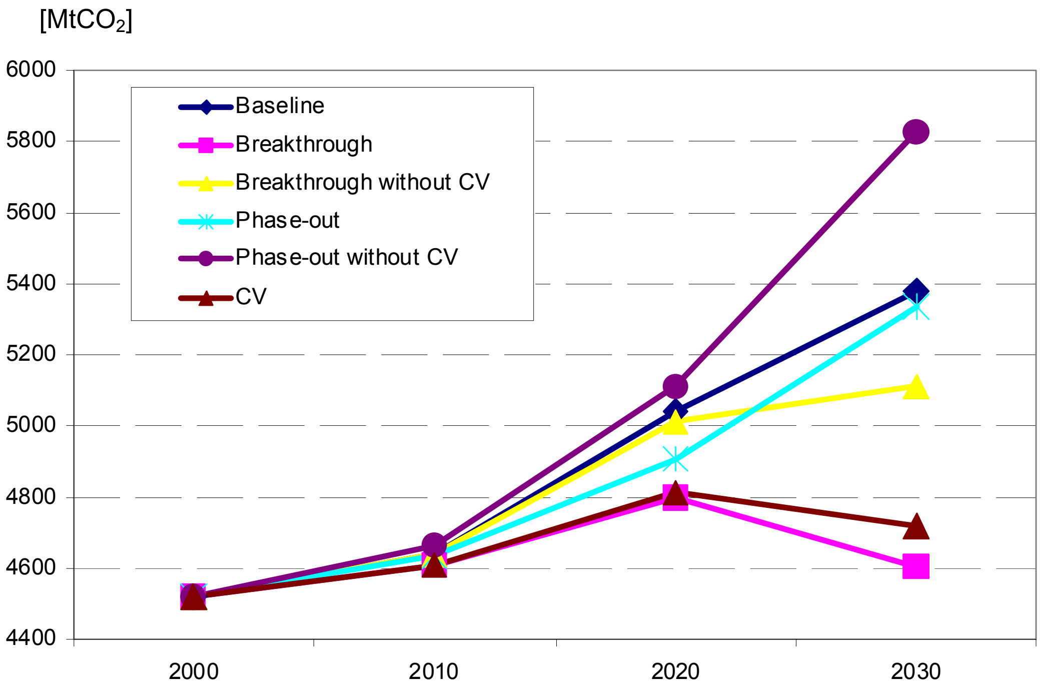

Figure 3.14 *Carbon emissions (EU-30, 2000-2030)*

There are two reference points to the CO_2 emission levels in the different scenarios. One reference is obviously the BAU emission level, but the scenario emissions should also be analysed relative to 'only CV' case. In this second case carbon emissions are 12% lower than in the reference. The nuclear breakthrough case further reduces CO_2 emissions to 86% of the reference emissions, however, the nuclear technology breakthrough alone would only reduce CO_2 emissions by 5%. The CV in this case creates additional demand for the nuclear energy, consequently further reducing emissions. Obviously the carbon value reduces emissions through other channels as well (e.g. increasing renewable and natural gas shares in total energy consumption).

The nuclear phase-out case has emission level very close to the reference. The phase-out significantly increases emissions (mainly through increasing coal use), which almost fully cancels out emission reductions achieved by the CV.

3.3.4 Conclusions and recommendations

The use of nuclear power is a sensitive issue among the European Union Member States, and there is high uncertainty about its future development. Some Member States started to phase-out their existing capacities, while others are facing public pressure to limit their use. The CM phase-out case is modelling a situation, where all Annex B countries follow a strategy to retire their nuclear sites at the end of their economic lifetime. The POLES results show, that this scenario is attainable, however this would impose very high burden on the system. If phase-out is connected to a carbon constraint (modelled by the exogenous CV path), countries characterized by higher shares of nuclear in their power generation face an electricity price increase in the range of 10-30% by 2030. At the same time, this policy makes achieving carbon targets more difficult and costly. Additionally the effects on the security of supply and on the diversity are clearly negative, as natural gas takes even higher shares in the primary energy mix than in the reference case.

The nuclear breakthrough case outlines a future scenario with more positive outlook concerning the future energy system of the EU. Nevertheless, the assumptions are optimistic in this case: not only the new nuclear design reactors become competitive in their economic performance but also their increased security features makes them acceptable for the whole community. The first element is modelled through the reduced investment cost, while the latter one is by not placing constraint on the use and availability of the new technology. If these conditions are fulfilled, the new technology has certainly a positive impact on the system: reduces import dependency, increases diversity, and provides an option to combat climate change. However, the uncertainty in this scenario is high. This is not only due to the technical nature of the issue, but also inherent social values, perception and attitude toward the use of nuclear power make the scenario ambiguous.

3.4 TIMES-EE

3.4.1 Introduction

The perspectives of nuclear power generation in Europe vary significantly among the different countries. For example, in 2003 Finland decided to build a new nuclear power plant in Olikiluoto, which is scheduled to start commercial operation in 2009. In July 2004 the Board of Directors of Electricité de France authorized the development of the Framatome-designed European Pressurized Water Reactor, starting with the site selection. On the other hand, several European countries like Belgium, Germany, Netherlands or Sweden passed agreements or laws with the target of nuclear phase-out. These national phase-out plans are already taken into account in the reference scenario.

Table 3.10 *Assumptions about the future use of nuclear power in the different countries and in the different scenarios*[17]

Country	Reference-Case	Nuclear breakthrough
Austria	No nuclear	No nuclear
Belgium	No new nuclear	New nuclear possible
Denmark	No nuclear	No nuclear
Finland	New nuclear possible	New nuclear possible
France	New nuclear possible	New nuclear possible
Greece	No nuclear	No nuclear
Germany	No new nuclear	New nuclear possible
Ireland	No nuclear	No nuclear
Italy	No nuclear	No nuclear
Luxembourg	No nuclear	No nuclear
Netherlands	No new nuclear	New nuclear possible
Portugal	No nuclear	No nuclear
Spain	No new nuclear	New nuclear possible
Sweden	No new nuclear	New nuclear possible
UK	Max. constant level of nuclear	New nuclear possible
Czech Republic	New nuclear after 2015 possible	New nuclear after 2015 possible
Poland	New nuclear after 2015 possible	New nuclear possible
Norway	No nuclear	No nuclear
Switzerland	New nuclear possible	New nuclear possible

The cost estimates used in TIMES_EE are based on several studies and literature (IEA/NEA 2005), (Briem et al., 2003). For the following power plants costs estimates have been carried out.

[17] The precondition for this assumption is that only if knowledge of operating power plants exist in country today new power will be build.

- European Pressurized Water Reactor (EPR) with a net capacity of 1590 MW_e and a net thermal efficiency of 37%. The fuel enrichment of about 4.9% and the average burn-up of 65 MWd/kg are taken into account.
- Coal-fired pulverized-fuel steam plant (PFC (hard coal)) with overcritical conditions (285 bar/600°C) of steam. The net capacity is 800 MW_e and the net thermal efficiency is about 46%.
- Coal-fired integrated gasification combined cycle (IGCC hard coal) has a net capacity of 450 MW_e and a net thermal efficiency of 51%.
- Coal-fired integrated gasification combined cycle with equipment for CO_2 capture (IGCC with CO_2 capture). This plant has a net capacity of 425 MW_e and a net thermal efficiency of 45%.
- Lignite-fired pulverized-fuel (PFC (lignite)) steam plant, with new sophisticated technology for drying lignite (BoA+) and overcritical steam conditions. The net electrical capacity is 1050 MW_e with a net thermal efficiency of 45%.

All cost estimates for steam cycle plants are based on plant types that are already built or approved. For nuclear plants, costs incurred during the time between plant shutdown and plant decommissioning is also taken into account and are covered by the specific capital investment costs. Table 3.11 shows an overview of the input data of the analysed power plants.

Table 3.11 *Technical and economical data of nuclear and fossil power plants for the year 2010*

	Unit	EPR	PFC (hard coal)	IGCC hard coal	IGCC with CO_2 capture	PFC (lignite)	CCGT
Electrical capacity	[MW_e]	1590	800	450	425	1050	1000
Net thermal efficiency	[%]	37	46	51	45	45	60
Specific capital investment costs	[€/kW]	1550	820	1200	1500	1150	440
Specific decommissioning costs	[€/kW]	155	34.5	53.3	58.5	32.4	15.8
Specific fixed O&M costs	[€/kW/yr]	30.0	36.6	56.4	68.9	35.5	18.8
Specific variable operating costs without fuel costs	[€/MWh]	3.6	2.7	3.2	3.8	1.0	1.6

All fossil fuel-fired power plants are designed to fulfil environmental protection standards. For coal-fired power plant with CO_2 capture (IGCC with CO_2 capture), a capture rate of 88% is taken into account.

The total power generating costs consist of the overnight capital costs, operation and maintenance (O&M) costs and fuel costs. Costs for refurbishment are considered as ‘fixed operating costs’ and are covered by the O&M costs. For fluctuating sources of electricity generation, such as hydro, wind and solar, additional costs have to be included considering adequate standby generation. The resulting total specific power generating costs for the power plants considered are shown in Figure 3.15. Electricity generation costs are calculated with an interest rate of 5%. It is assumed that the depreciation time is equal to the technical lifetime of a plant and that the average load factor of the nuclear as well as of the fossil plants is 85%. Referring to Figure 3.15 the lowest power generation costs of about 23.8 €/MWh are determined for the European Pressurized Water Reactor (EPR) and the highest costs of about 356 €/MWh are for the photovoltaic plant of roof panels (PV (roof panel)). In case of CO_2 capturing no credits or storage cost are taken into account.

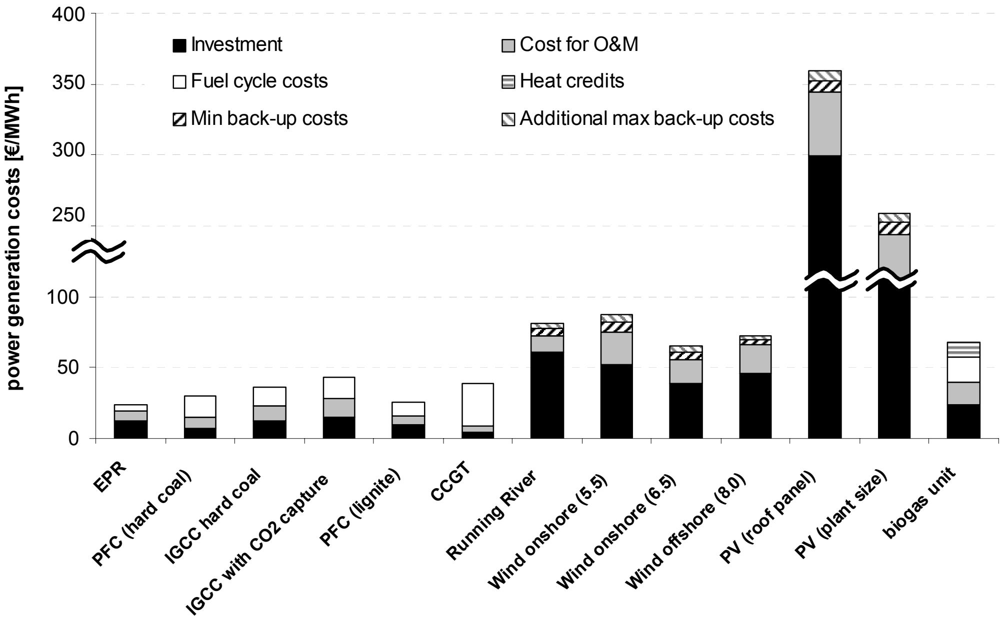

Figure 3.15 *Comparison of power generation costs among the technologies considered*

In Figure 3.16 the total power generation costs of nuclear and thermal power plants are shown as a function of the annual operating hours. The investment costs are calculated with a discount rate of 5%. The coal-fired integrated gasification combined cycle, which is equipped for CO_2 capture (IGCC with CO_2 capture) has the highest generating costs, independently from the amount of operating hours. The lignite- and coal-fired pulverized-fuel steam plant (PFC (lignite and hard coal)) and the nuclear power plant (EPR) offer the lowest electricity generation costs. The generation costs of these plants are in similar range and mainly depend on the discount rate.

According to the economic results, in the future nuclear power plants[18] would be built if other reasons like social acceptance did not exclude them. Thus, in some countries nuclear power plants will already be built in the reference scenario.

[18] In the case of nuclear power plants the cost for fuel processing and waste treatment are included.

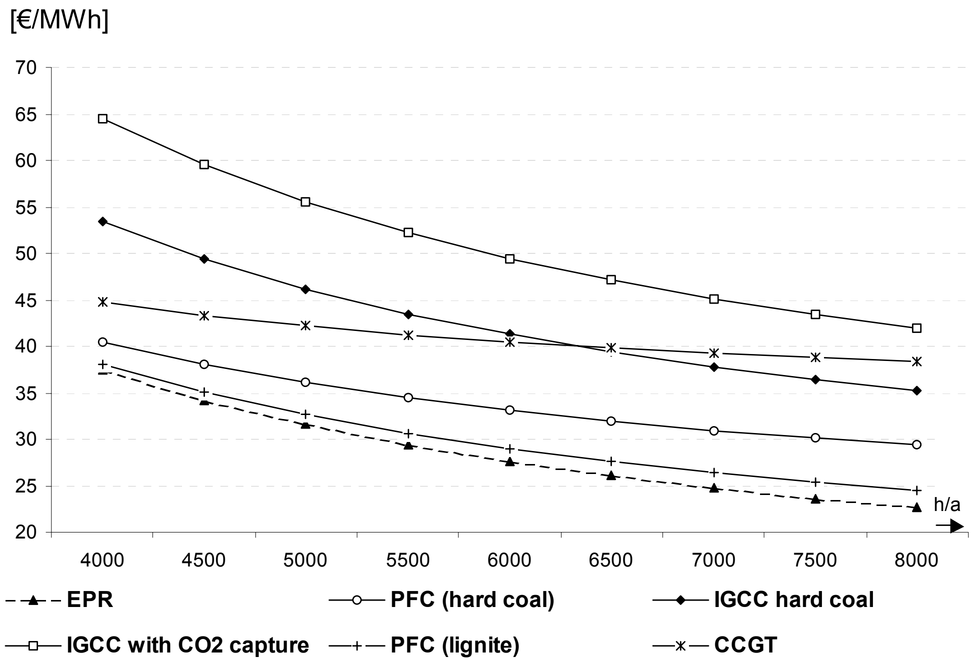

Figure 3.16 *Power generation costs as a function of the annual hours of operation*

In order to analyse the role of Nuclear power plants within the European electricity market the reference scenario is compared to a nuclear phase-out scenario and two nuclear breakthrough scenarios. The assumption for the nuclear phase-out scenario implies that the national phase-out agreements are still valid and additionally that other European countries which use nuclear power plants today will shut down these plants after an operational time of 35 years. In this scenario there is no option for extending the operational time for existing nuclear power capacities and furthermore, no new capacities can be built.

In the nuclear breakthrough scenarios it is assumed that the national phase-out agreements will be skipped and new nuclear power plants can be built after 2010. Additionally, it is assumed that in the future investment costs of nuclear power plants will be reduced by around 25% in compared to the investment costs of today.

Furthermore, in one nuclear breakthrough scenario and in the phase-out scenario a post-Kyoto target is assumed which imposes a CO_2 price with a path of 10 €/tCO_2 in the year 2010, 50 €/tCO_2 in 2020 and 100 €/tCO_2 in 2030.

Additionally, one separate nuclear breakthrough scenario and one separate scenario with a CO_2 price path will be carried out, in order to analyse the interaction of the nuclear breakthrough scenario and greenhouse gas emission reduction following a post-Kyoto target based on the given CO_2 price path.

3.4.2 Results

In the scenario with CO_2 prices (CV) and in the nuclear phase-out scenario (CVPO) the role of electricity generation based on natural gas will grow rapidly until the year 2030. The share of total net electricity generation in 2030 based on gas will reach a level of approx. 38% in the CO_2 prices scenario, over 65% in phase-out case (CVPO), about 23% in the nuclear breakthrough scenario (CVBT) and 17% in the reference scenario (REF). Mainly due to high CO_2 prices the electricity generation based on coal (hard coal and lignite) decreases from a level of around 40% in the reference case to 6.1% in the scenario with CO_2 prices (CV), to 5.8% in the nuclear phase-out (CVPO) and to 4.2% in the nuclear breakthrough scenario (CVBT).

Without the option of using nuclear power, the electricity generation by wind, biomass (others) and geothermal gain a bigger share, especially with higher CO_2 prices. In 2030 the electricity generation by renewables will increase from 374 TWh (REF) to 644 TWh in the nuclear phase-out case. Identical CO_2 prices all over Europe and the assumption that not all countries are able to build nuclear power plants lead to an increase of electricity trade and net losses. Hence, the total net electricity generation is slightly higher in the nuclear breakthrough scenario than in the other scenarios.

In the nuclear breakthrough scenario the electricity production out of nuclear power plants is more or less independent from the analysed CO_2 prices.

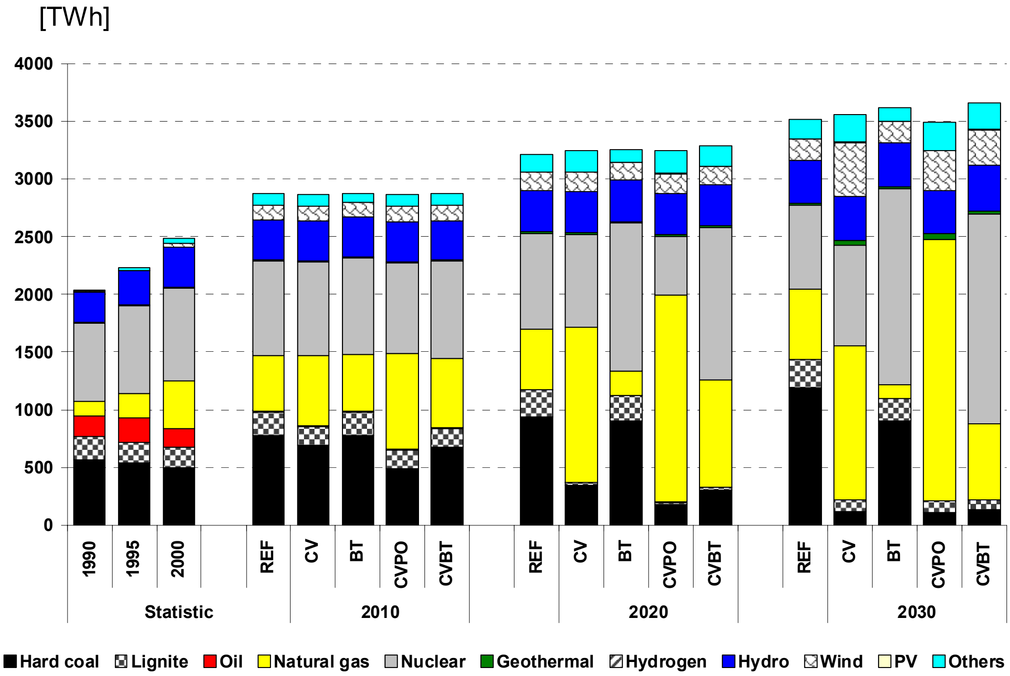

Figure 3.17 *Net electricity generation in the different scenarios*

The total capacity in the scenarios, with given CO_2 prices, is higher than in the reference case. The high CO_2 prices lead to a reduction of full working hours of existing power plants and an implementation of new power plants with higher thermal efficiencies. Furthermore, due to the limited full operating hours of 3300 h/a of wind power plants and their increased electricity generation additional wind capacities will be necessary in the nuclear phase-out scenario compared to the other two scenarios. The other energy carriers' capacities correspond to the quantities of their respective electricity generation. In the case of a nuclear breakthrough without CO_2 prices (BT) the capacity is comparable to the reference case.

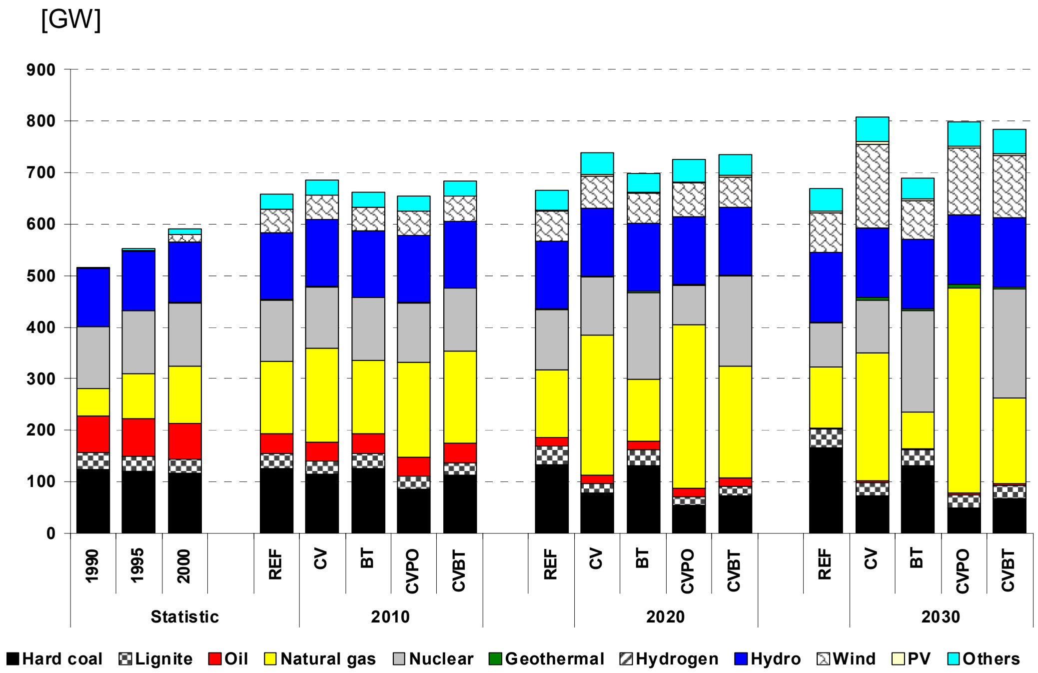

Figure 3.18 *Net electricity generation capacities in the different scenarios*

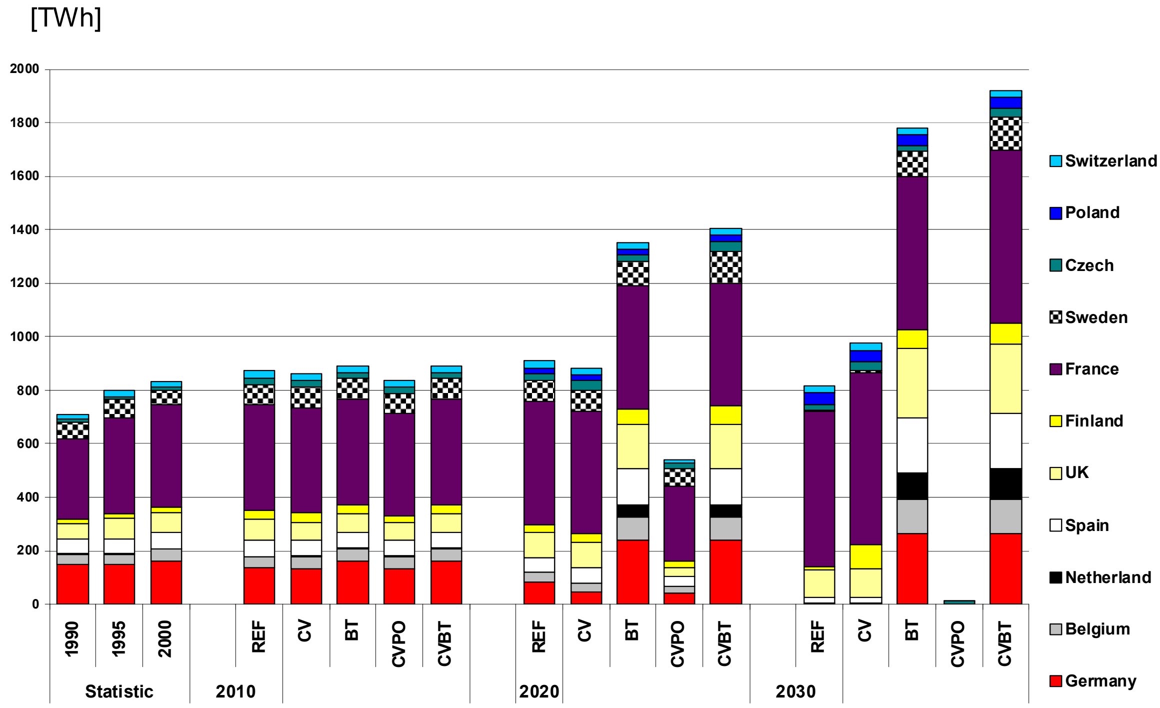

Figure 3.19 *Net electricity generation of nuclear plants in the different scenarios*

The electricity generation by nuclear power plants in the nuclear breakthrough scenarios will be more than 2 to 2.5 times higher than in the reference scenario. The share of electricity generation based on nuclear energy from France will account to 70.8% in the reference scenario and only approximately 34% in the nuclear breakthrough scenarios. The newly installed capacities in currently nuclear phasing out countries will generate approx. 800 TWh electricity in the year 2030.

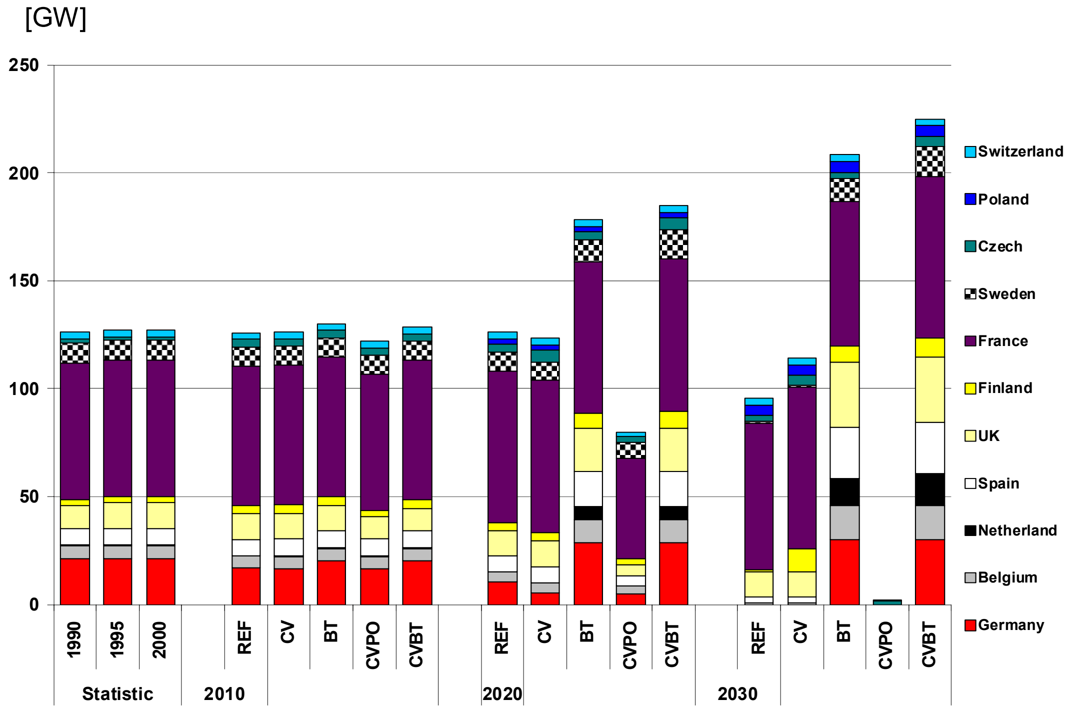

Figure 3.20 *Net electricity generation capacities based on nuclear plants in the different scenarios*

In all countries where the possibility of building up nuclear power plants exists, this option is used in the scenario nuclear breakthrough (see Figure 3.20 and Figure 3.21). In the nuclear breakthrough scenario additional capacities will be built up in France and Finland until 2030 due to the strong Kyoto-Target implemented with extremely high CO_2 prices. Compared to the reference case 7.5 GW nuclear capacity will be installed additionally in France till 2030 and 9.3 GW in Finland. A total level of 75 GW will be installed in France in 2030, comparable with the current capacity level, while the total European capacity of nuclear increases from 127.3 GW in the year 2000 to 224 GW in the year 2030.

The comparison between the two breakthrough cases shows that based on the CO_2 prices an additional 15 GW nuclear power plants will be built in the scenario CVBT compared to the scenario BT.

Due to the current age structure of existing nuclear power plants only a small fraction will still exist in the year 2030.

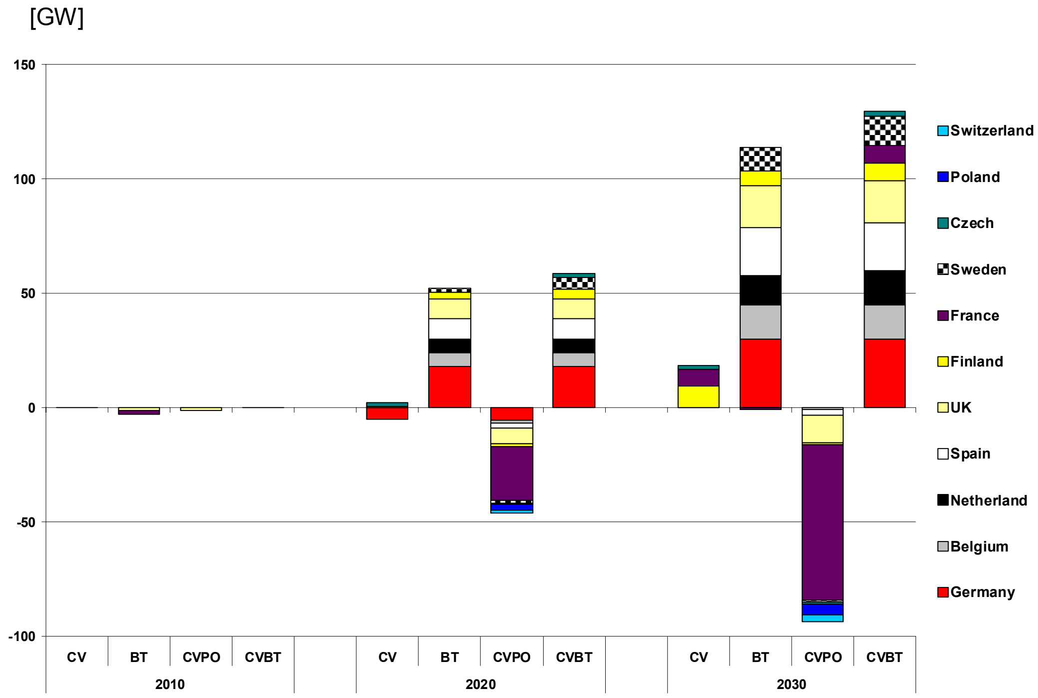

Figure 3.21 *Differences in the net electricity generation capacities based on nuclear plants compared to reference case in the different scenarios*

3.4.3 Consequences of a nuclear phase-out or breakthrough

Until 2010 the nuclear phase-out will not have a big influence on the CO_2 emissions from the European electricity generation. For all scenarios with CO_2 prices the CO_2 emissions in 2010 are just below the Kyoto target. This is due to the fact that the Kyoto reduction target is assumed to be fulfilled by all sectors proportionally to a CO_2 price of 10 €/tCO_2 (shown as a result of scenario CV).

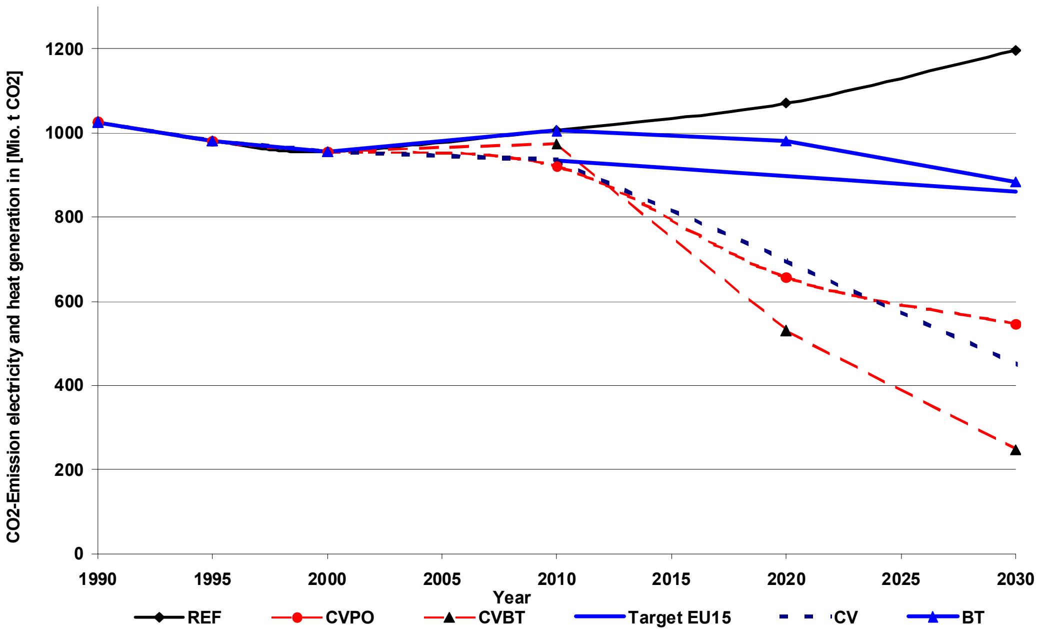

Figure 3.22 *CO_2 emission of the electricity and heat generation in EU-15 in the different scenarios*

In the year 2030 the CO_2 emissions in the nuclear breakthrough scenario (BT) are about 20 Mt CO_2 higher than the projected Kyoto target (additional reduction of 8% in the period between 2010 and 2030). In the nuclear breakthrough scenario with CO_2 prices (CVBT) the CO_2 emissions are round 580 Mt CO_2 lower than the target. Based on the higher share of electricity production by nuclear power plants the additional reduction in the nuclear breakthrough scenario (CVBT) will be approximately 250 Mt CO_2 in 2030 compared to the nuclear phase-out (CVPO) scenario.

Without a nuclear phase-out and with the assumed CO_2 prices (CV) the CO_2 emissions of the electricity generation system in 2030 are approx. 95 Mt of CO_2 lower than in the phase-out case (CVPO).

With high CO_2 prices the option of using fossil fuels combined with CO_2 capture and sequestration will become economical. Starting from the year 2020 CO_2 will be captured in both nuclear scenarios. In the year 2030 between 147.5 Mt CO_2 (CVPO) and 123 Mt CO_2 (CVBT) will be captured and stored annually. In the nuclear breakthrough scenario the option will be used because the build up of nuclear power plant is not possible in all countries and the maximum possible new capacities of new nuclear power plants is restricted.

Due to the higher share of natural gas power plants in the electricity generation sector and the high CO_2 prices in the nuclear phase-out scenario (CVPO) 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 and high CO_2 prices (CV). This means that the import dependency on natural gas from Russia, Algeria, Libya, Kazakhstan, Turkmenistan and Iran grows rapidly in the phase-out case. Additionally, the gas consumption can only be covered by an import share of over 25% of LNG. In the nuclear breakthrough scenario with CO_2 prices (CVBT) the total gas consumption in 2030 will be only 40% of the value in 2000.

The differences of the quantity of radioactive waste in 2010 are insignificant. The total amount of heat producing radioactive waste is approximately 1000 m^3/a and of weak radioactive waste 9000 m^3/a. In the reference case the yearly production of nuclear waste will be keep nearly constant until 2030. In the nuclear breakthrough scenario the heat producing radioactive waste increases to a level of about 1575 m^3/a and the weak radioactive waste of about 14400 m^3/a in Western Europe.

The total costs for the electricity sector of a nuclear phase-out in Western Europe will range at approximately € 224 billon. If a nuclear breakthrough will be realized in Western Europe until 2030, the costs for electricity generation would be reduced by approximately € 52 billion.

3.4.4 Conclusions and recommendations

A liberalized electricity market with free choice of electricity generation technologies is a basic requirement for a cost efficient electricity market. The electricity prices in 2030 are around 22.3 €/MWh higher then in the reference case if the CO_2 prices follow the scenario assumptions and Europe will phase-out nuclear power plants. The electricity prices in the nuclear breakthrough scenario will be 7.5 €/MWh lower than without a breakthrough.

With the assumption that CO_2 prices reach a level of 100 €/t CO_2 in 2030, nuclear power plants are one option to reduce the import dependency on natural gas. Additionally, the average electricity generation prices will be significantly lower. Nuclear appears to be a cost efficient option for achieving GHG reduction targets.

Independent technology improvements and the realization of cost reduction potentials for all electricity generation technologies are necessary in order to maintain flexibility with respect to future uncertainties.

4. Economic models

4.1 PACE

4.1.1 Introduction

In 2001, roughly 846 TWh of electricity were produced by nuclear power plants within the European Union. This represents about one third of the total EU electricity generation (as an aside, note that roughly one third of the world's total nuclear capacities in 2001 are located in the EU). Nuclear power plants are currently operated in eight European countries: Belgium, Finland, France, Germany, the Netherlands, Spain, Sweden and the United Kingdom. The shares of nuclear power generation in domestic electricity production for these countries range from 4% in the Netherlands up to 90% in France. Table 4.1 provides an overview of the current role of nuclear power across EU-15 member states.

Table 4.1 *Key figures of nuclear power generation in Europe*

	Nuclear capacity (net) [MW]	Share in nuclear capacity [%]	Electricity generation [TWh]	Share in nuclear generation [%]	Share in total generation [%]
Belgium	5331	4.43	43.7	5.16	51.47
Finland	2590	2.15	21.9	2.59	26.94
France	60636	50.42	401.3	47.43	89.44
Germany	21097	17.54	162.1	19.16	31.16
Netherlands	449	0.37	3.7	0.44	3.52
Spain	7749	6.44	61.1	7.22	28.33
Sweden	9273	7.71	69.3	8.19	46.11
United Kingdom	13133	10.92	83.0	9.81	22.58
EU	120258	100.00	846.1	100.00	33.57

Source: IEA/OECD

The perception of nuclear power at the superordinate EU level is ambiguous which reflects the heterogeneous role that nuclear power plays across various EU countries. Drawing upon the European Commission's Green Paper 'Towards a European strategy for the security of energy supply' the future role of nuclear power in Europe is uncertain. On the one hand, nuclear power is seen as a 'less than perfect' supply option, which applies to varying degrees also to fossil fuels (coal, oil, gas) as well as renewable energies. More specifically, nuclear power is classified as 'undesirable' and referred to as a 'source of energy in doubt' (as is the case for coal). On the other hand, nuclear power is seen as 'one of the elements in the debate on tackling climate change and energy autonomy'.

Most member states of the EU seem to be rather concerned on the use of nuclear power. Among the eight 'nuclear' EU countries, only France and Finland have decided not only to maintain nuclear capacities but also to extend nuclear power production by building new power plants. The British government has left open the possibility to extend the country's nuclear capacity with respect to energy supply security and greenhouse gas abatement requirements under the Kyoto Protocol. Five out of the eight countries that employ nuclear capacities (Belgium, Germany, the Netherlands, Spain and Sweden) have taken decisions towards the gradual phase-out of their nuclear power programs.

Although the current political attitude towards nuclear power across EU member countries is rather clear, it is hardly possible to make medium- to long-run predictions on the future role of nuclear power. Since major parties in EU member countries often have opposing views towards nuclear energy, its prospects can be strongly influenced by future election results.

Given this background, the nuclear power case study of the Cascade Mints project investigates the economic and environmental effects of phasing out nuclear power vs. a technology breakthrough in nuclear technology given post-Kyoto targets for Europe. Our objective is to provide quantitative insights into these scenarios based on an extended version of the PACE computable general equilibrium (CGE) model for Europe (EU-15). The model features a bottom-up description of power generation technologies for the electricity sector using detailed engineering data. The various electricity generation technologies are characterized by their specific cost structure, physical capacity constraints and the output shares in the bench-mark equilibrium (i.e. the baseline or business-as-usual evolution until 2020). The model set-up is described in more detail in the Cascade Mints Renewable Case Report (Böhringer and Löschel, 2004).

4.1.2 Scenarios

In our quantitative analysis, we examine three different scenarios relative to a business-as-usual development (BAU) scenario: Carbon Value (CV), Nuclear phase-out (OUT) and Nuclear phase-in (IN) following a technology breakthrough.

Business-as-usual (BAU)
The business-as-usual development in PACE is calibrated to the European Commission's business-as-usual assumptions on non-uniform growth rates for GDP as well as projections on fossil fuel production and use (the latter determining the carbon emissions) (European Commission, 1999). Autonomous energy efficiency improvement (AEEI) factors are employed which scale energy demand functions in order to match GDP forecasts with the energy production and consumption projections. To align the European Commission's projections on the baseline activity levels of the various power generation technologies up to 2020, we introduce technology-specific endogenous taxes and subsidies. The latter work as a tangible proxy for a variety of market regulation approaches in place within the various EU Member States. Furthermore, two technologies (Soft coal, Hydro) are fixed by explicit exogenous policy restrictions or natural capacity constraints. We have not incorporated the Cascade Mints baseline assumption of a 10 €/tonne CO_2 carbon value. The reason is that this assumption mimics to some extend the effects of imposing a CO_2 price path in the Carbon Value scenario.

Carbon Value (CV)
In this scenario we impose a CO_2 price path of 10 €/tCO_2 in 2010, 30 €/tCO_2 in 2015 and 50 €/tCO_2 in 2020. This additional scenario has been included in the Nuclear Case Report in order to distinguish the effects of different assumptions concerning nuclear power use from the effects of the imposed CO_2 prices following the post-Kyoto target.

Nuclear phase-out (OUT)
In this scenario we examine a nuclear phase-out scenario for the EU member states. More specifically, we use the information on installed capacities in the EU member states in the nuclear phase-out scenario as provided by IPTS to impose a decline of nuclear power. Table 4.2 shows our assumptions about electricity generation from nuclear in the BAU and the OUT scenario (in TWh_e) between 2000 and 2020 in Europe. In addition, we impose the carbon value path of the CV scenario.

Table 4.2 *Electricity generation from nuclear in Baseline and Phase-out scenario*

[Twh_e]		2000	2005	2010	2015	2020
Baseline	Belgium	46.9	47.6	46.6	46.9	43.9
	Finland	20.5	22.4	22.4	22.4	22.2
	France	410.9	427.3	431.6	448.9	453.4
	Germany	169.5	169.5	167.5	142.9	101.6
	Netherlands	4.1	3.7	0.0	0.0	0.0
	Spain	57.8	57.8	57.8	56.6	53.1
	Sweden	70.5	69.8	69.8	58.7	40.6
	UK	99.9	103.5	100.6	79.4	71.9
	EU-15	880.1	901.6	896.3	855.8	786.7
Phase-out	Belgium	46.9	47.6	46.6	46.9	31.1
	Finland	20.5	22.4	31.1	31.1	21.7
	France	410.9	427.3	431.6	448.9	415.0
	Germany	169.5	162.1	130.7	83.8	18.2
	Netherlands	4.1	3.3	0.0	0.0	0.0
	Spain	57.8	57.8	56.6	52.1	48.8
	Sweden	70.5	65.4	65.4	48.3	26.3
	UK	99.9	100.4	73.3	43.4	36.1
	EU-15	880.1	887.0	834.2	739.4	555.5

The administration of this premature phase-out of nuclear power as compared to BAU induces a supply-side gap that could be reduced or closed using, in principle, four options:
- reduction in energy demand
- increased utilisation of existing power plants
- increased electricity imports, or
- construction of new non-nuclear power plants.

Increasing the degree of utilisation during medium and peak loads, as well as load shifting, may cover only a small fraction of the base-load gap caused by a nuclear phase-out, because these measures are rather costly and limited in overall scope. Thus, three major options remain for closing the power supply gap: decrease in electricity demand, increase in electricity imports and the construction and operation of new non-nuclear power plants. The PACE model covers all three options.

Nuclear phase-in (IN)
In this scenario we assume a phase-in of nuclear power following a technology breakthrough in nuclear technology. The technology assumption of 25% reduction of capital costs of the cheapest nuclear option between 2010 and 2020 is translated into a cost reduction for electricity production from nuclear power (excluding fuel processing and waste treatment). These cost reductions are calculated on the basis of dynamic investment analysis with techno-economic data provided by IIASA. Accordingly, production costs from nuclear power are reduced by 5.8% in 2015 and 11.7% in 2020 in the scenario IN. In addition, we impose the carbon value path of the CV scenario.

4.1.3 Results

Electricity production and technology mix
Figure 4.1 visualizes the level and technology supply structure of electricity production between the years 2000 and 2020 under BAU for Europe. Electricity production increases by roughly 16%. Under BAU, Europe's electricity generation is predominantly based on nuclear power, hard coal and natural gas. Between 2000 and 2020 electricity production from oil decreases by about 25%, nuclear power decreases - due to exogenous phase-out constraints - by about 18%,

coal production is increased by about 22%, natural gas by more than 60%. With respect to renewables, there is a large increase in electricity supply from wind (almost 360%) and also to a lesser extent from biomass (31%). Hydropower production increases only slightly by 9%. The BAU share of renewable energy in electricity consumption increases from 15.3% in 2000 to 18.8% in 2020. For the baseline calibration of PACE we employ endogenous taxes and subsidies to ensure the BAU projections by the European Commission with respect to the production levels of the various electricity production technologies. These endogenous taxes and subsidies reflect the regulatory framework for power production across EU member countries.

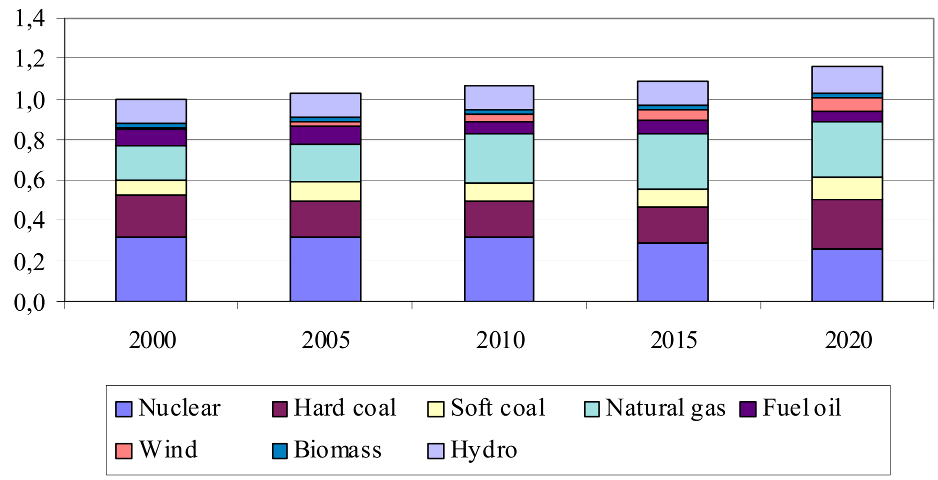

Figure 4.1 *Electricity production by supply technology under BAU*
(Index 2000 = 1)

In the scenario CV, a carbon value is imposed between 2010 and 2020 that is consistent with a post-Kyoto policy. The effect of the carbon value on the level and mix of electricity production is shown in Figure 4.2. Due to the imposed CO_2 prices, total electricity produced by the different electricity supply technologies decreases by more than 5.5% vis-à-vis the BAU level. As of 2020, electricity production from carbon-intensive technologies like hard coal, fuel oil and natural gas declines significantly vs. BAU levels, while carbon-friendly technologies like nuclear, wind and biomass increase production. By assumption, soft coal and hydropower production remain unchanged in absolute terms.

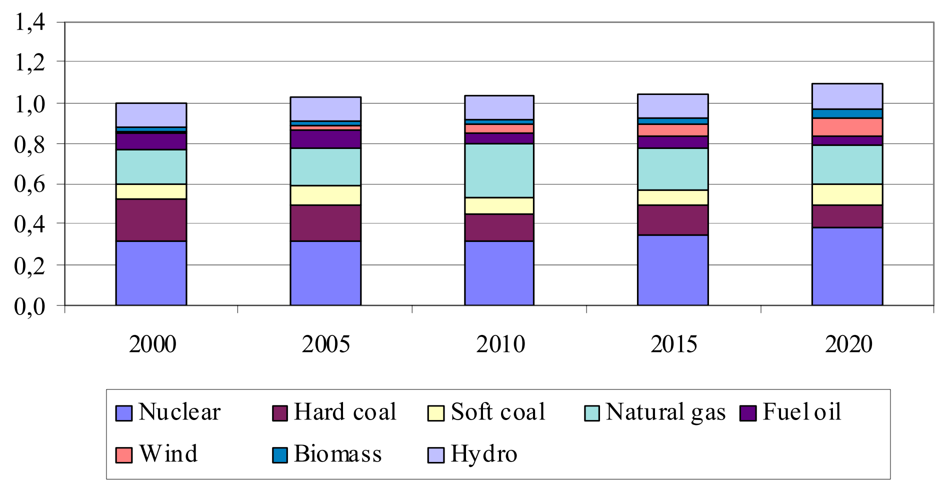

Figure 4.2 *Electricity production by supply technologies in scenario CV*
(Index 2000 = 1)

In the scenario OUT, nuclear power is phased out between 2010 and 2020 on top of the carbon penalty. The effect of the phase-out of nuclear power on the level and mix of electricity production is shown in Figure 4.3. Electricity production decreases now by more than 7.5% vis-à-vis the BAU level due to the decreased availability of the nuclear option. While in the CV scenario nuclear power production increases by almost 50% without investment constraints, the electricity generation from nuclear power is reduced by less than 9% vis-à-vis the BAU level in the scenario OUT. As of 2020, electricity production from hard coal, fuel oil and natural gas declines vs. BAU levels, while electricity production from technologies like wind and biomass increases.

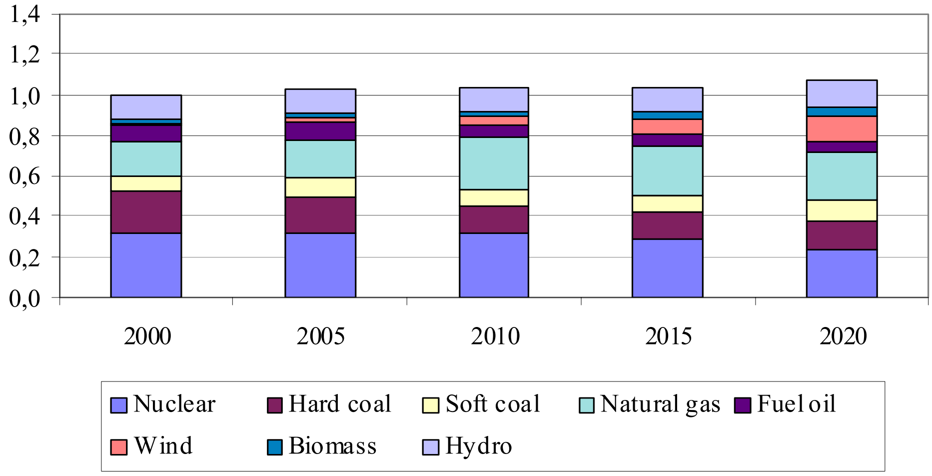

Figure 4.3 *Electricity production by supply technologies in scenario OUT*
(Index 2000 = 1)

In the scenario IN, electricity production from nuclear power is less costly due to the assumed technology breakthrough. Figure 4.4 shows the effect of the phase-in of nuclear power on the level and mix of electricity production. The effects of a reduction in capital costs overcompensates the effects of the carbon penalty on total electricity production: in 2020 electricity production increases by almost 3% vis-à-vis the BAU level. Nuclear power increases its production share significantly since it gains a competitive advantage due to both the imposed carbon value and the production subsidy. All other technologies loose production vis-à-vis the BAU level in 2020. Here, a caveat has to be made: due to a lack of data, we do not assume capacity limits for nuclear power extension nor adjustment costs for increasing the installed capacities in the current version of PACE. The effects on the nuclear production might thus be overestimated.

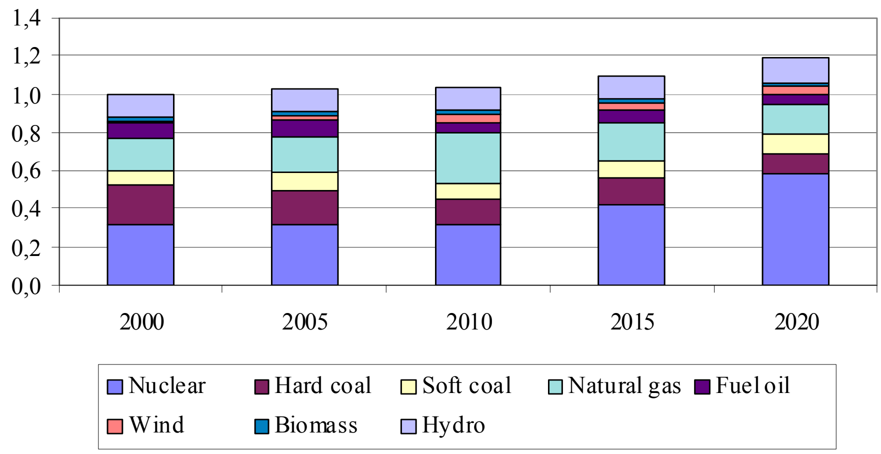

Figure 4.4 *Electricity production by supply technologies in scenario IN*
(Index 2000 = 1)

Electricity production costs, electricity prices and electricity demand
The imposition of a carbon price increases electricity production costs by almost 6% until 2020 in the scenario CV. This cost increase is accompanied by a decrease in electricity supply by almost 7% and electricity demand by about 4% in 2020. The administered phase-out of competitive nuclear power generation highlights the increase in electricity production costs. The nuclear phase-out implies a loss of productive resources due to the foregone use of existing cost-efficient nuclear capacities for electricity generation. The premature investment in replacement technologies raises power production costs, which in turn increases electricity prices as compared to BAU. Production costs increase by almost 10% in the scenario OUT. Electricity production costs vary between different EU countries. The variation in cost changes across these countries reflect country-specific differences in the opportunity costs of a premature phase-out as captured by the magnitude of 'lost' nuclear generation, the cost-potentials of replacement technologies (i.e. relative profitability of existing nuclear power plants vis-à-vis the back-up options) and the ease of economy-wide electricity savings. Not surprisingly, the increase in electricity prices has a negative impact on electricity demand. The higher the transitional increase in electricity prices the larger the decline in electricity demand. The increase in electricity production costs triggers a decrease in electricity demand by more than 5% (and electricity supply by more than 10%) in 2020. The remaining supply-side gap is closed through increased electricity imports. The reduction in nuclear capital costs in the IN scenario reverses the effects on the production costs of electricity. These costs are reduced by more than 2% until 2020 due to the cheaper nuclear electricity generation option. However, electricity demand is still slightly lower than in the BAU (partly because the electricity price also depends on the price of the imported electricity). Domestic electricity supply increases. Electricity imports differ significantly between the scenarios. While in the scenarios CV and OUT electricity imports increase to a large extent, import dependency is reduced in the scenario IN. Table 4.3 summarizes these results.

Table 4.3 *Electricity price, demand, supply and imports*

[% vs. *BAU*]	Scenario	2010	2015	2020
Electricity price	*CV*	3.11	2.68	5.78
	OUT	3.14	5.02	9.76
	IN	3.11	-2.36	-4.36
Electricity demand	*CV*	-1.63	-2.23	-4.02
	OUT	-1.64	-3.00	-5.20
	IN	-1.63	-0.46	-0.56
Electricity supply	*CV*	-3.08	-3.41	-6.81
	OUT	-3.11	-5.49	-10.23
	IN	-3.08	1.25	2.60
Electricity imports	*CV*	7.21	6.40	14.89
	OUT	7.28	12.94	26.99
	IN	7.21	-6.54	-11.78

Welfare
The choice of the appropriate welfare measure for a particular model is a key issue for model based economic analysis. To measure the overall impact of energy policies on national economic welfare, alternative macroeconomic variables besides real consumption and equivalent variation have been used in different studies, e.g. gross domestic product (GDP) or gross national product (GNP). Welfare implications of the different scenarios are measured in this report in Hicksian equivalent variation in income (HEV). Since our utility function is linearly homogeneous, percentage changes in the utility level U are equivalent to percentage HEV and U can be used directly as a welfare measure. With this convenient cardinalization of utility, percentage HEV is equivalent to percentage change in real consumption with respect to BAU. Overall welfare losses for Europe are small and range from 0.1% to 0.3%. The carbon emission reduction

decreases welfare by about 0.2% versus BAU in 2020 (Table 4.4). The welfare losses are accelerated (moderated) in the case of an administered phase-out of nuclear (technology breakthrough). The magnitude of welfare losses is closely related to the electricity production costs associated with the different scenarios.

Table 4.4 *Welfare (% change in Hicksian equivalent variation in income)*

Scenario	2010	2015	2020
CV	-0.12	-0.11	-0.23
OUT	-0.12	-0.15	-0.30
IN	-0.12	-0.05	-0.10

Carbon emissions
The imposition of a carbon value up to 50 €/tCO_2 in 2020 in the scenario CV reduces carbon emissions significantly by almost 16% in 2020 vis-à-vis BAU. A premature nuclear phase-out will increase carbon emissions as compared to CV since carbon free nuclear power will be in part replaced by electricity from fossil fuel based technologies. However, these effects are small. Emissions are still reduced by more than 13% in 2020 vis-à-vis BAU. Obviously, the costs of carbon abatement constraints will be increased when nuclear power, as a carbon-free energy option, is abandoned. The technology breakthrough helps to reduce carbon emissions even below the level in the CV scenario. But the relative change is very small since advanced nuclear power substitutes other non-carbon electricity technologies and part of the decarbonisation is offset in absolute emission terms since electricity production increases due to the subsidization of nuclear electricity production. The reduction in carbon emissions in the scenario IN is slightly higher than 16% in 2020.

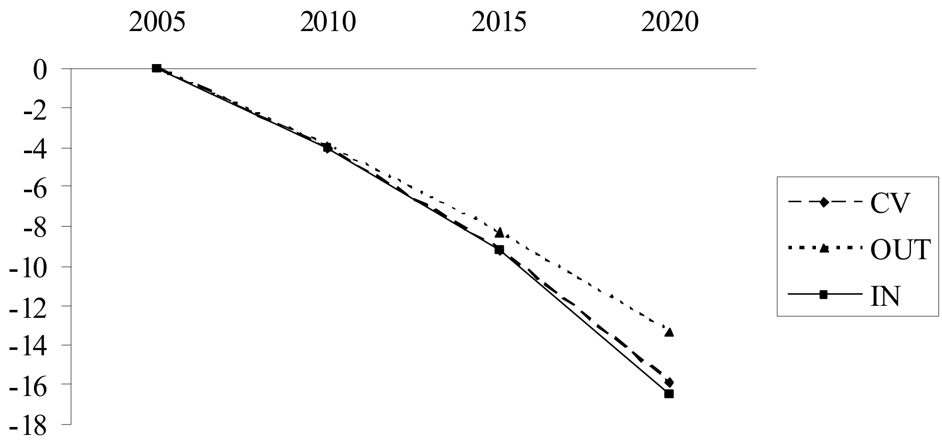

Figure 4.5 *Changes in carbon emissions (in % relative to 'Business as Usual')*

4.1.4 Conclusions

We have investigated the economic and environmental implications of the imposition of a carbon value, a nuclear phase-out in Europe and a technology breakthrough in nuclear technology. Our quantitative results show that a premature nuclear phase-out as well as the technology breakthrough in combination with a post-Kyoto target imposes small adjustment costs to the economy. From a climate policy perspective, an accelerated nuclear phase-out induces slightly higher carbon emissions since carbon-free nuclear power will be replaced to a larger extent by fossil fuel technologies. The technology breakthrough has - relative to the CV scenario - almost no effect on carbon emissions. Nuclear energy provides ancillary benefits as a carbon-free technologies will replace to some extent fossil fuel technologies - however, part of the technology substitution effect is offset by increased electricity production.

In our analysis, we have not accounted for the external costs of nuclear power due to the large uncertainties in the valuation of nuclear risks. Therefore, the adjustment costs presented in our analysis can not be interpreted as simple excess costs of energy policy interference, but must be viewed as the price tag for the risk reduction from nuclear power operation given additional constraints (preferences) on back-up technologies and carbon neutrality. The opposite applies for the increased dependency on nuclear power in the technology breakthrough case.

4.2 NEWAGE-W

4.2.1 Introduction

For some of the European countries the utilization of nuclear power plants is one of the major elements to reach the national emission targets agreed on by the Kyoto Protocol. Nevertheless, due to safety reasons of nuclear electricity generation some countries decided to gradually shut down their nuclear programs. Beside Belgium, Spain, Sweden and the Netherlands, Germany is following this policy. The first nuclear power plant that was shut down in Germany was Stade with 630 MW in northern Germany in the year 2003. The second one, Obrigheim with 340 MW in the south of Germany, will follow in 2005. According to the Atomic Energy Act (*Atomgesetz*) and given that no legislative changes will be carried out, the phase-out will be completed up to 2030 at the latest according to the plans of the current German government.

The discussion on the possibilities of a nuclear phase-out especially within Germany has to be considered in the context of security of supply regarding import dependency, cost efficient electricity supply, acquired technological know-how and environmental targets. On the other hand the problems of permanent disposal sites for nuclear waste have to be solved when utilizing nuclear power plants any further.

Within Europe roughly 34% of the electricity is provided by nuclear generation. Among the European countries there is a range from approximately 3% in the Netherlands up to almost 90% in France. Nuclear electricity supply in Belgium amounts to 51%, Finland has 27% nuclear electricity generation whereas one new power plant is decided to be built within the next years. Sweden's electricity supply is based on nuclear by 46%, Spain has a share of 28% nuclear and Great Britain 23%. In the year 2001 the share of nuclear electricity supply in Germany is 31%.

Due to the significant amount of nuclear electricity supply within Europe, it is important to analyse the possible impact of different policies regarding the utilization of nuclear power plants. Policies that will promote or restrict the future use of this technology are likely to have an effect on energy-related CO_2 emissions, electricity prices and economic performance. Forcing the nuclear electricity programs into one or the other direction will have a strong impact on the electricity production portfolios in Europe. All these aspects have to be taken into account when investigating various policy scenarios regarding the utilization of nuclear power plants.

For analysing the impact of these policies, an extended version of the global computable general equilibrium model NEWAGE-W is applied. Providing a more differentiated view on the effects within the electricity sector, a technology-based representation of electricity generation was implemented. Using physical capacity data for the various electricity generation technologies utilized within Europe and specific information on cost structures for the different supply options, NEWAGE-W follows a bottom-up approach for the electricity sector within a top-down framework. The capacity and cost data are based on IEA statistics and various technology information found in the literature.

The electricity production sector in NEWAGE-W is represented by 14 different generation technologies supplying electricity to three load segments, base, middle and peak load, respectively. To cover the broadly based generation portfolios in Europe, nuclear, hard and soft coal, gas, oil, hydro, wind, solar, biomass and geothermal technologies were implemented. Table 1 provides cost data (Capital, Labour, Intermediates and Energy) for different electricity generation technologies in NEWAGE-W. The cost shares were applied on the input-output data provided by GTAP 5.4 for the benchmark year 1997.

Table 4.5 *Cost data for various electricity generation technologies*

Load Segment	Generation Technology	Cost of Power Generation [$€_{2000}$/MWh]	Cost Shares Capital [%]	Labour [%]	Interm./Energy [%]
Peak	Pump Storage	252.1	77.50	12.60	9.90
	Gas GT	132.0	47.50	15.30	37.20
	Oil GT	213.6	50.60	0.80	48.60
Middle	Hard Coal	58.3	47.40	5.80	46.80
	Gas CC	56.0	25.90	8.30	65.80
	Oil	105.8	23.90	0.40	75.70
Base	Nuclear	48.9	54.60	4.20	41.20
	Soft Coal	53.7	41.50	5.10	53.40
	Hard Coal	53.7	41.50	5.10	53.40
	Gas	48.2	20.30	6.50	73.20
	Oil	93.8	17.70	0.30	82.00
	Hydro	64.3	77.10	12.50	10.40
	Biomass	111.1	47.80	2.60	49.60
	Geothermal	53.7	84.70	2.60	12.70
RES[1]	Wind	82.7	84.10	0.00	15.90
	Solar PV	662.1	97.30	0.00	2.70

[1] Fluctuating.

The calculated cost shares for the various generation production technologies are used to specify the Leontief production function for each type of generation. Electricity provided by the different generation options is aggregated in a specific production function taking the different elasticities of substitution for base, middle and peak load supply into account.

To capture a range of possible policy scenarios regarding nuclear energy in Europe three different cases, beside a Business as Usual (BaU), were calculated within the CASCADE-MINTS project. Covering environmental issues of the Kyoto Protocol on the one hand, a Carbon Value (CV) scenario was calculated. One the other hand, a nuclear Phase-Out (OUT) and a nuclear technology breakthrough (IN) scenario for Europe, respectively, were performed. Both scenarios were combined with the CV scenario to capture the impact of an OUT and IN scenario given the background of increasing prices for CO_2 emissions. The specific assumptions made for the four scenarios are described in detail in the following.

Business as Usual: The Business as Usual scenario in NEWAGE-W is calibrated to the harmonized baseline assumptions made in the CASCADE-MINTS project. Regarding the structure of the regional electricity generation portfolios, IEA, Eurolectric and national data and projections are used. Figure 4.6 presents the baseline projections for electricity generation in Western Europe up to the year 2030.

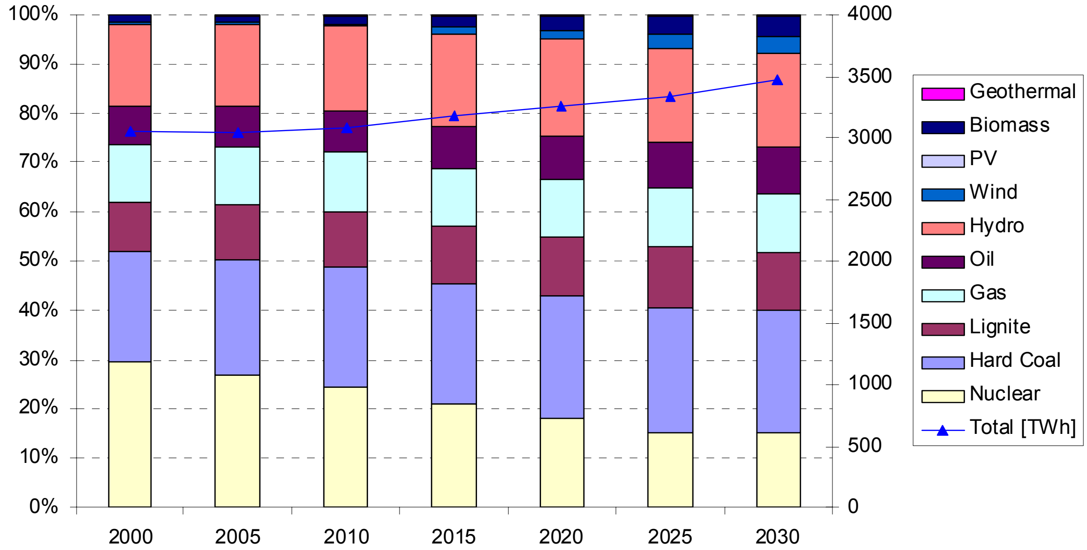

Figure 4.6 *Electricity generation for Western Europe to 2030 in WEU (baseline scenario)*

The assumed baseline nuclear phase-out is based on the policies in Germany and Belgium. Taking the baseline assumptions for a gradual phase-out of nuclear electricity supply for Western Europe into account, one can see that the shut down nuclear capacities are replaced by coal, hydro, gas, biomass and wind. Approximately 40% of the year 2000 nuclear capacities are left.

Carbon Value: The Carbon Value scenario imposes an increasing price path for CO_2 emissions of € 10 per tonne CO_2 in 2010, € 50 per tonne in 2020 and € 100 per tonne in 2030. The CO_2 price path reflects a stronger emission reduction regime for the post-Kyoto phase.

Phase-Out: Within the Phase-Out scenario a significant abandonment of electricity supply by nuclear generation for Western Europe is assumed. Up to the year 2030 only 4% of the electricity produced comes from nuclear power plants. The phase-out path is presented in Table 4.6.

Table 4.6 *Electricity generation from nuclear capacities to 2030 in the phase-out scenario*

[TWh]	2000	2010	2020	2030
WEU	922	867	655	129
NAM	748	718	479	165
REF	202	198	176	59
ALM	24	36	36	36
ASA	61	168	168	168
PAO	396	372	281	79

Nuclear Breakthrough: Within the Nuclear Breakthrough scenario a technological development of nuclear power plants from 2010 on is assumed. The technological progress is reflected by a decrease of specific investment costs. The investment, i.e. capital costs are decreasing linearly by 25% between 2010 and 2020. The decrease of capital costs implemented in NEWAGE-W is 8% in 2010, 17% in 2015 and 25% in 2020. As a consequence, cost shares for nuclear power generation change slightly. The share of capital decreases to 52.5% in 2010, to 50.0% in 2015 and 47.4% in 2020. Shares of labour and intermediates rise correspondingly.

Subsidy Case: As an additional scenario to be analysed, a subsidy on investment cost for nuclear power plants is implemented within NEWAGE-W. Similar to the Nuclear Breakthrough scenario, the specific investment costs for nuclear generation capacities are assumed to decrease between 2010 and 2020. In contrast to the Nuclear Breakthrough scenario, a subsidy ensures lower investment costs due to government promotion of nuclear power plants. The decrease of specific cost of capital input has to be financed by the households within the economy. This financial aspect of subsidies allows for analysing the economic impact of promoting a specific technology, which could not be implemented without inducing impact on household expenditure. Taking these financial aspects into account, the technology breakthrough of nuclear electricity generation between 2010 and 2020 is not free for the economy. The effects on households' income one the one side and the related impact on macro economic indicators have to be taken into account within the analysis. The subsidy reflecting the decrease of capital cost is 8% in 2010, 17% in 2015 and 25% in 2020.

4.2.2 Results

In the context of the emission trading regime within the Kyoto Protocol, an increase in CO_2 prices could be expected. To investigate the effects of rising CO_2 prices, a price path to 2030 is assumed. Within NEWAGE-W this price path is implemented by a carbon tax on fossil fuel inputs for production and consumption. As a consequence of this policy, substitution effects are triggered, leading to less carbon intensive production structures.

For the electricity production sector a change in the generation portfolio can be observed. Figure 4.7 presents the development of the technological production mix as the differences to the Business as Usual scenario.

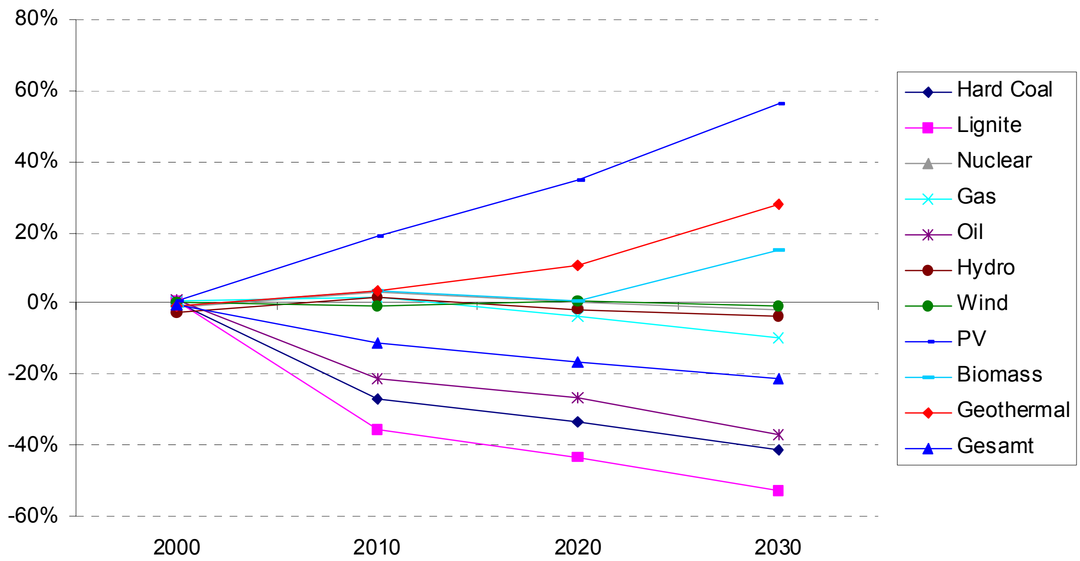

Figure 4.7 *Changes in the electricity generation structure, CV versus BaU [%] in WEU*

Due to the strong increase of CO_2 prices a decrease of hard and soft coal can be observed. Hard coal decreases by approximately 41% between years 2000 and 2030 in Western Europe and soft coal by even 53%. Electricity production by oil power plants reduces to 37% in the year 2030 compared with the baseline. The changes in the electricity generation mix leads to a stronger deployment of renewable energy sources such as biomass, geothermal and solar PV. Compared with the baseline development, the increase of electricity production from biomass amounts to 15%. Geothermal production increases by 28%, whereas solar PV rises by even 56%. Nuclear remains the same, due to the baseline assumptions regarding restrictive nuclear policies. The significant growth of electricity production by renewable energy sources can not balance the loss of conventional electricity generation from fossil fuels. As a consequence one can observe a decrease in overall electricity generation of approximately 21% in 2030 compared to the Business as Usual scenario. This decrease in overall electricity generation can be lead back to endogenous substitution of electric with non-electric energy within the production function due to estimated substitution elasticities. As CGE models capture technological changes e.g. by price induced substitution effects in production, these effects can be overestimated if specific constraints are not considered.

The carbon tax and the changes in the electricity production structure also have an impact on sectoral output prices. Electricity prices rise 20% above the price level in the baseline for the year 2030. Iron and steel as well as chemical production are about 3% more expensive compared to the baseline in 2030, whereas the other sectors do not face any significant price increases due to their weaker dependency on energy inputs.

To analyse the impact of various nuclear policies, the carbon value scenario was combined with a nuclear phase-out and a nuclear breakthrough scenario. In the nuclear phase-out scenario the electricity production from nuclear power plants decline as assumed (see Table 4.6). The nuclear phase-out scenario is implemented within NEWAGE-W by adding a upper bound on the production function for nuclear electricity generation. As a consequence of the limited and declining share of nuclear electricity supply, changes in the production mix are initiated. Similar to the pure carbon value scenario a decline in electricity generation from hard and soft coal can be observed, but partially to a less extent. The decline of approximately 43% in soft coal electricity production is a bit smaller. The supply from renewable energy sources rises significantly, analogous to the pure carbon value scenario. Biomass, geothermal and solar PV profit the most from the shut down of the nuclear capacities. Figure 4.8 presents the changes in the electricity production structure in Western Europe.

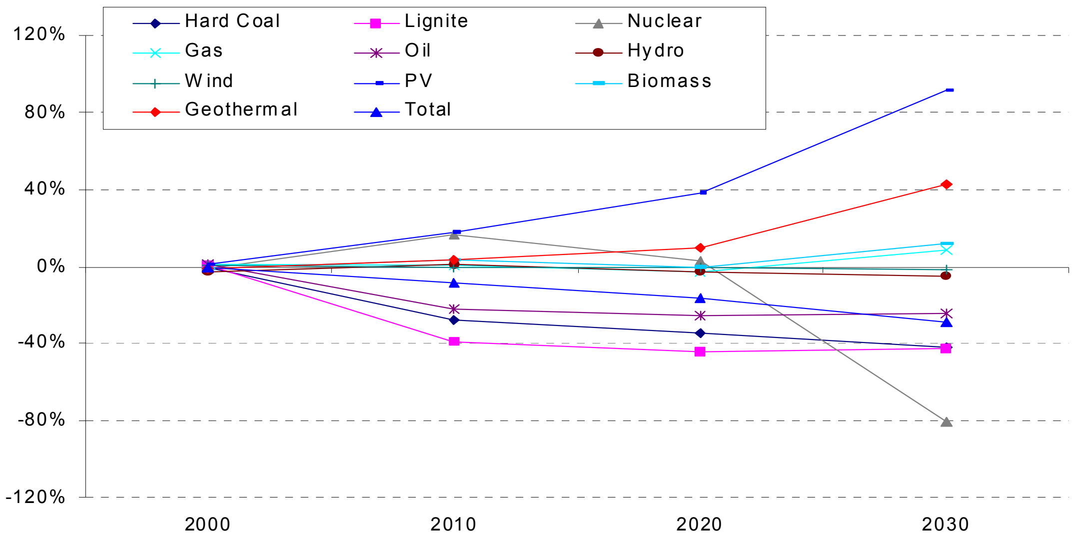

Figure 4.8 *Changes in electricity generation structure, OUT versus BaU [%] in WEU*

Due to the changes in generation the electricity prices increase by approximately 28% in the year 2030 compared to the Business as Usual scenario. It can be subsumed, that a premature phase-out of the nuclear capacities will intensify the deployment of renewable energy sources but partly reduce the decrease of carbon intensive production technologies triggered by increasing CO_2 prices.

In contrast to the nuclear phase-out the technology breakthrough scenario leads to a strong increase in nuclear capacities. Due to a decline in specific investment, i.e. capital costs for nuclear power plants between 2010 and 2020 and the abolishment of the phase-out plans in Western Europe and the other world regions, the share of electricity production from nuclear energy increases by a factor of six. Figure 4.9 presents the changes in the electricity generation mix due to a technology breakthrough between 2010 and 2020.

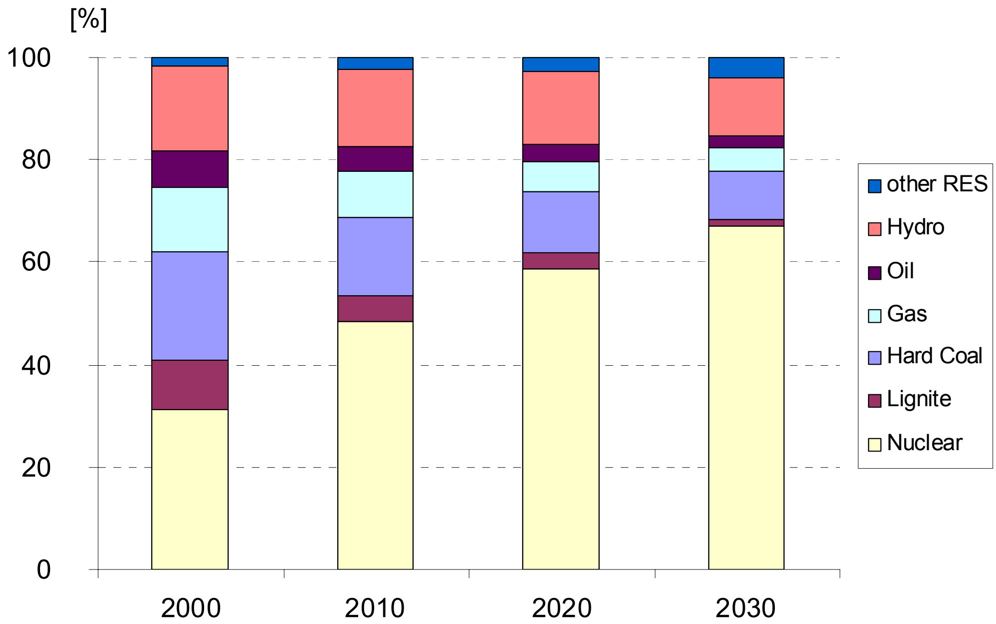

Figure 4.9 *Electricity generation by technology in WEU; Breakthrough scenario*

The renaissance of nuclear energy in Western Europe is induced by a decline in capital costs, which are assumed to be costless for the economy. The technological progress in nuclear electricity production, leading to 25% lower investment cost in 2020 is not determined by an increase in R&D investment or public subsidies paid to the electricity industry. The fact that no additional investments or efforts have to be taken into account to achieve the cost reduction falsifies the scenario results slightly.

When taking into account the additional costs of an e.g. R&D induced increase of power plant efficiency or subsidized capacity investments, weakening impact on economic indicators can be expected. Due to the negative effects on household expenditure, related to the financial aspect of the subsidy, one has to revaluate the results of the technology breakthrough scenario slightly. Considering the same carbon price up to 2030, the costs of subsidizing the nuclear electricity generation capacities lead to a lower GDP in Western Europe by approximately 0.03% in 2015, 0.04% in 2020 and 0.02% in 2030 compared to the Nuclear Breakthrough scenario. The slight decrease in GDP can be led back on the negative effects on household income due the subsidy. The financing of the subsidy changes the household's disposable budget for consumption and investment plans comparable to a negative tax revenue.

Regarding the energy related and environmental impact of the subsidized investments in nuclear electricity generation capacities, no significant changes can be observed. Except the GDP induced impact on primary energy and electricity use, respectively, the structure of energy demand and electricity generation remains the same compared to the IN scenario. The nuclear focused development of the electricity production portfolio shows the same changes as the technology breakthrough scenario, connected with a strong decrease of CO_2 emissions compared to the BaU scenario.

Figure 4.10 presents the changes in electricity production due to the technology breakthrough compared to the baseline for Western Europe. Similar to the development in the generation structure presented in Figure 4.9, a decrease in nearly all technologies beside nuclear can be observed. There is a small increase in renewable energy supply up to 2010. By implementing the cost reduction for nuclear power plants after 2010, these effects for RES induced by the carbon tax are compensated by the strong deployment of new nuclear capacities.

Taking the significant shifts in the electricity supply structure into consideration that are induced by the various policy scenarios, different economic and environmental impact should be expected. With regard to energy related CO_2 emissions, one can observe that the nuclear policies combined with a carbon tax have a significant impact (see Figure 4.11).

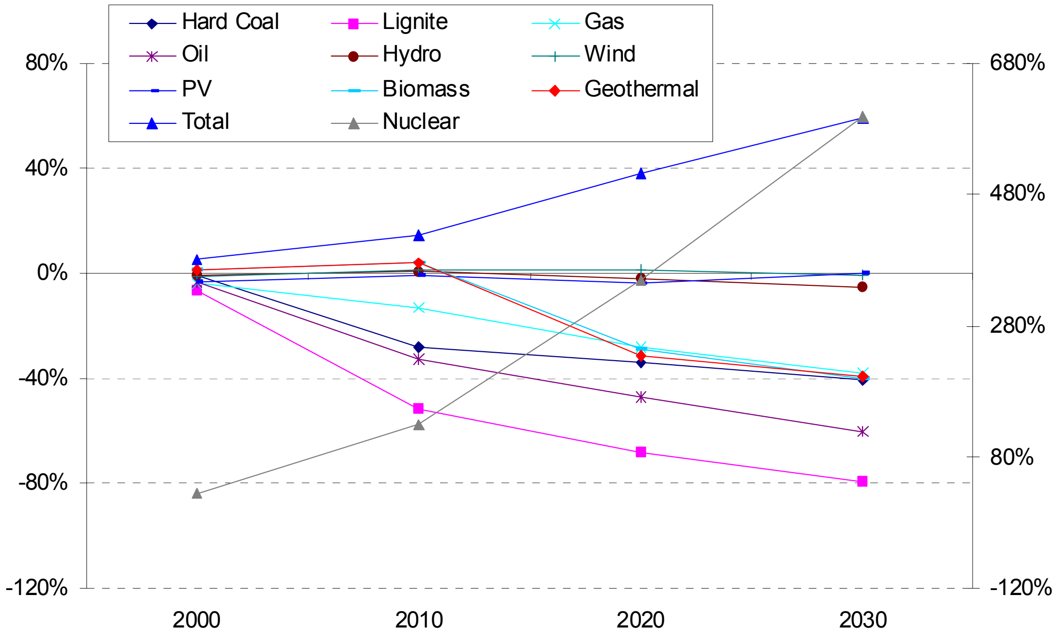

Figure 4.10 *Change in electricity generation, IN versus BaU [%] in WEU*

The strongest reduction in CO_2 emission compared to the Business as Usual scenario could be seen in the IN scenario. The CO_2 emissions from electricity generation decrease by 46% in the year 2030. A reduction of almost 27% is caused by the increasing carbon taxes. Shutting down most of the nuclear capacities partly counteracts the emission reduction induced by rising CO_2 prices. In the OUT scenario, the CO_2 emissions from electricity generation are only reduced with 17% compared to the baseline. Overall emissions decline by 18% (IN), 13% (CV) and 10% (OUT).

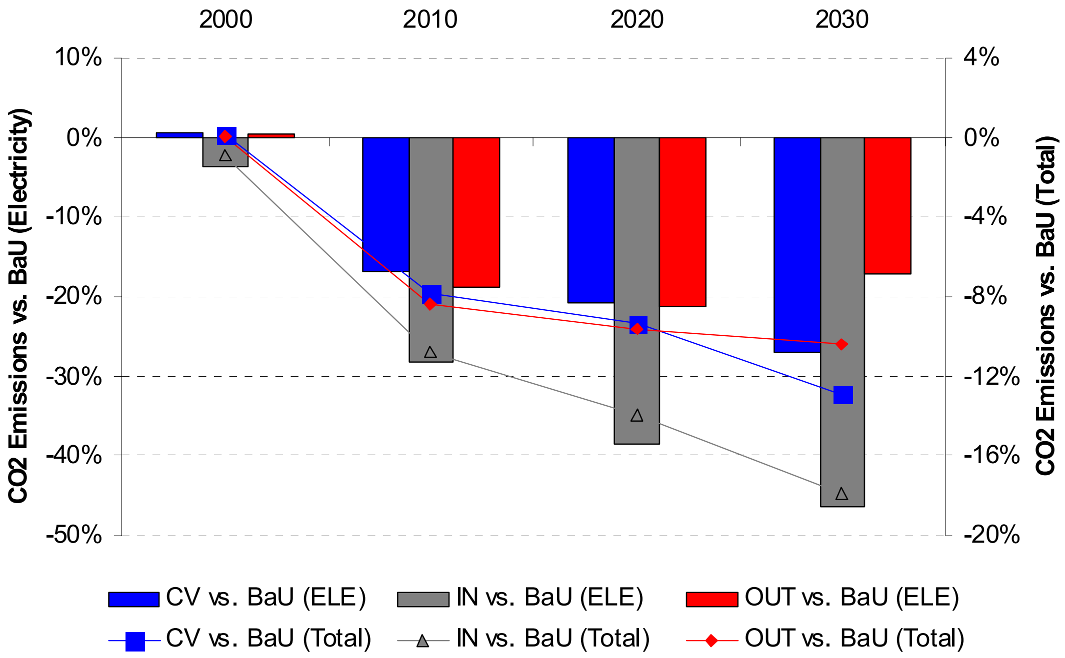

Figure 4.11 *Changes in CO_2 emissions [%] in WEU*

The impact of the various policy scenarios on GDP are shown in Figure 4.12. For the CV scenario it can be observed that an increase in carbon taxes can have a positive effect on GDP (+0.67%) for the year 2010 compared to the Business as Usual scenario. This impact is induced by increasing income of the households due to an increase in tax revenue accruing from the carbon taxation. Within the first years, this positive income effect compensates the negative production effect by rising carbon taxes, i.e. rising production costs. In the year 2020 the positive effect slackens and after 2030 a negative impact on GDP could be observed.

When adding a nuclear phase-out policy to the CV scenario, the positive income effect on GDP, which can be observed for 2010 as well, already slackens off in the year 2020. As of 2030 the strongest depletion in GDP of almost 2% could be seen in the OUT scenario. This is mainly caused by an increase in electricity prices, i.e. rising input cost for electricity intensive industrial production. Beside the negative impact on GDP in the CV and the OUT scenario, a positive impact follows a technology breakthrough for nuclear production. 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.

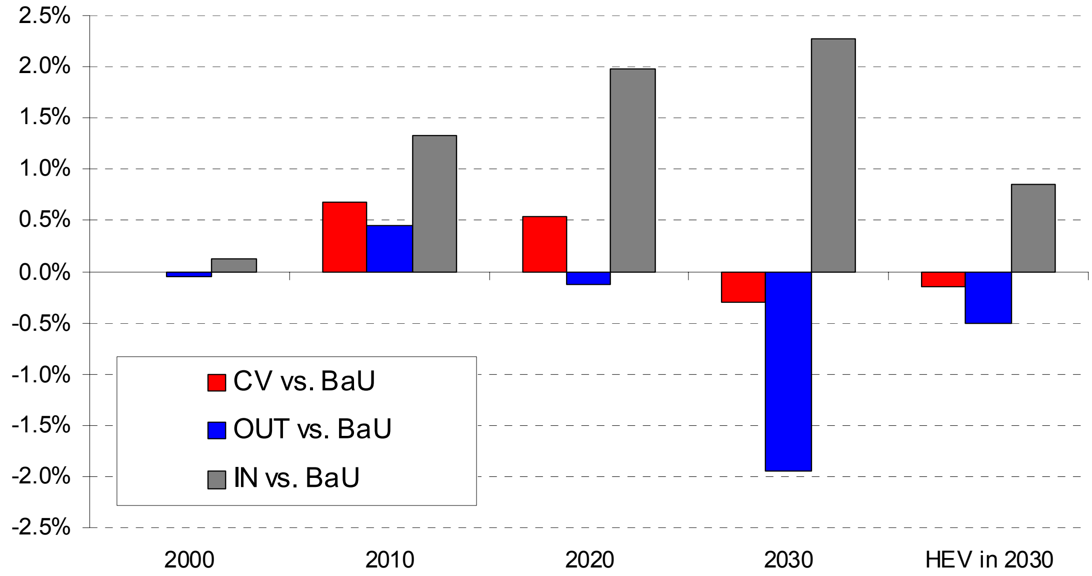

Figure 4.12 *Changes in GDP and HEV [%] in WEU*

Another indicator for the overall impact of a policy could be seen in changes of welfare, measured by the Hicksian Equivalent Variation (HEV). For the year 2030, the HEV is negative for the CV and the OUT scenario, whereas it is positive for the IN scenario.

4.2.3 Conclusions and recommendations

The analyses of the various nuclear policies combined with a carbon tax scenario showed significant differences regarding the development of the electricity generation structure, the environmental impact, i.e. CO_2 emissions and slightly effects on economic variables.

Forcing an electricity generation technology out of the market by a premature phase-out could lead to higher electricity generation costs and therefore higher input cost for electricity intensive production. The phase-out of nuclear generation capacities could partly compensate emission reduction caused by increasing CO_2 prices.

A renaissance of nuclear energy in Western Europe induced by a decline in specific investment or capital cost, respectively, could have positive impact on CO_2 emissions and economic development. Due a decline in electricity prices a positive impact on GDP and welfare can be observed. The impact of technology breakthrough for nuclear considerably depends on the assumptions made for financing the investment, i.e. capital cost reduction. Without taking the financial aspects of a technology specific efficiency target into account, the analysis could bring misleading results. The analysis of a subsidy for financing a decrease in investment costs for nuclear generation capacities shows small negative impact on GDP compared to the Breakthrough case without subsidising the technology, due to the effects on the household's disposable budget. Beside the financial aspects, one has to take possible external effects into account, such as risk of nuclear electricity generation and environmental impact of conventional fossil fuelled generation technologies, respectively.

4.3 NEMESIS

4.3.1 Introduction

The nuclear scenarios studied with NEMESIS consider two possible alternative evolutions for the nuclear sector in Europe: A nuclear 'phase-out' and a nuclear 'breakthrough'. In the nuclear 'phase-out' case there is no lifetime extension for existing capacities and no new capacities are built. It is introduced in the model as an exogenous bound on electricity production from nuclear sources. In particular, the nuclear installed capacities per country are either limited or constrained as shown in Table 4.7. Countries not represented in Table 4.7 are principally countries that do not have nuclear power plants in the baseline.

Table 4.7 *Change per country in the nuclear 'phase-out' scenario from the installed capacities in 2010; relative to the baseline*

$[GW_e]$	2015	2020	2025	2030
Belgium	0	-1764	-1900	-2367
Finland	0	-1380	-1630	0
France	0	-5564	-26500	-19325
Germany	-4593	-9634	-4240	0
Spain	-466	0	-4008	-3166
Sweden	0	0	-1240	-1110
United-Kingdom	-2588	-620	-5880	0

In the 'breakthrough' scenario, two groups of countries are considered: Those who do not build new nuclear plants and those who decide to extend their existing nuclear power capacities. This introduces the possibility for an extension of nuclear capacities in Europe. These assumptions are presented in Table 4.8.

Table 4.8 *Assumptions behind the implementation of the nuclear 'break through' scenario*

Do not build new nuclear plants	Build new nuclear plants
Austria	Belgium
Denmark	Finland
Greece	France
Ireland	Germany
Italy	Spain
Luxembourg	Sweden
Netherlands	United-Kingdom
Norway	
Portugal	

The policy scenarios have been implemented in NEMESIS considering a 'post-Kyoto baseline' with no constraint on nuclear capacities. This post-Kyoto baseline is set-up with a permits price (grandfathering) for CO_2 emissions equal to 50 $€_{2000}$ in 2020. This permits price is transmitted into the price of fuels leading to a rise of 7% of the nuclear capacity in EU-15 plus Norway in 2020, compared to the baseline previously used for the renewable case studies. In this post-Kyoto baseline, the share of RES in total energy consumption is increased by 18% and total GHG emissions in CO_2 equivalent are reduced with about 15%.

All results we present for nuclear in the following sections are for the medium term 2020 and for EU-15 plus Norway.

4.3.2 Results

The nuclear 'phase-out' case, reducing the use of nuclear energy production, leads to an increase of renewables whereas the nuclear 'breakthrough' scenario increases nuclear sources mainly at the expense of gas and oil (Figure 4.13).

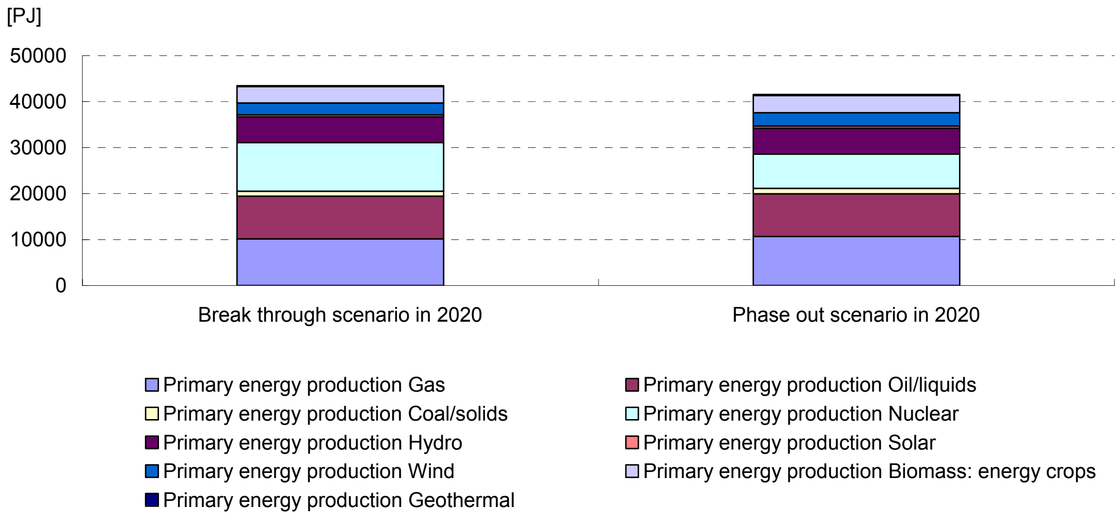

Figure 4.13 *Primary energy production in 2020 in the 'breakthrough' and the 'phase-out' scenarios*

Compared to the post-Kyoto baseline scenario, in the nuclear 'phase-out' case, no more nuclear capacities come up leading to a 12.4% reduction of primary energy production from nuclear in 2020. The implications for other energy sources of phasing out nuclear are a slightly rising contribution for natural gas (+1.5% in 2020) and coal/solids (+1.9% in 2020). In the 'breakthrough' scenario, the amount of nuclear energy is increasing by almost +1.9% in 2015 and +24.5% in 2020. This contributes to drop primary energy production from gas, coal/solid and wind (respectively with a -3.2%, -9% and -5.1% decrease in 2020 compared to the post-Kyoto baseline).

Table 4.9 *Impacts of nuclear scenarios on the share of renewable energy sources (difference from the baseline in 2020)*

	Phase-out	Breakthrough
RES/total primary consumption	2.57	-3.82
RES/gross electricity production	3.12	-4.78

The nuclear phasing out policy promotes significantly the development of renewable energy shares in Europe as shown in Table 4.9 (+ 3.12% for RES/ gross electricity production in 2020). The reduction of nuclear capacities results in a higher energy production from wind (+5.9% in 2020) and to a lesser extent from hydraulic, geothermal and biomass energy crops (with respectively +0.4%, +0.2% and 1.9% in 2020). On the opposite side, by comparing the post-Kyoto baseline and the nuclear 'break through' scenario, it can be seen that developing nuclear power capacities lowers the contribution of renewables (the share of RES in gross electricity production is declining by 4.78% in 2020).

Effects on the primary energy consumption

As a consequence of implementing a nuclear 'phase-out' or 'break through' scenario, the share of nuclear power in the total primary energy consumption respectively decreases of -12.4% and rises of +24.5% in 2020. Compared to the post-Kyoto baseline, the total gross inland consumption does not change at the European scale in both scenarios. This is mainly due to compensation between nuclear and other energy sources.

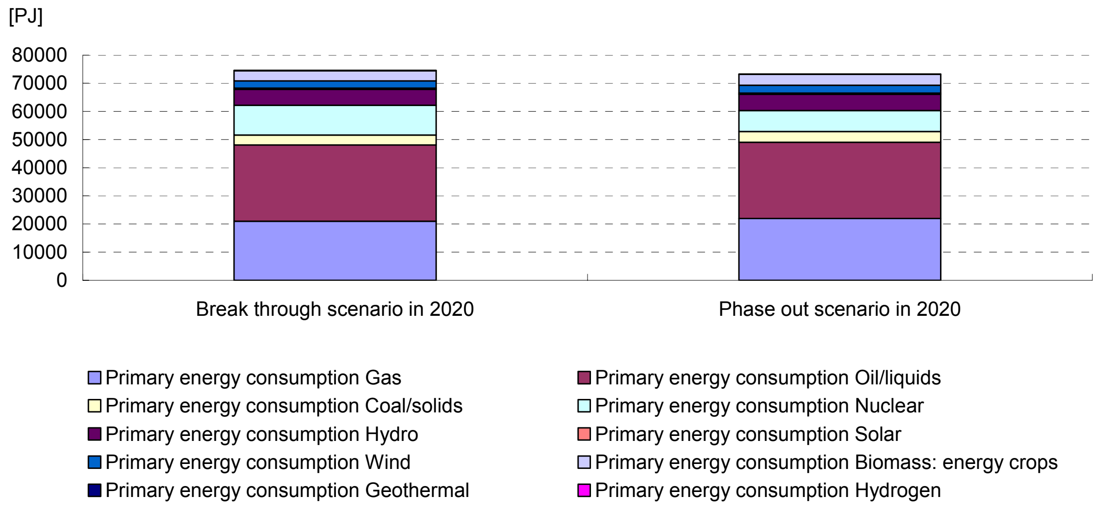

Figure 4.14 *Primary energy consumption in 2020 in the baseline, the 'breakthrough' and the 'phase-out' scenarios*

The contribution of renewable energy declines with a decrease of biomass (-4% in 2020) and of wind (-5.1% in 2020) in the 'breakthrough' scenario; it is the reversal in the 'phase-out' scenario where wind consumption increases by 5.9% in 2020. The primary energy consumption of oil/liquids remains constant in both scenarios.

Effects on the fuel mix used in electricity generation
In medium term, phasing out nuclear source in Europe (-13.9% in electricity net generation capacities in 2020) induces a growth in gas (+3.6%) and coal/solid (+3%) used as inputs for power generation (Figure 4.15). There is also a growth of electricity generation of 1.2% in the break through scenario mainly due to a 24.5% rise in gross electricity generation by nuclear.

Developing nuclear capacities also result in decreasing gas, coal/oil and biomass for power generation (respectively -7.2%, -9.7% and -9.4% in 2020) compared to the post-Kyoto baseline (Figure 4.16). The shares of solar and hydro used are nearly the same in both scenarios. Total coupled production-cogeneration declines by -4.2% in the 'break through' case whereas one obtains a rise of almost 2.1% in the 'phase-out' scenario.

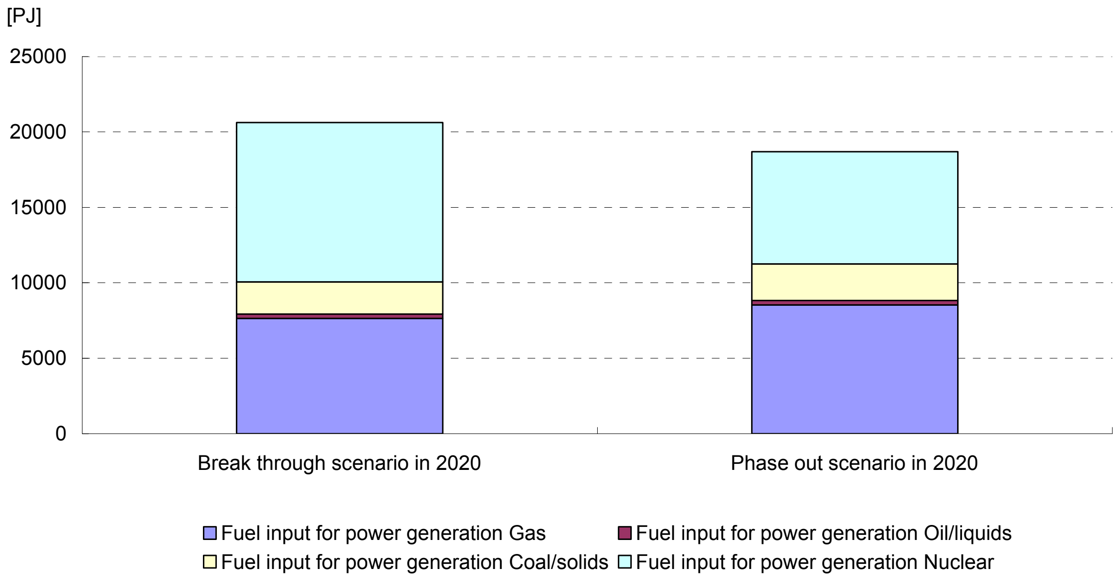

Figure 4.15 *Fuel input for power generation in 2020 in the 'break through' and the 'phase-out' scenarios*

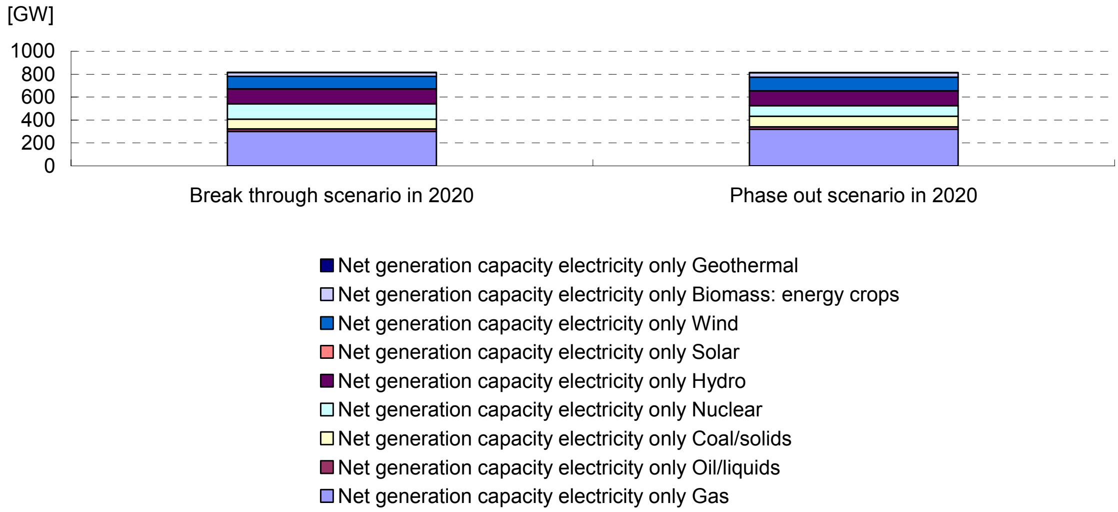

Figure 4.16 *Net electricity generation by fuel in 2020 in the 'breakthrough' and the 'phase-out' scenarios*

Security of supply indicators

The alternative policies for nuclear energy system present different result on the security of supply in Europe. Phasing out nuclear capacities induces a significant increase in net imports by fuel whilst developing nuclear reduces the European dependency from abroad.

Table 4.10 *Net import by fuel (difference from the post-Kyoto baseline in 2020)*

	Phase-out [%]	Breakthrough [%]
Gas	1.44	-2.55
Oil/liquids	0.04	-0.07
Coal/solids	2.06	-4.88

In the post-Kyoto baseline the Shannon diversity index has a value of 68%, which shows the variety of primary energy consumption in Europe. As a consequence of nuclear cases, this index is increasing with +0.3% in the 'break through' scenario and is declining with -0.2% in the 'phase-out' scenario. It implies that Europe's dependency on imported fuels is higher compared to a situation where nuclear capacities are unconstrained.

Change in carbon emission

The importance of nuclear capacities in Europe matters for the reduction of greenhouse gases in a post-Kyoto framework. Since the permits price is 50 $€_{2000}$ per tonne in 2020, emissions are declining in the post-Kyoto baseline. The outcome for CO_2 emission is of course linked to the reduction of energy consumption and depends on the nuclear scenario. Total CO_2 emissions per capita increase with 0.8% in the 'phase-out' scenario and decrease with 1.9% in the 'break through' scenario.

Table 4.11 *Impacts of nuclear scenarios on CO_2 emissions*

	Phase-out [%]	Breakthrough [%]
Energy sector	0.83	-1.93
Power sector	3.33	-7.81
(Other) conversion	0.37	-0.81
Industry	0.18	-0.43
Residential, commercial and service sector	0.02	-0.04

Note: Impacts of nuclear scenarios on CO_2 emissions. Difference from the post-Kyoto baseline in 2020.

Note that the post-Kyoto baseline implies a significant emission reduction already. Next, the effect of the nuclear breakthrough scenario is explained by a decreasing contribution of gas and coal in net electricity generation capacities (respectively -4.3% and -3.1% in 2020). As nuclear appears as a les polluting form of energy, emissions are higher in a 'phase-out' scenario. Indeed, in the latest case, the power sector is polluting more using gas, coal and oil energy fuel for power generation (respectively +3.6%, +3.1% and +1.7% in 2020) even if the final energy demand is slightly reduced.

Macroeconomic impacts

The nuclear cases are evaluated in a post-Kyoto baseline with a permits price of 50 $€_{2000}$ in 2020. This post-Kyoto baseline shows a reduction of GDP of about 1.3% in 2020, implied by the rise from 10 to 50 €/tonnes CO_2 of the carbon penalty, compared to the baseline used previously for renewables case studies. The rise of carbon penalty increases the final price of natural gas, solid fuels, liquid fuels and electricity respectively by 11.45%, 40.41%, 28.28% and 14.59% in 2020.

The inflationary impact of increased energy prices reaches 3.49% for the GDP deflator and the impact on the private consumption deflator is again more important, + 4.72%, as a consequence of the importance of energy in the budget of households. This reduces real wages of about 0.75%, the fall of real wage limiting the negative impact of GDP fall on employment level, with only 1% decrease against 1.3% for GDP.

Table 4.12 *Macroeconomic impacts of the post-Kyoto scenario*

	2020 [%]
GDP	-1.25
Private consumption	-1.34
Total investment	-0.91
Extra European exports	-2.30
Extra European imports	0.87
GDP deflator	3.49
Consumption price	4.64
Nominal wage	3.89
Employment	-1.00

Note: Macroeconomic impacts of the post-Kyoto scenario: Difference from the post-Kyoto baseline in 2020.

The inflationary pressures reduce also competitiveness of European firms. Exports decrease by 2.3% in the post-Kyoto scenario in reason of the rise of terms of trade while imports increase about 0.87% as a result of substitution effects between European and foreign goods.

The post-Kyoto constraint of 50 €/tonne CO_2 in 2020 has also contrasted impacts on EU-15 countries, depending on the level of their initial dependency on fossil fuels.

Table 4.13 *Impacts on national GDP of the post-Kyoto scenario*

	2020 [%]
Austria	-1.57
Belgium	-1.61
Denmark	-0.59
Finland	-0.65
France	-0.92
Germany	-1.53
Greece	-1.97
Ireland	-0.82
Italy	-1.01
Netherlands	-1.15
Norway	-1.17
Portugal	-0.78
Spain	-1.47
Sweden	-0.68
United-Kingdom	-1.63
EU-15	-1.25

Note: Impacts on national GDP of the post-Kyoto scenario. Difference from the post-Kyoto baseline in 2020.

Table 4.13 indicates in that direction that GDP losses range between -0.59% for Denmark to -1.97% to Greece; this could be reduce by recycling the carbon penalty, for example by reducing the rate of employers' social contributions.

For the 'phase-out' and 'breakthrough' scenarios, we did not find additional significant macro-economic impacts to the post-Kyoto scenario. The reason is that these scenarios induce mostly substitutions in the power sector, with too limited impacts on the price of electricity to influence GDP growth in EU-15 countries.

These scenarios have nevertheless a direct impact on the level on CO_2 emissions through the contribution of fossil fuels to power generation, and if we take now into account this retroaction of nuclear capacity on the post-Kyoto's carbon constraint, that is on the level of the carbon penalty necessary to reach the level of GHG emissions of the post-Kyoto scenario, we get this time significant macroeconomic impacts for the two scenarios.

For example, in the 'breakthrough' scenario, GHG emission are reduced of about 2% in 2020, and this allows to reduce the carbon penalty around € 5 per tonne CO_2 equivalent for the same level of GHG emissions in 2020 in Europe. We see on Table 4.14 below that GDP is consequently 0.15% higher in the 'breakthrough' scenario than in the post-Kyoto scenario, with GDP gains ranging from 0.1% in Denmark to 0.2% in Greece. These GDP gains will be of course very more important if we were looking at the long-term horizon of 2050.

Table 4.14 *Impacts on national GDP of the 'Phase-out' and 'Breakthrough' scenarios*

	Phase-out [%]	Breakthrough [%]
Austria	-0.08	0.19
Belgium	-0.08	0.19
Denmark	-0.04	0.10
Finland	-0.04	0.11
France	-0.05	0.13
Germany	-0.07	0.18
Greece	-0.09	0.20
Ireland	-0.05	0.13
Italy	-0.05	0.13
Netherlands	-0.05	0.14
Norway	-0.06	0.14
Portugal	-0.06	0.11
Spain	-0.04	0.19
Sweden	-0.08	0.01
United-Kingdom	-0.07	0.17
EU-15	-0.06	0.15

Note: Impacts on national GDP of the 'Phase-out' and 'Breakthrough' scenarios. Difference from the post-Kyoto baseline in 2020.

Table 4.14 shows equally that the 'phase-out' has on the contrary a negative impact on GDP, the progressive phasing-out of nuclear capacities from 2011 leading to an increasing carbon penalty, which reach about 52 €/tonne CO_2 in 2020 compared to only € 50 in the post-Kyoto scenario. Here again, the change in GDP is still very limited in 2020, with a loss of GDP of -0.06% for EU-15, but it should increase importantly until 2050 with the rise of the carbon penalty necessary to maintain a constant level of post-Kyoto GHG emissions, with this time an increased contribution of fossil fuels to power generation.

5. US and Canada

5.1 NEMS (US)

5.1.1 Introduction

The focus of this report is the potential contribution of nuclear electricity generation to the U.S. power sector and its potential impacts on energy consumption, fuel prices, the U.S. macroeconomy, and the associated carbon emissions under alternative assumptions of nuclear costs, performance and regulatory environment. Five cases were analysed, as described in Table 5.1 below. The reference case is the *Annual Energy Outlook 2005* (*AEO2005*)[19] which was developed using the National Energy Modeling System (NEMS)[20]. The detailed assumptions of the Reference case are provided on the Energy Information Administration's (EIA) website[21].

Table 5.1 *The scenarios analysed for the study*

Scenario Name	Scenario Description	Nuclear Capacity in 2025 [GW]
AEO2005	The Reference case	102.7
CARBFEE	AEO2005 with a carbon price of € 10 per metric tonne CO_2 in 2010, rising linearly to € 75 per metric tonne CO_2 in 2025.	146.5
LOWNUC	Reference case with no new nuclear and no new license renewals beyond what had already been granted as of July 2004.	48.4
FEELOWNUC	LOWNUC with a carbon price of € 10 per metric tonne CO_2 in 2010, rising linearly to € 75 per metric tonne CO_2 in 2025.	48.4
HINUC	Reference case with the starting overnight cost of nuclear reduced by 25% (to 1502 €/kW).	129.6
CAPHINUC	HINUC case with a carbon target set to the carbon emissions result from the CARBFEE case.	360.3

Source: AEO2005 Reference case: AEO2005.D102004A; CARBFEE: CARFEE05.D042605A; LOWNUC: AEOLONUC.D110204A; FEELOWNUC: CARNONUC.D042505A; HINUC: AEOHINUC.D042105A; CAPHINUC: CARCAP05.D052505A.
Note: All of the capacities shown for 2025 are model projections based on the cost, performance and regulatory assumptions of the cases. The LOWNUC and FEELOWNUC cases do not permit the addition of new nuclear capacity.

The assumptions of *AEO2005* were based on laws, policies and regulations in force on October 1, 2004. Consequently, any subsequent changes in laws (e.g., the Energy Policy Act of 2005[22]) and regulations (e.g., the Clean Air Interstate Rule[23] and Clean Air Mercury Rule[24]) enacted af-

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19 Energy Information Administration, *Annual Outlook 2005, with Projections to 2025*, DOE/EIA-0383(2005),(Washington, D.C., February 2005), web site http://www.eia.doe.gov/oiaf/aeo/index.html.

20 Energy Information Administration, *National Energy Modeling System*, *An Overview 2003*, DOE/EIA-058(2003) (Washington, D.C., March, 2003), web site http://www.eia.doe.gov/oiaf/aeo/overview/index.html.

21 Energy Information Administration, *Assumptions to the Annual Outlook 2005, with Projections to 2025*, (Washington, D.C., March 2005), web site http://www.eia.doe.gov/oiaf/aeo/assumption/pdf/0554(2005).pdf.

22 Energy Policy Act of 2005,signed August 8, 2005, http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=109_cong_reports&docid=f:hr190.109.pdf.

23 U.S. Environmental Protection Agency, Clean Air Interstate Rule, March 10, 2005, http://epa.gov/cair/index.html.

24 U.S. Environmental Protection Agency, Clean Air Mercury Rule, March 15, 2005, http://www.epa.gov/oar/mercuryrule/rule.htm.

ter that point are not included in the Reference case or in the sensitivity cases. The new laws and regulations are expected to have some impact on the projected choices of technologies in the mid-term but they will not be formally evaluated by the Energy Information Administration (EIA) of the U.S. Department of Energy until December 2005.[25]

The carbon price scenarios impose the specific carbon dioxide price path ('carbon price') on the entire energy sector as defined for these scenarios. For NEMS, the carbon price begins in 2010 and increases linearly until 2025, the last projection year for NEMS. Within NEMS, the carbon price is added to the delivered price of the various fossil fuels based on the carbon content of the fuel. The CARBFEE case uses the Reference case assumptions and overlays the specified carbon price path to get a new equilibrium solution for consumption, fuel and capacity mix, energy prices, and carbon dioxide emissions for the U.S. energy-economy. The new carbon dioxide emissions achieved are then used as the carbon dioxide emissions path for the advanced nuclear case assumptions and solved for a new energy-economy equilibrium (CAPHINUC). For the cases analysed, it was assumed that the emissions target would be met in each year, that no banking of emissions from year to year is allowed, and there would be no credit for other sources of greenhouse gas reductions, including international trading, sequestration, etc. - an admittedly restrictive set of assumptions.

The LOWNUC case assumes that new nuclear power construction is not permitted and that existing nuclear units must retire at the end of their operating licenses. Currently, U.S. nuclear operating companies are showing an interest in extending operating lives beyond the initial 40-year license period, with well over half the current fleet in the process of applying for license renewal or formally announcing intentions to apply. For the LOWNUC scenario, the retirement dates were based on license expiration dates, as published in the Nuclear Regulatory Commission's 2004-2005 Information Digest[26]. This included 25 units that have already received approval for license renewal. Units that have not yet applied, or were still in the review process, were assumed for this case to retire based on their original licenses, resulting in 57 units (54 GW) retired between 2009 and 2025. The *AEO2005* reference case allowed the model to evaluate whether it was economic to continue to run the existing nuclear units, and resulted in no retirements through 2025.

The HINUC scenarios assumed that initial costs for the advanced nuclear technology were 25% below EIA's reference case assumptions. This resulted in an initial cost of 1502 €/kW compared to 2003 €/kW in the reference case (Table 5.2). The lower cost assumption resulted in new nuclear capacity additions in a reference case (27 GW in the HINUC scenario), while the *AEO2005* reference case had no new additions.

Since NEMS endogenously represents 'learning-by-doing' in the electricity sector by component and captures the spill-over learning from alternative generation technologies which have the same 'component' (e.g., turbines are in both the IGCC and gas combined cycle technologies), the relative starting costs of the competing technologies could have a significant bearing on when (or if) a technology penetrates the market and how quickly it may do so.

Table 5.2 illustrates the cost and performance assumptions for key generation technologies.

[25] The analysis will formally be incorporated in the new reference case of the Annual Energy Outlook 2006.
[26] Nuclear Regulatory Commission, Information Digest, 2004-2005 Edition (NUREG-1350, Vol. 16), July 2004.

Table 5.2 *Cost and performance characteristics of new central station electricity generating technologies*

Technology	Online Year[1]	Size (mW)	Leadtimes (Years)	Base Overnight Costs in 2004 (2000 EU/kW)	Contingency Factors: Project Contingency Factor	Contingency Factors: Technological Optimism Factor[2]	Total Overnight Cost in 2004[3] (2000 EU/kW)	Variable O&M[5] (2000 EU/mwh)	Fixed O&M[5] (2000 EU/kW)	Heatrate in 2004 (Btu/kWhr)	Heatrate nth-of-a-kind (Btu/kWr
Scrubbed Coal New	2008	600	4	1,161	1.07	1.00	1,242	4.16	24.93	8,844	8,600
Integrated Coal-Gasification Combined Cycle (IGCC)	2008	550	4	1,341	1.07	1.00	1,435	2.65	35.01	8,309	7,200
IGCC with Carbon Sequestration	2010	380	4	1,863	1.07	1.03	2,053	4.02	41.21	9,713	7,920
Conv Gas/Oil Comb Cycle	2007	250	3	553	1.05	1.00	580	1.87	11.30	7,196	6,800
Adv Gas/Oil Comb Cycle (CC)	2007	400	3	529	1.08	1.00	571	1.81	10.59	6,752	6,333
ADV CC with Carbon Sequestration	2010	400	3	1,015	1.08	1.04	1,140	2.66	18.02	8,613	7,493
Conv Combustion Turbine[5]	2006	160	2	385	1.05	1.00	405	3.23	10.97	10,817	10,450
Adv Combustion Turbine	2006	230	2	365	1.05	1.00	383	2.87	9.53	9,183	8,550
Fuel Cells	2007	10	3	3,766	1.05	1.10	4,350	43.40	5.12	7,930	6,960
Advanced Nuclear	2013	1000	6	1,734	1.10	1.05	2,003	0.45	61.48	10,400	10,400
Distributed Generation -Base	2007	2	3	787	1.05	1.00	826	6.45	14.51	9,950	8,900
Distributed Generation -Peak	2006	1	2	946	1.05	1.00	993	6.45	14.51	11,200	9,880
Biomass	2008	80	4	1,650	1.07	1.02	1,799	3.03	48.29	8,911	8,911
MSW - Landfill Gas	2007	30	3	1,435	1.07	1.00	1,535	0.01	103.46	13,648	13,648
Geothermal[6,7]	2008	50	4	3,030	1.05	1.00	3,182	0.00	107.46	45,335	36,468
Conventional Hydropower[6]	2008	500	4	1,350	1.10	1.00	1,485	4.70	12.64	10,338	10,338
Wind	2007	50	3	1,085	1.07	1.00	1,161	0.00	27.44	10,280	10,280
Solar Thermal[7]	2007	100	3	2,575	1.07	1.10	3,030	0.00	51.42	10,280	10,280
Photovoltaic[7]	2006	5	2	3,959	1.05	1.10	4,573	0.00	10.58	10,280	10,280

1 Online year represent the first year that a new unit could be completed, given an order date of 2004
2 The technical optimism factor is applied to the first four units of a new, unproven design, it reflects the demonstrated tendency to underestimate actual costs for a first-of-a-kind unit.
3 Overnight capital cost including contingency factors, excluding regional multipliers and learning effects. Interest charges are also excluded. These represent costs of new projects initiated in 2004.
4 O&M = Operations and maintenance
5 Combustion turbine units can be built by the model prior to 2006, if necessary, to meet a given region's reserve margin
6 Because geothermal and hydro cost and performance characteristics are specific for each site, the table entries represent the cost of the least expensive plant that could be built in the Northwest Power Pool region, where most of the proposed sites are located.
7 Capital costs for geothermal and solar technologies are shown before the 10% investment tax credit applied.

Source: The values shown in this table are developed by the Energy Information Administration, Office of Integrated Analysis and Forecasting, from analysis of reports and discussions with various sources from industry, government, and the Department of Energy fuel Offices and National Laboratories. They are not based on any specific technology model, but rather, are meant to represent the cost and performance of typical plants under normal operating conditions for each plant type.

5.1.2 Results: The Impact of an Alternative Nuclear Regulatory Environment and Nuclear Cost Reductions on Consumption, Fuel Mix and Carbon Dioxide Emissions

This section analyses two cases of energy market impacts that are expected to result from: (a) a moratorium on nuclear life extensions and new nuclear capacity additions (LOWNUC), and (b) a significant cost reduction for new nuclear capital costs with no changes to the regulatory environment (HINUC).

Key Impacts

Primary Consumption and Generation Mix Changes. Petroleum consumption is projected to be relatively unaffected by the policies in the LOWNUC and the HINUC cases, relative to the Reference case in the United States (Figure 5.1). Total primary energy consumption in 2025 is projected to decline in the LOWNUC case by about 1.6 Exajoules (EX) while consumption is relatively unchanged in the HINUC case relative to the Reference case. However, such measures are flawed because of the conventions used for measuring primary energy equivalents for nuclear and renewable resources. The more useful measure for this study is fossil fuel consumption - e.g., oil, coal and natural gas. Fossil fuel consumption in 2025 in the Reference, LOWNUC and HINUC cases is 122 EX, 124.7 EX, and 120.4 EX, respectively.

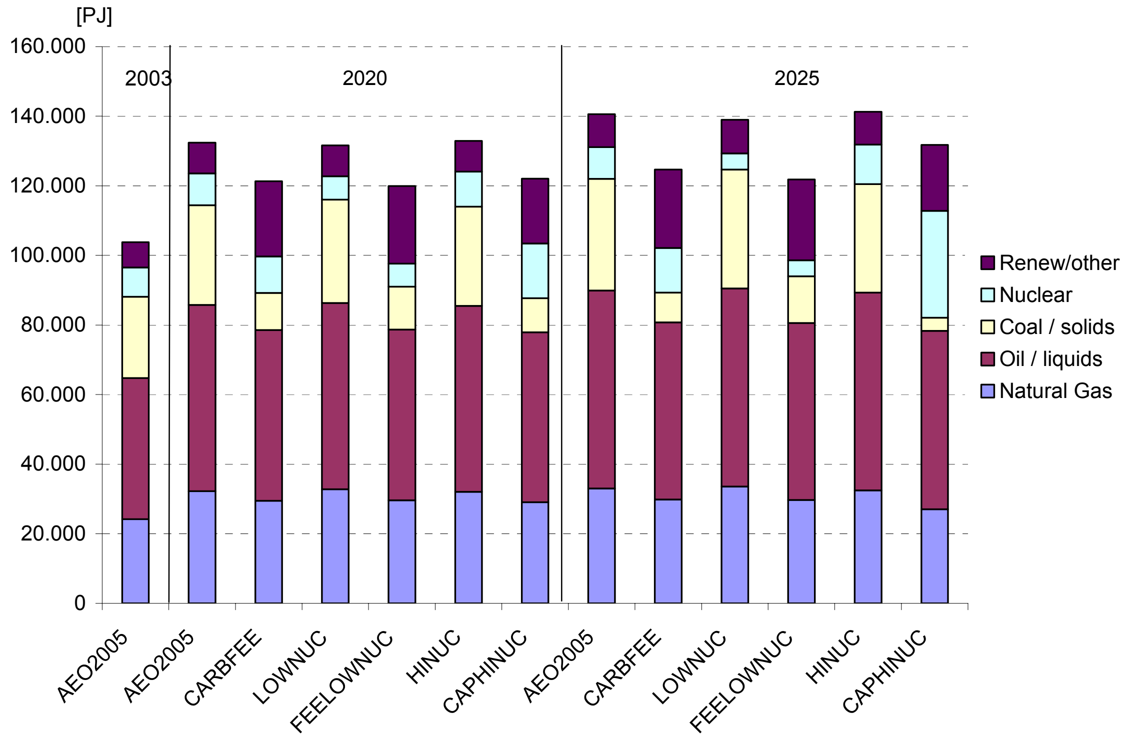


Figure 5.1 *Projected U.S. Primary Energy Consumption by Fuel*
Sources: AEO2005 Reference case: AEO2005.D102004A; CARBFEE: CARFEE05.D042605A; LOWNUC: AEOLONUC.D110204A; FEELOWNUC: CARNONUC.D042505A; HINUC: AEOHINUC.D042105A; CAPHINUC: CARCAP05.D052505A.

The increase in fossil fuel consumption in the LOWNUC case represents the need to replace nuclear generation resulting from the decommissioning of 54.3 GW of nuclear capacity by fossil fuel and renewable generation technologies. The LOWNUC case projects a net reduction of 61 TWh of electricity available to the grid in 2025 because of a 5.4% increase in the delivered price of electricity. The LOWNUC case projects a reduction of 409 TWh of nuclear generated electricity, an increase of 89 TWh natural gas generated electricity, an increase of 251 TWh coal generated electricity, and the remainder is from renewable and oil fired generation. About two-thirds of the coal fired generation increase is from advanced coal integrated gasification combined cycle (IGCC) plants.

Relative to the Reference case in 2025, the assumed lower nuclear capacity costs in the HINUC case result in a very slight increase in electricity sales (less than 10 TWh) but an increase of 208 TWh of electricity generated by new nuclear plants in 2025 from the additional 26.9 GW of nuclear capacity added during the projection period. The additional nuclear capacity results in a reduction of generation from natural gas (81 TWh) and coal-fired capacity (108 TWh) and a reduction of fossil fuel consumption of about 1.5 EJ. The remaining electricity generation reductions occur from a combination of renewable and oil-fired generation (Figure 5.2).

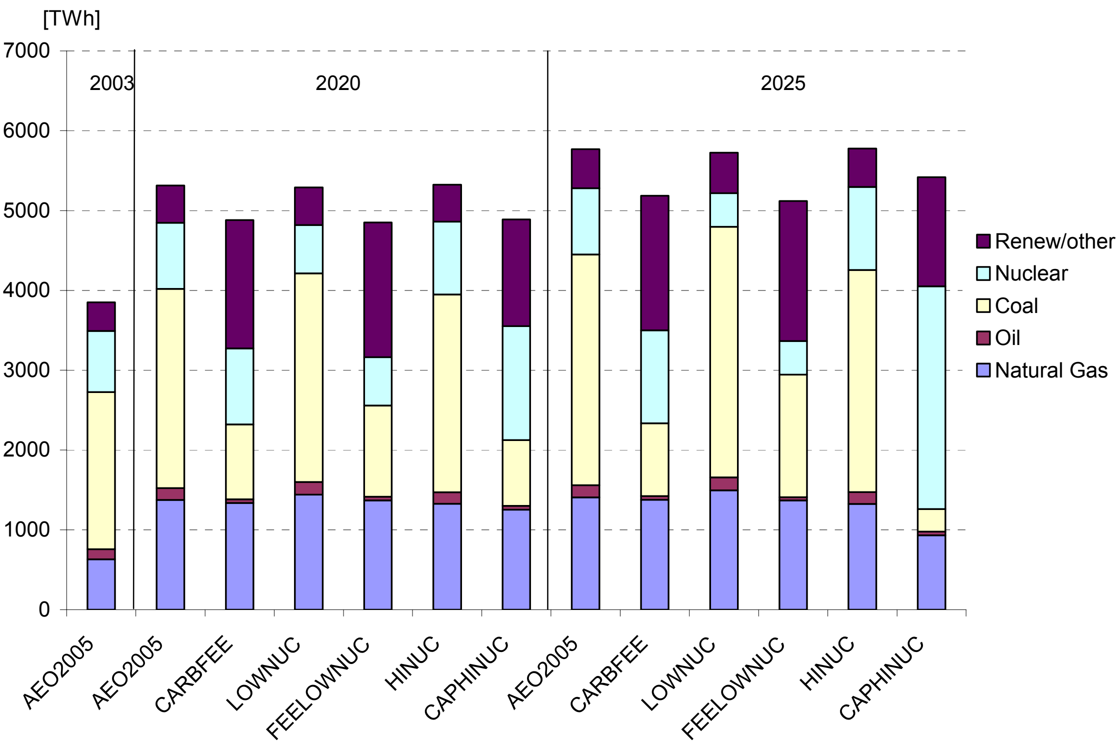


Figure 5.2 *U.S. Electricity Generation by Fuel*

Sources: AEO2005 Reference case: AEO2005.D102004A; CARBFEE: CARFEE05.D042605A; LOWNUC: AEOLONUC.D110204A; FEELOWNUC: CARNONUC.D042505A; HINUC: AEOHINUC.D042105A; CAPHINUC: CARCAP05.D052505A.

Natural gas and coal consumption in the LOWNUC case are projected to be higher then the Reference case by about 0.54 EJ and 2.1 EJ respectively, largely because of the substitution of coal and natural gas generation for nuclear generation. In the HINUC case, natural gas consumption is about 0.54 EJ lower and coal consumption is about 0.94 EJ lower than the Reference case because of the increase in nuclear generation.

Delivered Fuel Prices. Delivered fuel prices in 2025 for natural gas and coal are higher in the LOWNUC case than the Reference case because additional consumption of both fuels is required to replace the displaced nuclear generation. In the LOWNUC case, the average delivered price of natural gas and coal to all users in 2025 is 1.8% and 4.6% higher than the Reference case, respectively.

In the HINUC case in 2025, the reduction in natural gas and coal demand results in a 0.5% reduction for the average delivered price of natural gas and a 3% reduction in the delivered coal price.

Average delivered electricity prices in 2025 are 5.4% higher in the LOWNUC case and 0.6% lower HINUC case relative to the Reference case.

Impacts on Carbon Dioxide Emissions. Carbon dioxide emissions are projected to increase by 221 million metric tonnes (2.7%) in 2025 in the LOWNUC case relative to the Reference case when the regulatory environment is assumed to be hostile to nuclear relicensing, life extensions, or new nuclear plant construction. Figure 5.3 illustrates the carbon dioxide emissions from power generation in the alternative scenarios. When the regulatory environment remains unchanged from the Reference case and capital costs of nuclear are reduced by 25% as in the HINUC case, the construction of the added nuclear capacity results in a reduction of 113 million metric tonnes of carbon dioxide, 1.4%, relative to the Reference case. Carbon intensity (metric tonnes carbon dioxide per million dollars GDP) is 2.8% higher in the LOWNUC case and 1.4% lower in the HINUC case than the Reference case in 2025, reflecting the changes in fossil fuel consumed because of the changes in nuclear capacity.

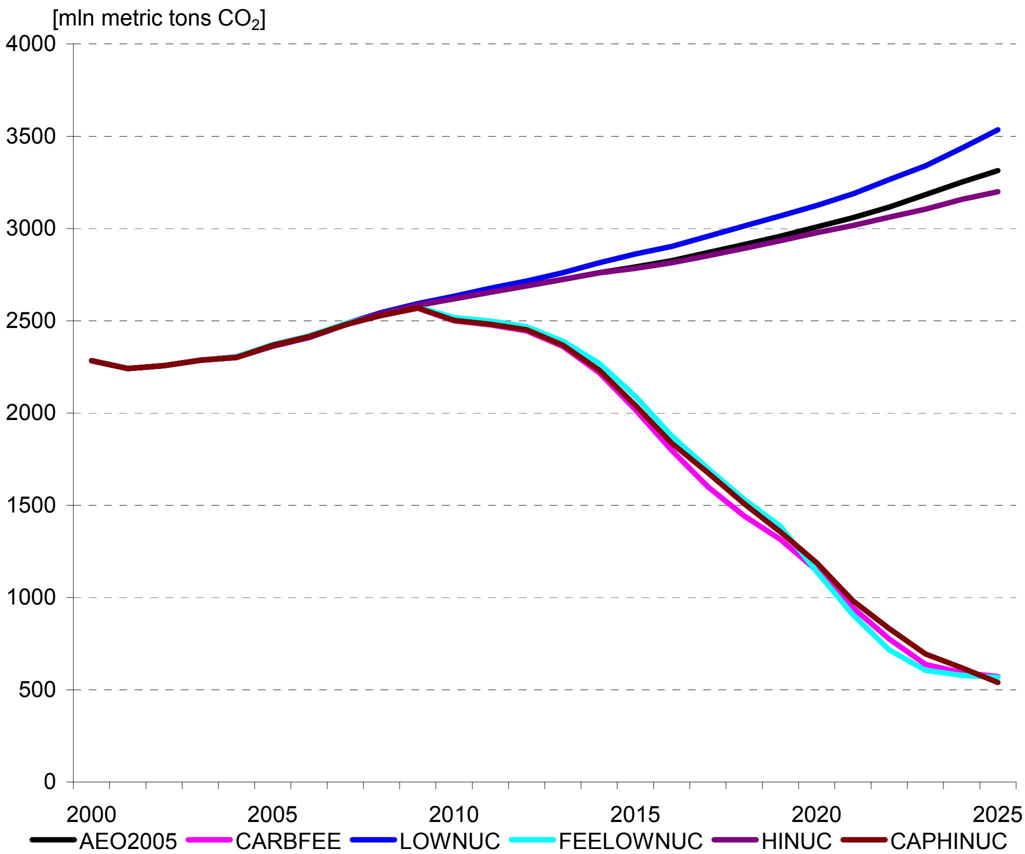


Figure 5.3 *U.S. CO_2 Emissions from Electricity Generation*
Sources: Energy Information Administration. AEO2005 Reference case: AEO2005.D102004A; CARBFEE: CARFEE05.D042605A; LOWNUC: AEOLONUC.D110204A; FEELOWNUC: CARNONUC.D042505A; HINUC: AEOHINUC.D042105A; CAPHINUC: CARCAP05.D052505A.

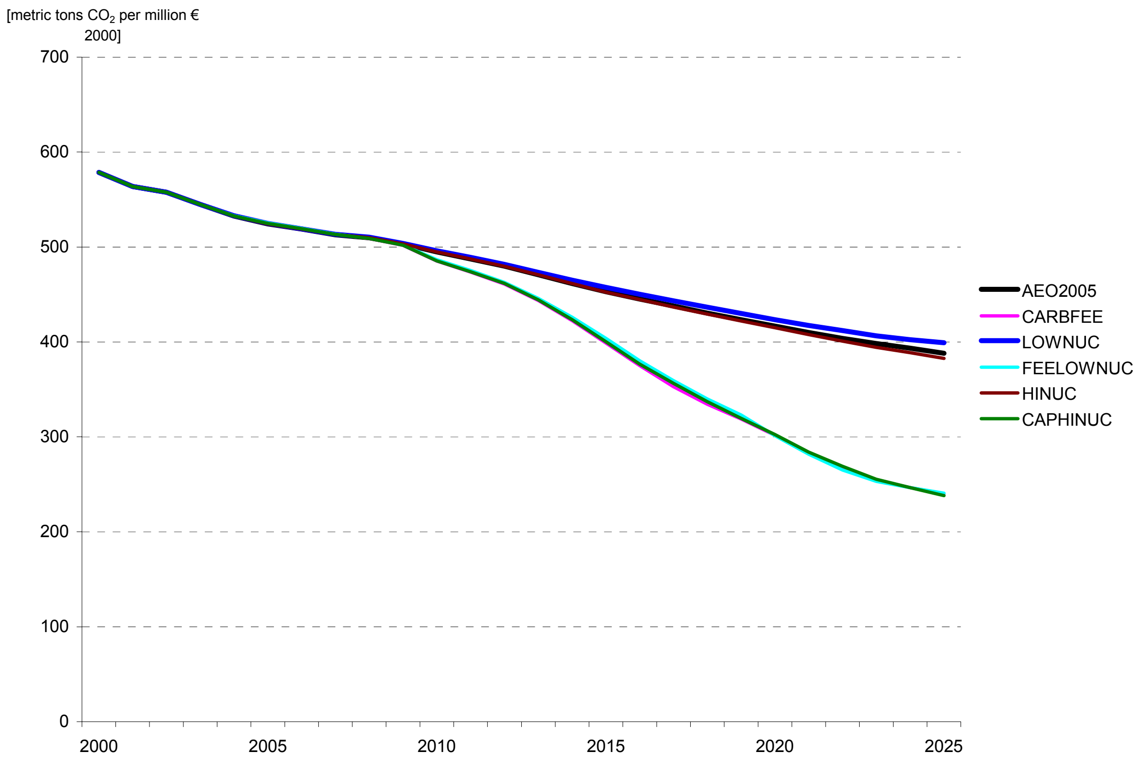


Figure 5.4 *U.S. Carbon Intensity*
Sources: Energy Information Administration. AEO2005 Reference case: AEO2005.D102004A; CARBFEE: CARFEE05.D042605A; LOWNUC: AEOLONUC.D110204A; FEELOWNUC: CARNONUC.D042505A; HINUC: AEOHINUC.D042105A; CAPHINUC: CARCAP05.D052505A.

Macro-economic impacts. The two cases, LOWNUC and HINUC, have negligible impacts on GDP and the macro-economy relative to the reference case, primarily because the aggregate energy price impacts on the U.S. economy are small.

5.1.3 Consequences of carbon dioxide emission targets or carbon dioxide emission prices on the LOWNUC and HINUC cases for U.S. energy markets

Three additional cases that build on the results of the LOWNUC and HINUC cases previously described are examined in this section. Specified carbon dioxide costs, based on the emitted carbon content of a fuel, were added to delivered prices in the Reference case to determine the resulting carbon dioxide emissions levels for the period 2010 to 2025 (CARBFEE). These same carbon dioxide costs were also added to the LOWNUC case to create the FEELOWNUC case. Although the mix of technologies built in the two carbon fee cases were very different, the resulting carbon emissions forecast was very similar. The reductions were achieved by different methods, but the carbon paths were almost the same. Therefore, only one carbon limit scenario was run, based on the path from the CARBFEE case. This path was used as the carbon dioxide emissions limit for the case with the HINUC assumptions to estimate how much the reduced nuclear capital costs would impact primary energy consumption, fuel mix, fuel prices, and the macro-economy to meet the same target achieved in the Reference case (and LOWNUC case) with the specified carbon dioxide emission prices. An important assumption used in these cases is that banking of carbon dioxide allowances is not permitted. Had this been permitted, it is expected that some banking of allowances would have occurred early in the 2010 to 2025 projection period and the resulting carbon dioxide permit price would have been smoother with a slightly lower peak-year value.

Key impacts

Delivered Energy Prices. Delivered energy prices for fossil fuels are increased according to the carbon content of the fuels as shown in Figure 5.5. Consequently, delivered coal prices are penalized the most and delivered natural gas prices are penalized the least. The price increases relative to the Reference case in 2025 are shown in Table 5.3.

Table 5.3 *Percentage delivered price Increases relative to the reference in 2025*

	CARBFEE	FEELOWNUC	CAPHINUC
Natural Gas	49.9	49.5	24.9
Petroleum	48.7	49.0	31.1
Coal	556.4	565.4	344.4
Electricity	49.6	60.0	21.2

In 2025, delivered coal prices are the most penalized fuel prices in the carbon-constrained cases, increasing above the Reference case by about 344% in the CAPHINUC case to 565% in the FEELOWNUC case. By 2025, the CAPHINUC case is able to achieve roughly the same carbon emissions at a lower carbon price than the FEELOWNUC due to the additional nuclear capacity, and lower cost of new nuclear capacity. Therefore, the delivered fossil fuel prices are much lower in CAPHINUC relative to FEELOWNUC, due to both lower fossil fuel consumption and lower carbon price adders. Since the marginal cost of generation is usually derived from natural gas prices, the percentage increases in electricity prices usually follow the percentage increases in natural gas prices, about 50% and 25% respectively in the CARBFEE and CAPHINUC cases. However, in the FEELOWNUC case, because of the assumptions on nuclear, the marginal generation technology alternates between several technologies during the year. Consequently, in 2025 the increase in average cost of electricity is 60% above the Reference case compared to the 50% price increase for natural gas relative to the Reference case.

The increase in delivered fuel prices in the carbon-constrained cases is projected to cause reductions in energy consumption, significant fuel mix changes in the power generation sector, and negative impacts on the U.S. macro-economy.

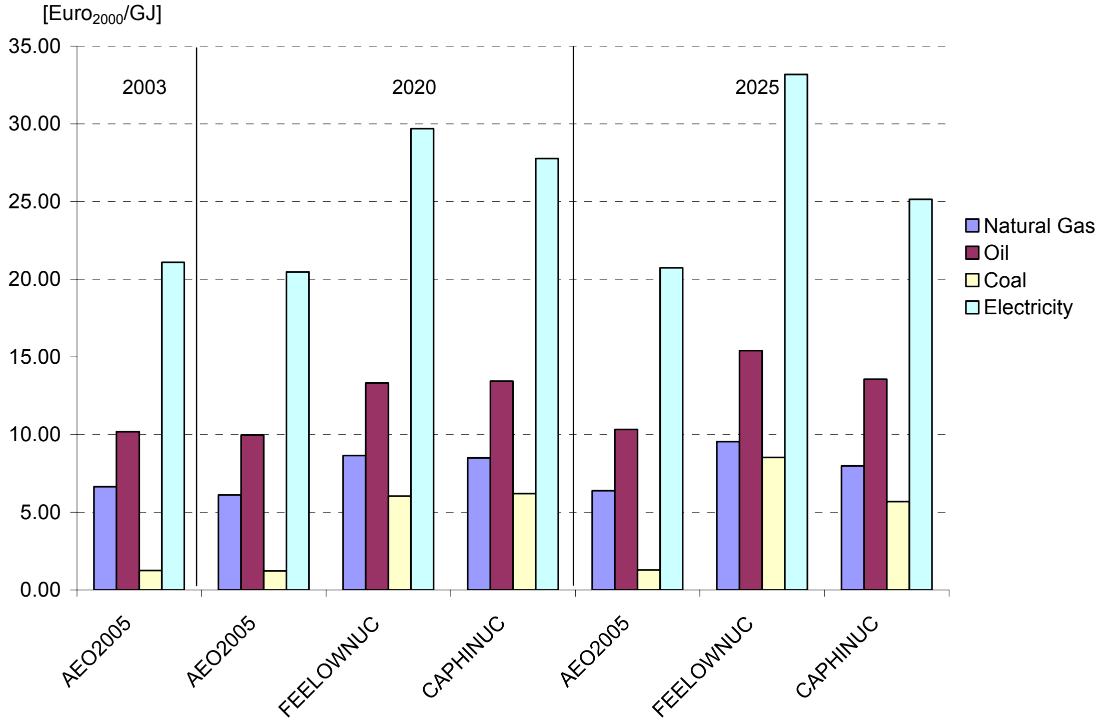


Figure 5.5 *Projected U.S. Delivered Fuel Prices*
Sources: Energy Information Administration. AEO2005 Reference case: AEO2005.D102004A; FEELOWNUC: CARNONUC.D042505A; CAPHINUC: CARCAP05.D052505A.

Macro-economic impacts. While the year-to-year GDP impacts for the LOWNUC and HINUC cases are relatively small, the same cannot be said for the cases which would impose the prescribed carbon dioxide permit prices or the carbon cap that results from imposing the carbon prices in the Reference case (Figure 5.6). The peak-year GDP loss occurs in 2025 in the FEELOWNUC case, about €258 billion; the loss is higher in the FEELOWNUC case than the CARBFEE case because of the unfriendly regulatory environment for nuclear generation limits the generation technology options and results in higher energy prices to the economy.

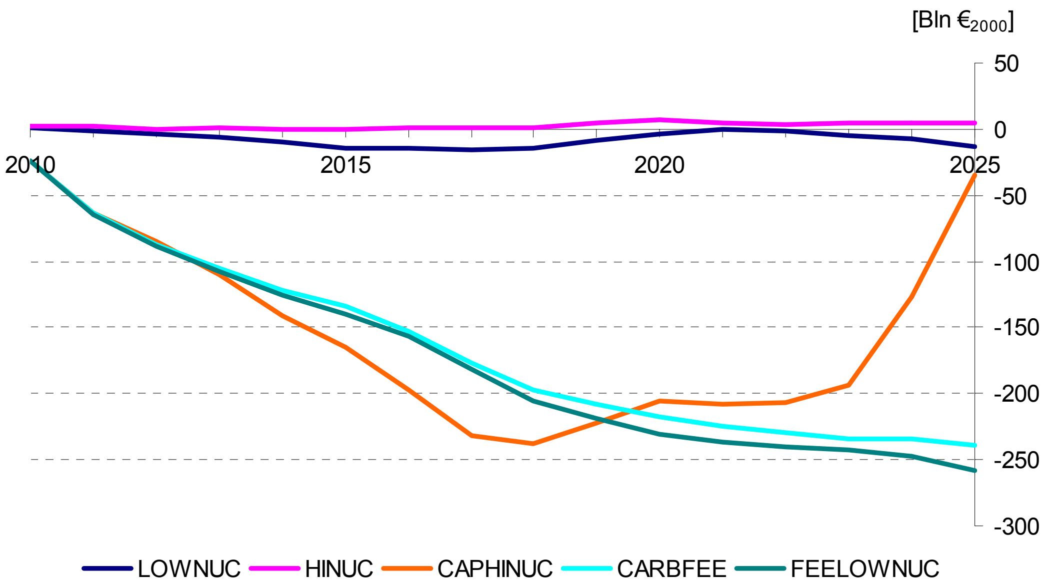


Figure 5.6 *GDP Change From Reference*
Sources: Energy Information Administration. AEO2005 Reference case: AEO2005.D102004A; CARBFEE: CARFEE05.D042605A; LOWNUC: AEOLONUC.D110204A; FEELOWNUC: CARNONUC.D042505A; HINUC: AEOHINUC.D042105A; CAPHINUC: CARCAP05.D052505A.

On a net present value (NPV) basis, using a real discount rate of 5% and discounting back to year 2010, GDP losses are far more substantial in the carbon constrained cases, as shown in Figure 5.7. Over the 15-year period from 2010-2025, the FEELOWNUC case has the highest GDP losses relative to the Reference case (€ 1.79 trillion) while the CAPHINUC has the lowest losses (€ 1.66 trillion). Note that the losses would have appeared to be lower had they been discounted back to year 2005 but it seemed more reasonable to show losses in the year the carbon policies begin.

Fossil Fuel Consumption. Fossil fuel consumption, and energy demand in general, are significantly affected by carbon dioxide emission fees and carbon dioxide emission constraints. Figure 5.1 shows primary energy consumption, including all fuels for years 2020 and 2025 while Figure 5.8 shows the aggregate fossil fuel consumption in 2025 for the main carbon constrained cases. Fossil fuel consumption levels in the CARBFEE, the FEELOWNUC, and the CAPHINUC in 2025 differ in fuels used and the generation capacity added and used for electricity generation. When new nuclear capacity expansion is permitted and the costs and regulatory environment are characterized by the reference case assumptions (CARBFEE), all low carbon and no carbon emitting technologies penetrate the U.S. energy market in the process of responding to the carbon dioxide prices, including IGCC and NGCC with sequestration as well as advanced nuclear and renewable generation technologies. When nuclear contributions are constrained to be below the Reference case (the FEELOWNUC cases), all of the remaining technologies are projected to increase their contributions when faced with carbon price or carbon constraint. In the FEELOWNUC case, IGGC *with sequestration* makes the largest contribution in making up for the absence of the nuclear technology relative to the CARBFEE case and hence coal consumption (and fossil fuel consumption) is highest in the FEELOWNUC case. When the nuclear capital costs are reduced by 25% and the carbon constraint is imposed (the CAPHINUC case), the nuclear technology is projected to displace almost all of the sequestration technologies in the CARBFEE case and greatly reduce the use of coal and fossil fuel generation technologies.

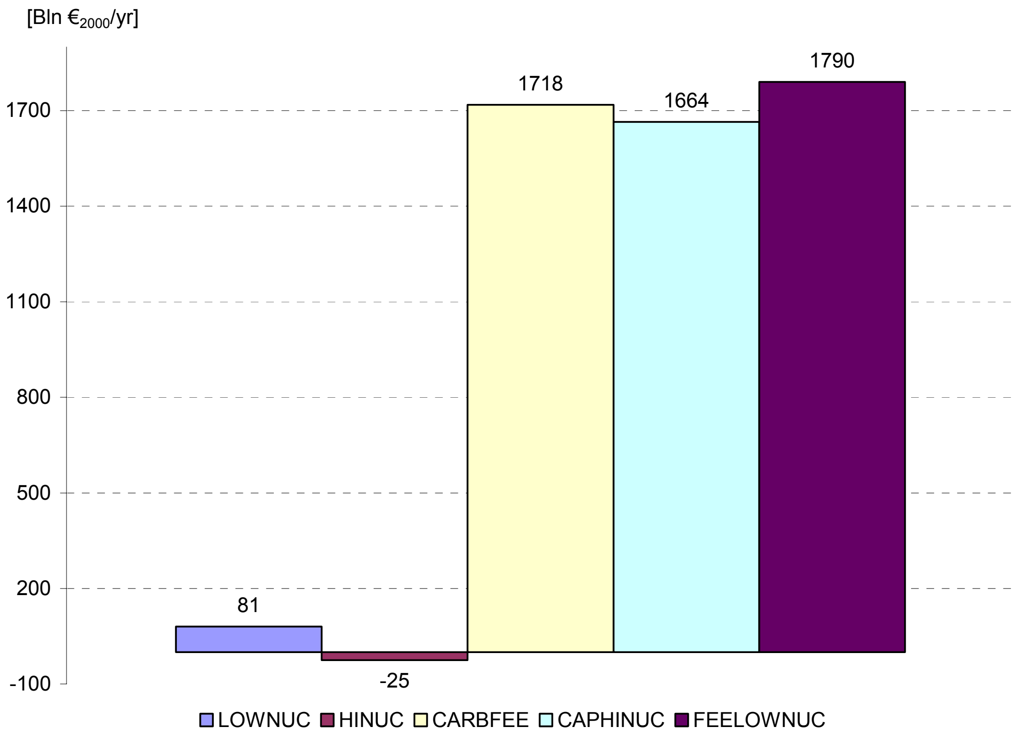


Figure 5.7 *NPV of GDP Losses, 2010-2025 (5% discount rate, discounted to 2010)*

Sources: Energy Information Administration. AEO2005 Reference case: AEO2005.D102004A; CARBFEE: CARFEE05.D042605A; LOWNUC: AEOLONUC.D110204A; FEELOWNUC: CARNONUC.D042505A; HINUC: AEOHINUC.D042105A; CAPHINUC: CARCAP05.D052505A.

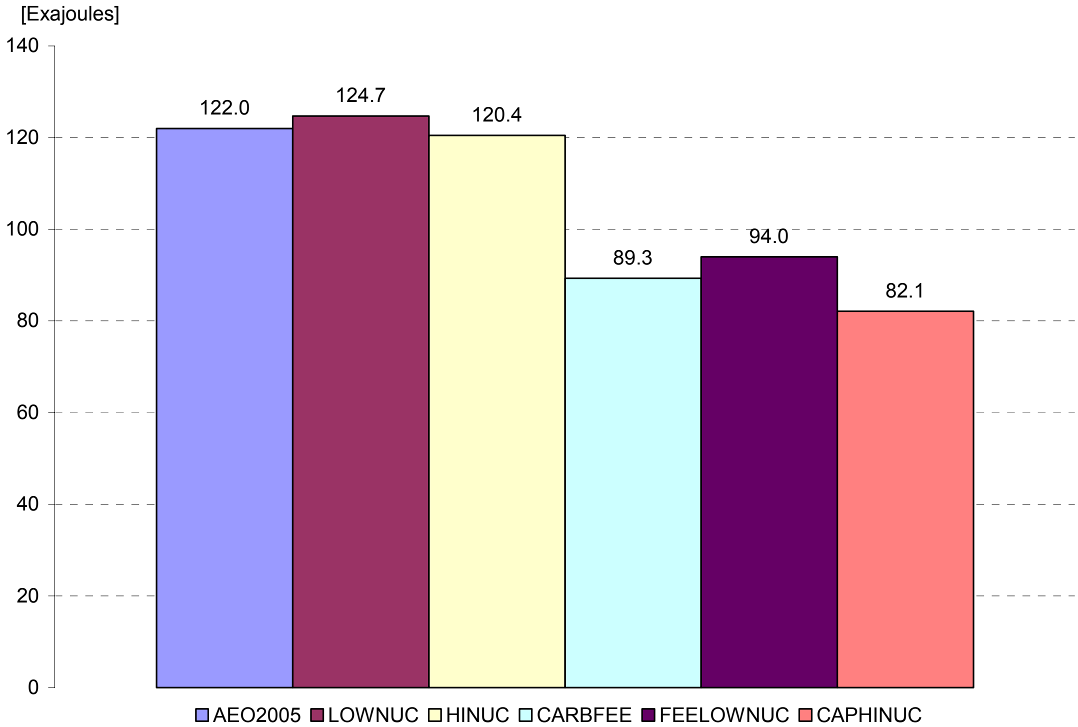


Figure 5.8 *Projected U.S. Fossil Fuel Consumption in 2025*
Sources: Energy Information Administration. AEO2005 Reference case: AEO2005.D102004A; CARBFEE: CARFEE05.D042605A; LOWNUC: AEOLONUC.D110204A; FEELOWNUC: CARNONUC.D042505A; HINUC: AEOHINUC.D042105A; CAPHINUC: CARCAP05.D052505A.

Fuel Mix Changes. In the CARBFEE case, advanced integrated coal gasification combined cycle (IGCC) *with sequestration* and advanced gas combined cycle (NGCC) *with sequestration* are projected to significantly penetrate the market by 2025, to about 110 GW for IGCC with sequestration and 45 GW for NGCC in the CARBFEE case. About 44 GW of new nuclear capacity is also projected to be added in the CARBFEE case. With the same carbon price path and no new nuclear capacity additions permitted and no relicensing of existing nuclear allowed (FEELOWNUC case), over 200 GW of new IGCC capacity *with sequestration* and 49 GW of NGCC *with sequestration* are added. Figure 5.9 illustrates electricity generation capacity additions by fuel in 2025 in the main cases and Figure 5.10 highlights the generation by nuclear in each of the six cases. It should be noted that the feasibility of geologically sequestering CO_2 from 250 to 300 GW worth of fossil fuelled generation has not been rigorously evaluated for the United States and may not be feasible by 2025. When the lower capital costs of the HINUC case are assumed, only 2 GW of IGCC *with sequestration* and 1 GW of NGCC with sequestration become economic because new nuclear capacity additions are more economic and nuclear capacity increases by 258 GW relative to the Reference case. See Figure 5.11 for an illustration of levelised costs of generation in 2025. Note that the levelised costs for the fossil technologies shown are the versions without sequestration, so in the CAPHINUC case the fuel component includes the full carbon price based on no sequestration. In this case, the ability of the nuclear industry to ramp up its manufacturing quickly enough to meet the projected demand for advanced nuclear capacity in the carbon-constrained CAPHINUC case is highly uncertain.

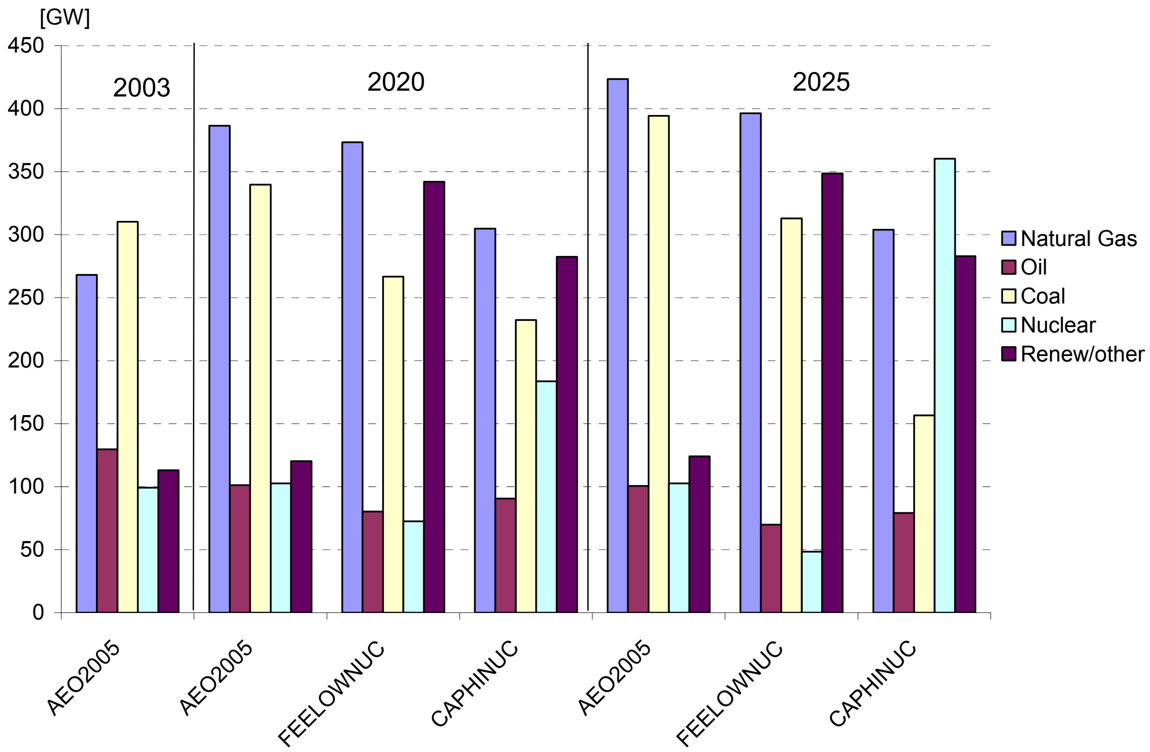


Figure 5.9 *Projected U.S. Electricity Capacity by Fuel*
Sources: Energy Information Administration. AEO2005 Reference case: AEO2005.D102004A; CARBFEE: CARFEE05.D042605A; LOWNUC: AEOLONUC.D110204A; FEELOWNUC: CARNONUC.D042505A; HINUC: AEOHINUC.D042105A; CAPHINUC: CARCAP05.D052505A.

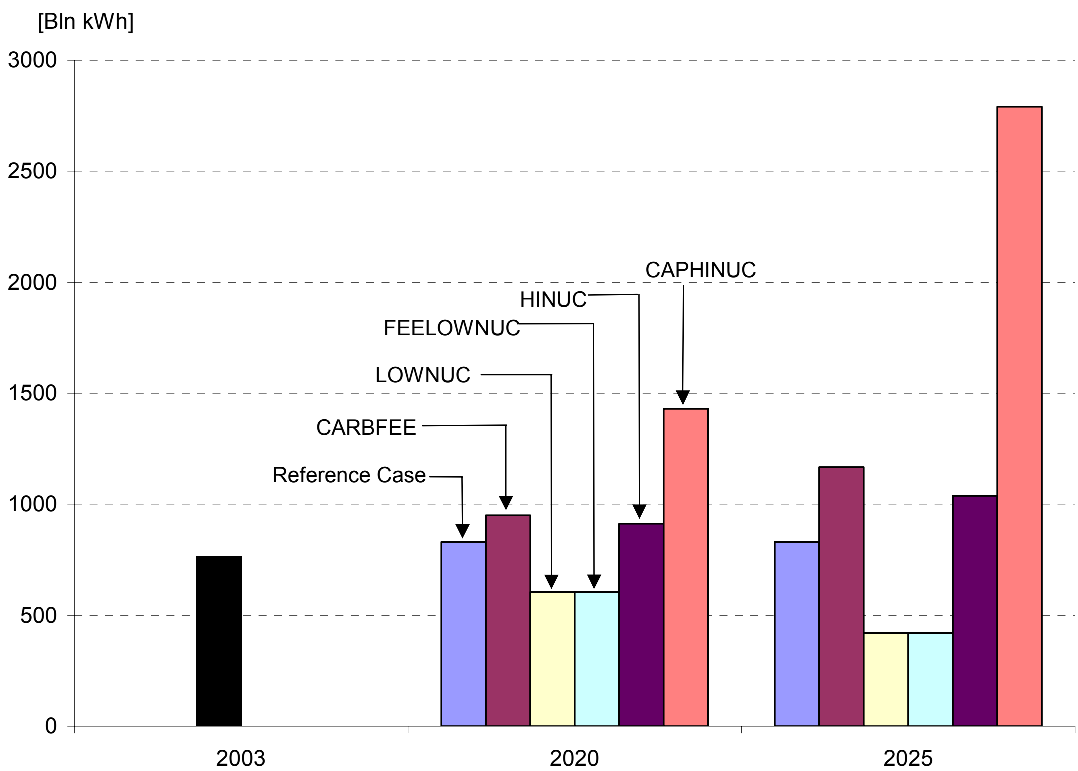


Figure 5.10 *Projected U.S. Electricity Generation from Nuclear*
Sources: Energy Information Administration. AEO2005 Reference case: AEO2005.D102004A; CARBFEE: CARFEE05.D042605A; LOWNUC: AEOLONUC.D110204A; FEELOWNUC: CARNONUC.D042505A; HINUC: AEOHINUC.D042105A; CAPHINUC: CARCAP05.D052505A.

Costs to the Power Industry. The vast majority of the costs of meeting carbon constraint requirements are primarily met by the power industry because it is the most price-responsive of all energy market segments in the U.S. economy. Important but often neglected measures of transition cost which is not directly reflected in the macro-economic impacts are 'resource costs' to the power sector which include capacity, transmission, retrofit, fixed O&M, non-fuel O&M, fuel costs, capital additions, purchased power, and any other credit costs. For the carbon dioxide emission constrained or carbon price cases (CARBFEE, CAPHINUC, and FEELOWNUC), the cumulative NPV resource costs for the 2010 to 2025 period, using a 5% discount rate discounted to 2010 are € 587 billion, € 288 billion, and € 725 billion respectively, all in euros of the year 2000. These costs are significant and indicate an additional, largely unaccounted for, economic impact on the U.S. economy other than GDP loss measures.

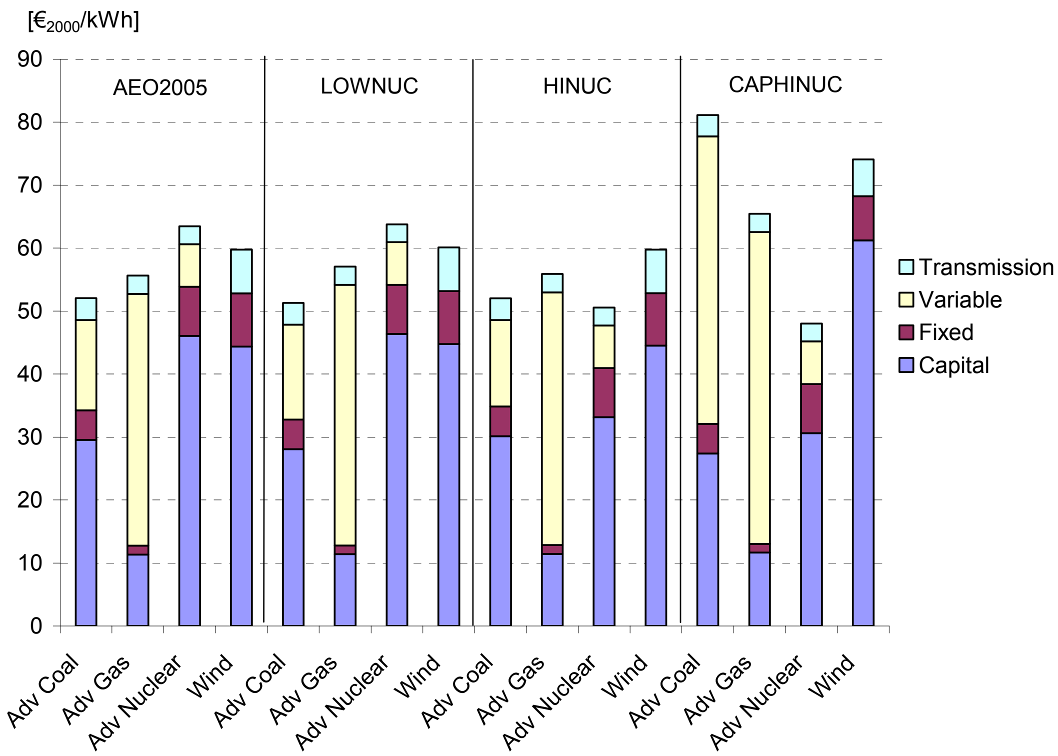


Figure 5.11 *Projected U.S. Levelised Costs of Electricity Generation By Plant Type, 2025*
Sources: Energy Information Administration. AEO2005 Reference case: AEO2005.D102004A; CARBFEE: CARFEE05.D042605A; LOWNUC: AEOLONUC.D110204A; FEELOWNUC: CARNONUC.D042505A; HINUC: AEOHINUC.D042105A; CAPHINUC: CARCAP05.D052505A.

Impacts on Carbon Emissions. All of the carbon cases reach approximately 1990 levels of energy-related carbon dioxide emissions by 2025 although the path is slightly different among the cases. The FEELOWNUC case has slightly higher carbon emission levels than the other two carbon emission cases.

5.1.4 Caveats and Conclusions of the Study

The results of the carbon dioxide emissions constraining or price cases imply a huge penetration of renewable resources, advanced nuclear and advanced sequestration technologies - some of which are not yet commercially available. The second issue derives from the speed with which an economy can change the mix of capital, labour, materials and energy without causing severe economic dislocations. The third is how quickly can industries such as the advanced nuclear industry, the wind generation industry, the biomass generation industry, and the carbon sequestration industry build up? What specifically is likely to limit market diffusion for each industry?

It seems unlikely that the U.S. nuclear power industry can build an additional 250 GW of new nuclear power starting in 2015 without having solved the nuclear waste disposal siting issue and without satisfactory resolution of public opposition to new nuclear power (the not in my back yard syndrome - NIMBY). The initial capacity expansion of advanced nuclear power in the United States is likely to be at a cautious and relatively measured pace while the public and the investors gain comfort with the safety and economic aspects of the technology.

For IGCC or NGCC with sequestration, three aspects of the technology are uncertain: the actual costs of generation and sequestration, the availability of sufficient volumes of depleted wells and other storage options to allow for long-term geologic sequestration, and the reliability of geologic sequestration for long-term storage of carbon dioxide.

For wood and biomass generation (e.g., wood and other biomass gasified in an IGCC-like technology), major engineering problems remain for the biomass-processing phase. Using dual processing trains at extra costs can solve the capacity factor problem. Moreover, like nuclear and IGCC with sequestration, can the industry build fast enough to add over 110 GW in a span of 10 to 12 years? Would an additional 110 GW of biomass generation capacity create competition for the land?

For the wind industry, the primary issue focuses on the adequacy of a suitable number of sites to reach the levels indicated in these cases and public acceptance of the technologies - the NIMBY syndrome.

The cases analysed for this study clearly indicate that for the United States, the policy imposition of the carbon dioxide targets or constraints assumed in this study will impose significant costs on the U.S. economy and the power sector. Nevertheless, those costs could be higher if the nuclear power generation option were limited. Without the nuclear option, capacity additions between 2010 through 2025 for biomass generation would have to reach 110 GW, wind additions would have to exceed 100 GW, geothermal generation capacity would have to rise to 10 GW, solar technologies might have to be used and energy demand would have to decline below the CARBFEE case.

5.2 MAPLE-C (Canada)[27]

5.2.1 Introduction

Canada has about 16,000 MW of nuclear capacity; all but 1,200 MW is located in Ontario. All generating units use the CANDU heavy water reactor. In 2000, nuclear generation accounts for about 13% of Canadian electricity supply, but 40% in Ontario.

Note that no new large hydro plants were included in the baseline, nor the phase-out case.

In 1997, 4,500 MW was taken off-line; some 2,100 MW of that capacity was returned to service in 2003. In the baseline case it is assumed that all units return to service by 2012. Each refurbished unit was assumed to cost C$1 billion (€ 625 million). Decommissioning costs are required to be accrued through the operating life the plant and are recovered through electricity prices, hence are not included.

[27] These results are based on key assumptions developed by the Cascade-Mints project team. The results do not necessarily reflect the views of the Government of Canada.

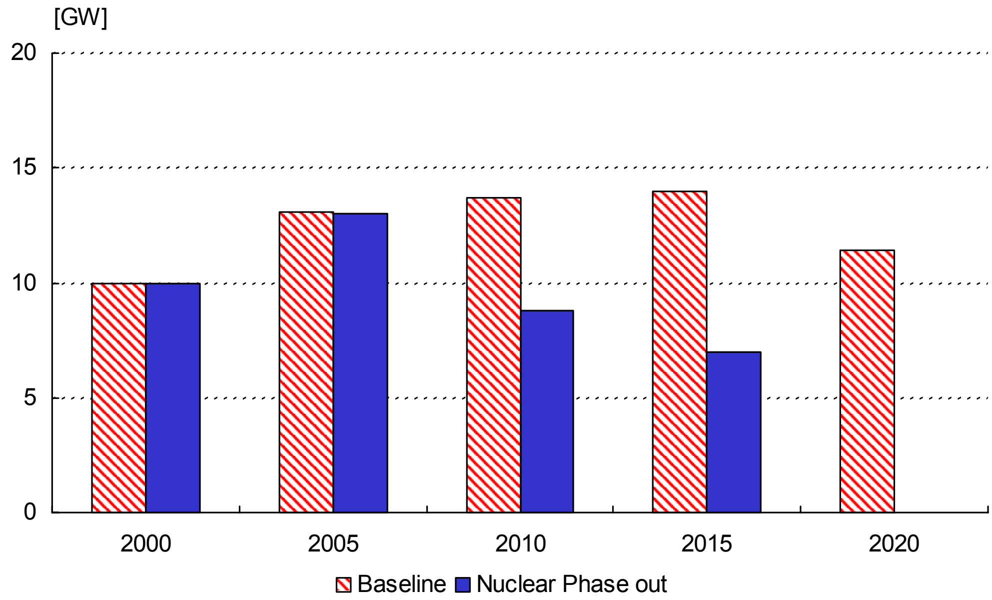


Figure 5.12 *Nuclear capacity*

For the phase-out case, it was assumed that the units currently not in service do not return and that the other units retire on their scheduled retirement dates. Retirements start in 2008 and all units will be retired by 2018. Figure 5.12 shows the capacity trend over time.

The breakthrough case presented some difficulties. Atomic Energy Canada Limited, the sole provider of nuclear generation in Canada has a new design, CANDU NG, which is estimated to have a capital cost that is 30% lower than the current technology. However, none have been built, causing some uncertainty with the real cost of the first units. Moreover, with the aggressive nuclear refurbishing program in the baseline, the relatively low cost of coal, even with a carbon cost and the long lead-time for new nuclear construction, at least 10 years, the generation mix in the breakthrough case would be virtually the same as the baseline to 2020. Therefore, this analysis will focus on the nuclear phase-out and the baseline.

5.2.2 Results

This analysis did not precisely follow the Cascade-Mints baseline in that the carbon value (10 €/tonne) CO_2 was not used in the baseline, or the nuclear phase-out case. The effect of this is negligible, since that value of carbon is not sufficient for a change to the electricity generation mix. The potential impacts of the carbon value of € 10/€ 50/€ 100, although not analysed are discussed in a qualitative manner in the conclusions (Section 5.2.4).

As noted above these results will compare the baseline to the nuclear phase-out case. The MAPLE model carries out simulations to 2020; therefore key comparisons will be made for 2010 and 2020.

Effects on the primary energy consumption

In 2010 primary energy in the phase-out case is about 100 PJ (1%) less than the baseline (Figure 5.13). By 2020, it is about 500 PJ less (4%). Final energy demand also declines moderately, and nearly all of the decline is attributable to electricity.

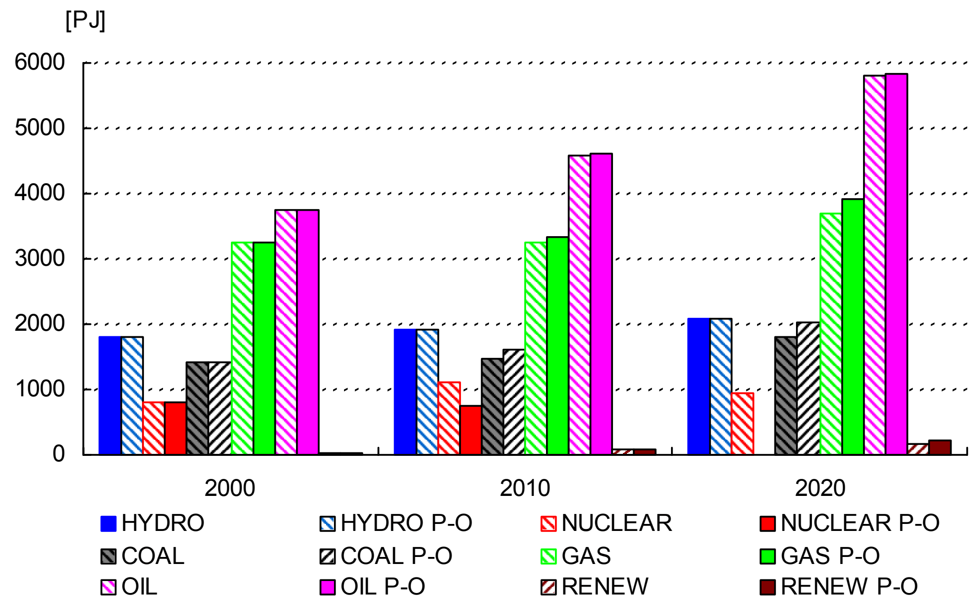


Figure 5.13 *Primary demand by fuel*

Effects on the fuel mix used in electricity generation, impact on renewables
As the nuclear plants are phased out coal and gas make up the difference in about equal shares up to 2010, generally using existing capacity at a higher rate. By 2020 some 4000 MW of new coal and 3000 MW of new gas capacity is added relative to the baseline (Figure 5.14). Note that hydro capacity is held constant by assumption. Other renewables, such as wind increase by almost 500% in 2010 and 40% in 2020, relative to the baseline; however the quantities are small, less than 2% of total capacity.

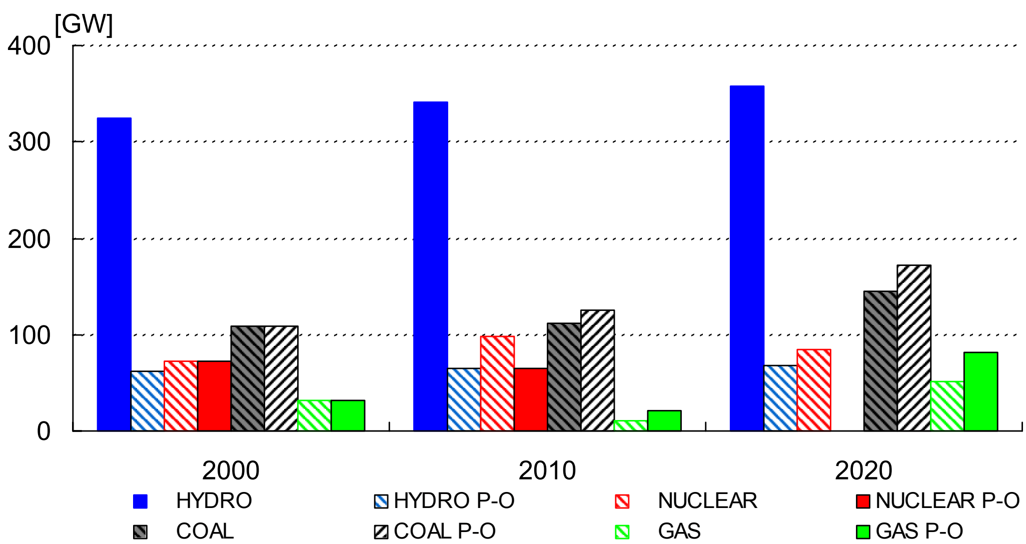


Figure 5.14 *Electricity generation by fuel*

Effects on the fuel, electricity prices
Since most of the phase-out of capacity occurs in Ontario, the prices in that province will be examined. Note that electricity prices vary considerably across Canada depending on the fuel used for generation. End use electricity prices increase about 5% in the industrial sector, as the marginal cost of new coal-fired electricity is more than the cost of the refurbished nuclear plant (Figure 5.15). The natural gas price, in the nuclear phase-out case, is virtually unchanged, since increased demand would be supplied by reducing exports, rather than increasing production.

Coal prices increase about 5% in Ontario, but are not affected in other regions, since this coal is imported from the US.

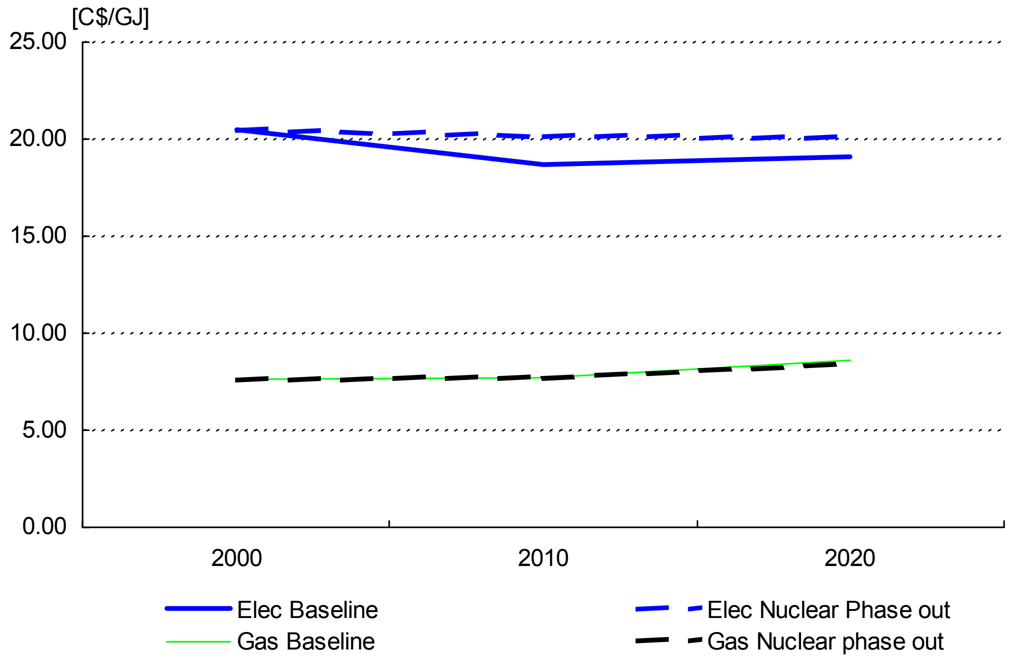


Figure 5.15 *Natural gas & electricity prices*

5.2.3 Consequences of a nuclear phase-out

Effects on the security of supply indicators

Canada is a net exporter of energy, so there is no impact on the security of supply. However, imported coal plays a larger role in the replacement generation in Ontario. Coal imports from the US are assumed to continue. Should this not be the case, there are many alternatives for coal imports, or even domestic supply.

Changes in carbon emissions

Emissions from the power sector increase by 15 Mt CO_2 in 2010 and by 22 Mt in 2020 as the nuclear generation is replaced by coal and gas fired generation (Figure 5.16). Other emissions are virtually unaffected.

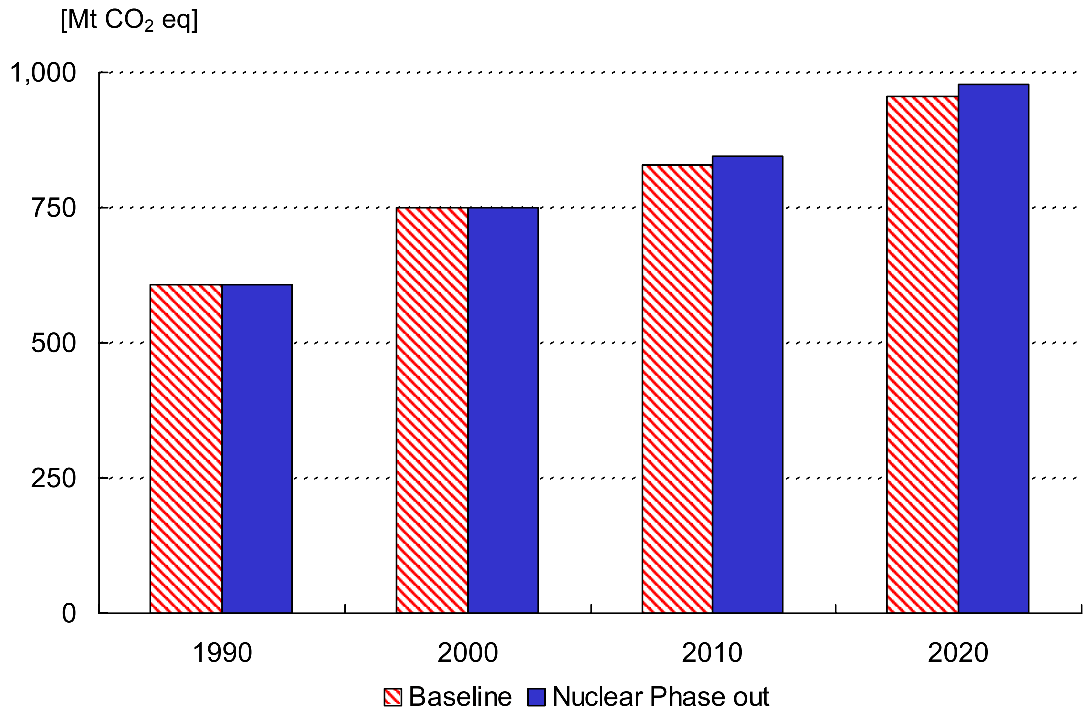


Figure 5.16 *Total GHG emissions*

Macro economic impacts
The effects on GDP and employment in Canada are too small to measure

Impact of either case on proliferation, international security and waste management
There would be no impact beyond the baseline.

5.2.4 Conclusions and recommendations

Canada ratified the Kyoto Protocol in 2002, and its target in the first commitment period must average 571 Mt per year. In this baseline, the level GHG emission reductions would be over 250 Mt. As the nuclear phase-out case indicates an increase in emissions, Canada's level of effort would increase accordingly, with not inconsequential costs to its economy. Therefore, the success of the refurbishment is of prime importance.

Had the higher carbon values been implemented, it is likely that the coal-fired generation projected in the phase-out case would be largely replaced by natural gas. This change would have the effect of increasing the GHG emissions in 2010 by about 8 Mt, instead of the 15 Mt indicated above. Additionally, it may be expected that electricity prices would rise substantially, perhaps as much 20%, with some consequences for lower energy demand. It is this authors view that combining the high carbon value with nuclear phase-out could mask some of the effects of a no-nuclear policy.

6. World models

6.1 GMM

6.1.1 Introduction

Main objective of this modelling exercise was to provide the long-term insights in the role that nuclear power can play in achieving post-Kyoto GHG reduction targets. A set of four policy-scenarios has been analysed in order to assess impacts of a strict phase-out of nuclear generation capacities and contrasted with scenarios allowing for a nuclear technology breakthrough under a specific carbon tax regime. The set-up of scenarios under examination in this report is summarized in Table 6.1.

Table 6.1 *Scenarios description*

Scenario	Carbon constraint/tax	Technology assumptions
Baseline	OOECD region applies carbon value 10 €/tCO_2 in 2010-2050	See Table 6.2
Baseline/ Breakthrough	OOECD region applies carbon value 10 €/tCO_2 in 2010-2050	Capital cost of nuclear systems in all regions reduced by 25% between 2010-2020
Carbon value	OOECD and EEFSU regions apply a carbon value of 10 €/tCO_2 (2010), 50€/t CO_2 (2020), 100 €/t CO_2 (2030-2050); NAME, ASIA and LAFM regions apply a carbon value of 50 €/t CO_2 (2020), and 100 €/t CO_2 (2030-2050)	The same as in Baseline
Carbon value/ Breakthrough	The same as above	Capital cost of nuclear systems in all regions reduced by 25% between 2010-2020
Carbon value/ Phase-out	The same as above	Nuclear capacity phase-out in OOECD, NAME & EEFSU regions (Annex B) according to Table 6.3. No new nuclear capacity in ASIA and LAFM allowed after 2020

There are two nuclear-power technologies implemented in GMM. The first one aggregates conventional nuclear power plants present in today's generating mix. The second technology represents a new generation of nuclear plants that are expected to enter the electricity market after 2010. New reactor designs anticipate increased safety standards, higher burn-up rates of nuclear fuel, shorter construction times, and an improved cost-competitiveness. Introduction of advanced nuclear reactors might lead to capital cost reductions due to accumulated experience during construction and operation of new reactor-units. Therefore, the advanced nuclear plants are defined in GMM as 'learning' technologies with rather conservative progress ratio of 96% in the Baseline, and of 94% in the Breakthrough cases in order to reach a 25% cost reduction by 2020. Cost- and performance-parameters of both generic nuclear power plants are presented in Table 6.2.

Table 6.2 *Specification of nuclear power technologies in GMM*

Technology *(generic)*	Start year	Life time[1]	Load factor (max.)		Efficiency (URN to ELC)[2]		Investment cost[3]	Fixed O&M cost	Variable O&M cost	Fuel cost	Progress ratio[4]
		[yr]	start	2050	start	2050	[$/kW]	[$/kW/yr]	[$/GJ]	$[\$/GJ]_{th}$	
Conventional nuclear plant	2000	30	0.80	0.90	0.327	0.327	1800	90	2.19	1	n.a.
Advanced nuclear plant	2010	30	0.85	0.90	0.345	0.345	1900	70	1.19	1	0.96 (0.94)

[1] Life-extension and decommissioning cost are not included.
[2] The fossil-fuel equivalent of 3 is used.
[3] 5% discount rate applied for both systems.
[4] A higher learning rate is used for nuclear breakthrough cases.

Nuclear technology phase-out scenario assumes an exogenous scheme of shutting down existing reactor-units for Annex B countries, forcing the full elimination of nuclear plants by 2050. For the non-Annex B countries, the phase-out scenario foresees completion of capacity units, which are presently under construction, and no new capacity investments are allowed for periods after 2010. The phasing out scheme applied in the GMM model run is shown in Table 6.3.

Table 6.3 *Nuclear phase-out path for world regions of GMM*

Year	2000	2010	2020	2030	2040	2050
Annex B			*Existing nuclear capacity [GW/yr]*			
OOECD	184.4	174.2	130.4	36.3	6.3	0.0
NAME	111.2	107.0	71.6	24.7	6.5	0.0
EEFSU	48.9	47.7	42.6	14.2	9.7	0.0
Non-Annex B			*New nuclear investment capacity [W/yr]*			
ASIA		13.7	0.0	0.0	0.0	0.0
LAFM		1.6	0.0	0.0	0.0	0.0

6.1.2 Results

Primary energy consumption

Imposition of carbon tax at the levels specified for this modelling exercise results in substantial shifts in consumption of primary energy carriers. A general observation for the two carbon-constrained scenarios is that global energy system reacts by a rapid reduction of fossil fuels use and this reduction is balanced by increased use in carbon-free carriers, i.e., nuclear, hydro and renewable energy. The contribution of nuclear energy in the nuclear breakthrough scenario increases over the Baseline by factor of 2.5 in 2050, and the renewables increase the contribution to the primary supply in 2050 by more than 60% as compared to the reference development. In the case of nuclear phase-out under carbon-tax regime, the reduction in fossil fuels demand is less pronounced and the demand for natural gas, especially for the power generation sector, increases over Baseline by 2030 in order to substitute for nuclear energy. The contribution of non-hydro renewables increases in 'the end of horizon' by a factor of 1.8. As shown in Figure 6.11, the 25% reduction in capital cost for nuclear plants results in increased nuclear energy consumption in the Baseline/Breakthrough scenario. The increase over Baseline is most pronounced in 2020 and continues with a lower pace until 2050, while the role of coal and hydropower is slightly lowered.

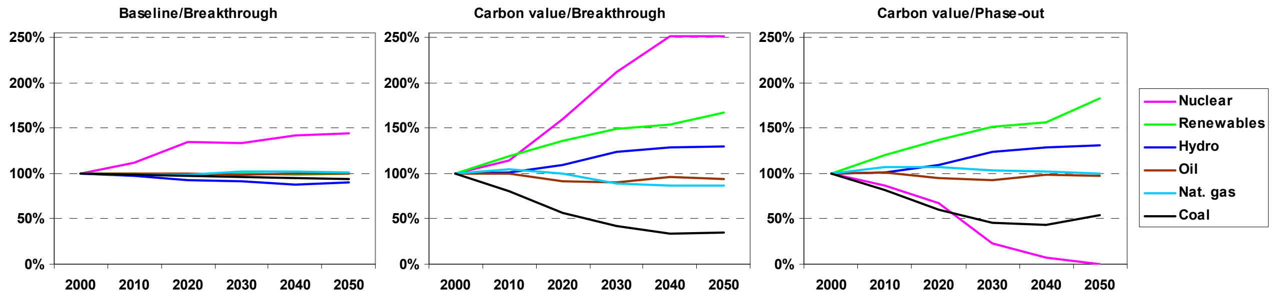


Figure 6.1 *Change in the global primary energy consumption relative to the Baseline*

The time evolution of global primary energy use shown in Figure 6.2 suggests that the carbon value of 100 €/tCO_2 applied from 2030 onward would cause an important demand reduction in primary fuels over the reference scenario, particularly in the use of coal. The total primary energy demand reduction is the highest in the nuclear phase-out case and accounts for 9% in 2050. On the other hand, the cost reduction of nuclear power in the Baseline/Breakthrough scenario implies 1% increase in the total primary energy demand in 2050 over the Baseline.

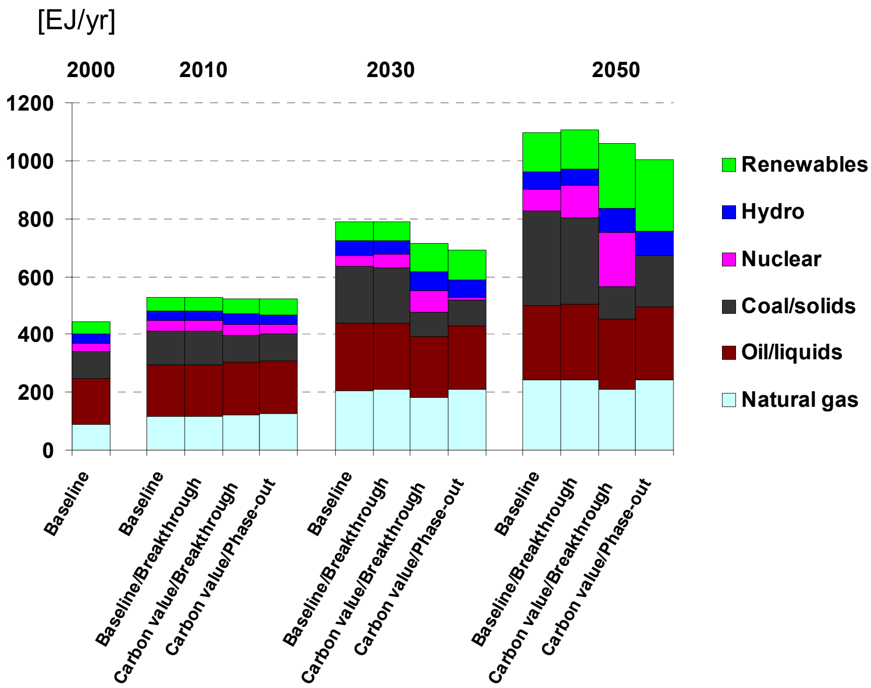


Figure 6.2 *Global primary-energy use for the Baseline and policy scenarios*

Electricity generation

As shown in Figure 6.3, adoption of the carbon constraint induces considerable changes to the electricity generation market regardless of the assumptions made on nuclear power. However, nuclear energy influences substantially the ways in which the power sector reacts to the carbon value imposed. A common trend is observed across the CO_2 value-scenarios as compared to the Baseline development: the amount of power generation based on fossil fuels combustion undergoes substantial reduction over the time horizon and is balanced by an increased contribution from advanced fossil systems with CO_2 capture and from carbon-free sources. The shift towards renewables and systems with CO_2 capture is most pronounced in the Carbon value/Phase-out scenario as this scenario excludes the nuclear power plants from the portfolio of carbon-abatement technologies. At the same time this scenario suggests the lowest reduction in fossil-based power generation due to an increased role of the NGCC plants. While both the Carbon value and Carbon value/Breakthrough scenarios allocate similar changes in fossil and renewable power production between 2010 and 2050, nuclear plants' cost reductions in the Carbon value/Breakthrough scenario increases significantly the contribution of nuclear energy over the whole time horizon and the power production from systems with CO_2 capture is proportionally lower as compared to the Carbon value scenario.

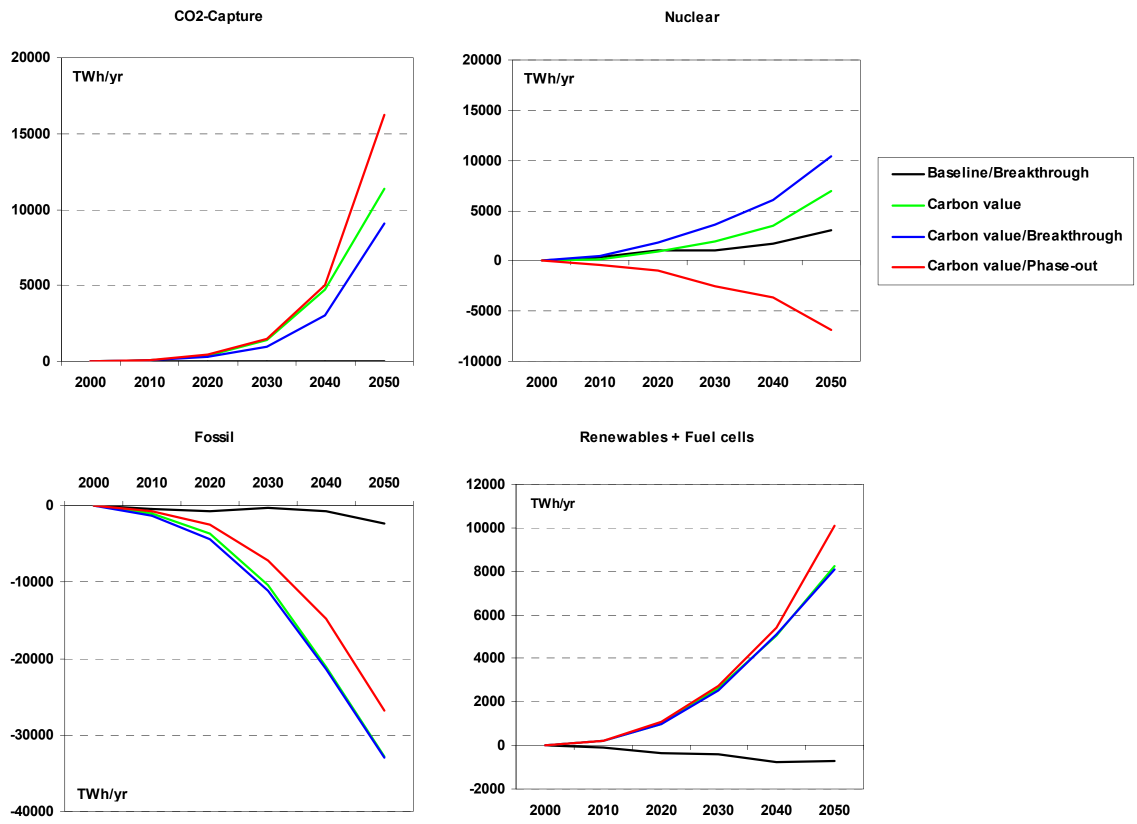


Figure 6.3 *Change in the global electricity generation over the Baseline for all scenarios*

Notes: Nuclear refers to conventional and advanced nuclear plants; Renewables + Fuel cells graph refers to the aggregated contribution from hydro power, wind, biomass, geothermal, solar electricity and all types of fuel cells; CO_2 capture aggregates coal and natural gas technologies equipped with carbon capture systems; Fossil comprises all generation sources based on combustion of coal, natural gas and oil without CO_2 capture.

Figure 6.4 illustrates the power generation mix in the year 2050 for the set of scenarios under examination in this case study. While the power generation in 'the end of horizon' for the Baseline scenario is dominated by conventional and advanced coal systems, natural gas combined cycle (NGCC) becomes the main source of electricity for carbon-constrained scenarios. The only coal-based systems that undergo substantial increase over the Baseline are the advanced coal plants with CO_2 capture and integrated coal gasification combined cycle (IGCC) with CO_2 capture. Penetration of these technologies is the highest in the Carbon value/Phase-out scenario, and the lowest in the Carbon value/Breakthrough scenario. The same observation is reported for the generation from the renewable sources. Generation from the Solar Photo Voltaic (SPV) and hydrogen fuel cells (FC) in the Carbon value/Phase-out scenario, however, increases remarkably over the development in other two carbon-constrained cases. Competitiveness of nuclear plants increases substantially under the carbon-tax regime, as well as in the Baseline/Breakthrough scenario. In the Carbon value/Breakthrough scenario, the conventional and advanced nuclear power plants contributes by almost one third to the total electricity production in 2050.

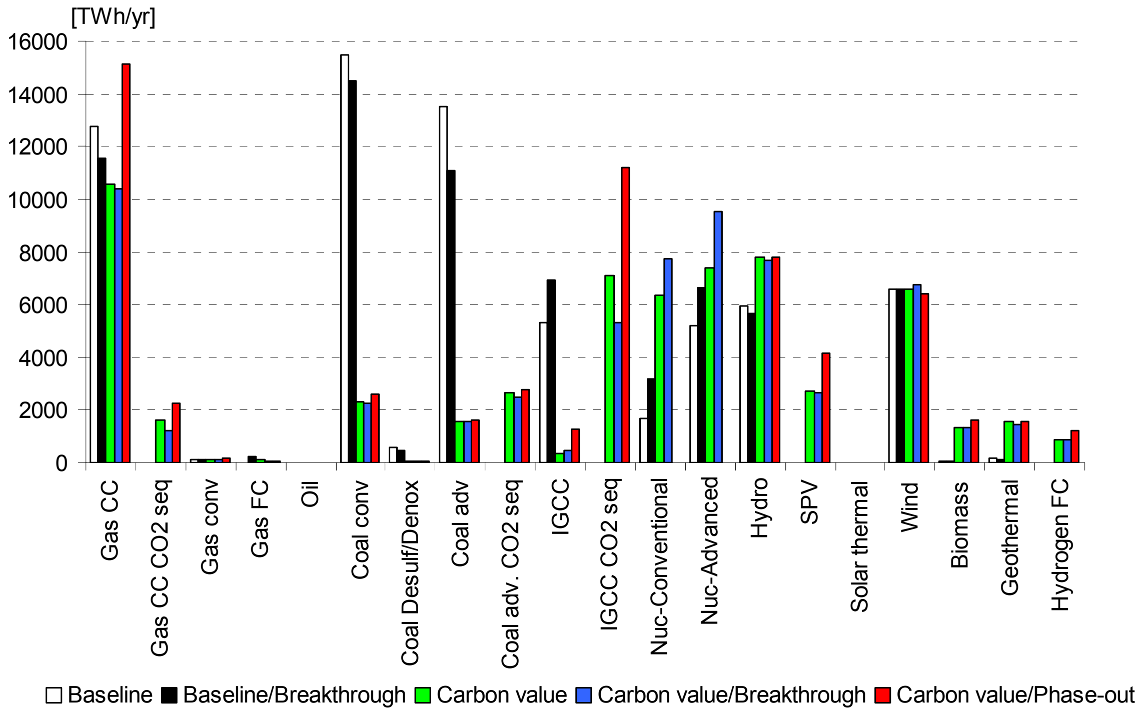


Figure 6.4 *Contribution of technologies to the global electricity generation mix in 2050*

Nuclear power provides presently about 17% of worldwide electricity and this share is projected to decrease by 2050 to 10% in the Baseline. Capital cost reductions of nuclear reactors anticipated in the Baseline/Breakthrough scenario results in nuclear-power penetration that is by 44% higher than in the Baseline by the end time horizon. As shown in Figure 6.5, under the carbon mitigation constraint the fraction of nuclear electricity rises to 28% in the Carbon value/Breakthrough scenario in 2050, which represents a 65% increase over the today's level. Main bulk of increased nuclear-power production is attributed to the advanced nuclear systems that gradually replace conventional reactors.

In today's nuclear plants, 22 tonnes of uranium are typically needed to generate 1 TWh of electricity (UNDP, 2000). The cumulative nuclear-based electricity generation in 2000-2050 for the Carbon value/Breakthrough scenario corresponds to 451.5 PWh, which means that about 10 million tones of uranium are needed. UNDP (2000) reports the reasonably assured uranium reserves recoverable at less than 130 $/kg Uranium to be about 3.2 million tones. Additional uranium resources at extraction costs at less than 260 $/kg Uranium are estimated to be 5.1 million tones. Finally, speculative resources (i.e., without cost specification) might add about 12.1 million tonnes.

To avoid the potential threats of costly uranium supplies and the high costs of waste disposal, which may drive a closing of the fuel cycle, additional technology improvements are probably needed in terms of improved fuel burn-up rates in advanced reactors, implementation of plutonium/minor-actinide recycle to mitigate the waste-disposal problem, development of thorium reactors, or (eventually) a larger utilization of breeder reactors (to address both the resource and the waste problems). If the development of an improved nuclear fuel cycle performance does not take place, the results reported above might be unrealistic, since the high fuel-cycle costs of both reduced uranium resources, reprocessing (if required), and waste disposal will deteriorate the future competitiveness of nuclear energy. Unfortunately, the present version of GMM does not allow examination of the alternative nuclear fuel cycles.

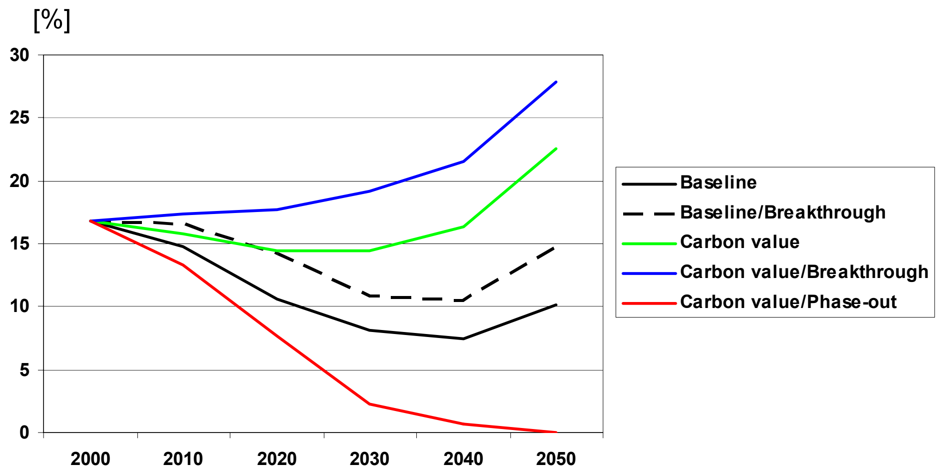


Figure 6.5 *Share of nuclear energy in the global electricity generation*

Figure 6.6 provides the time dependency of regionally distributed additions in the nuclear generation capacity over Baseline for the Baseline/Breakthrough scenario and for the Carbon value/Breakthrough scenario. In the first case, the largest increment in the nuclear capacity between 2010-2040 is reported for the ASIA region. In 2050, the highest capacity additions are projected for regions of NAME and EEFSU. Under the carbon-tax regime the installation of new capacities is substantially accelerated as the nuclear energy plays an important role in the carbon abatement. Increased nuclear-power production is further enforced by endogenous learning effects for advanced reactors and by exogenous capital cost reductions of the conventional nuclear plants. The NAME and OOECD regions contribute by more than two thirds of the total capacity growth in 2050, followed by the EEFSU region. Nuclear capacity increases in the ASIA and LAFM appear at a smaller extend suggesting that other CO_2 mitigation options (e.g., CO_2 capture, renewables or demand cuts), prevail in these regions.

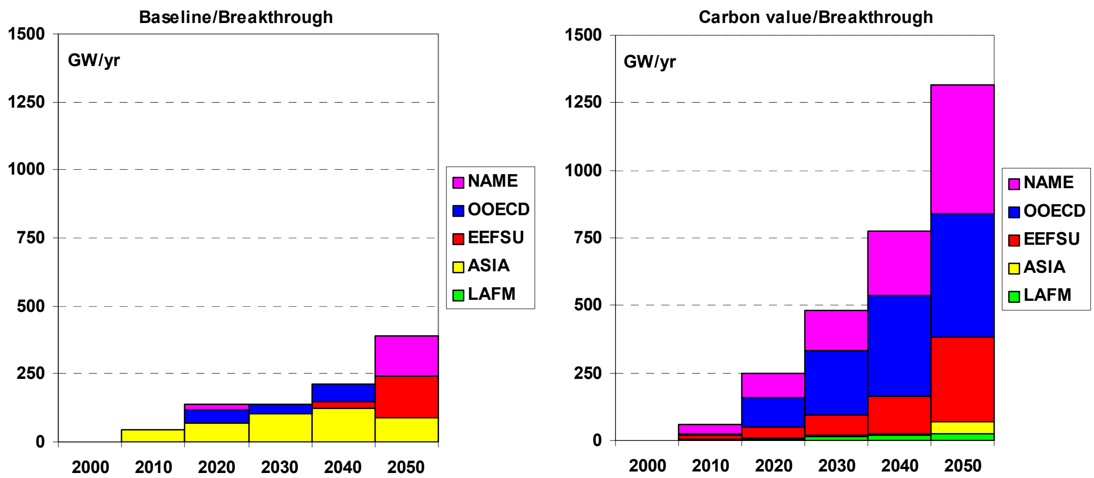


Figure 6.6 *Regional distribution of the additional nuclear electricity generation capacities relative to the Baseline scenario*

The growth in nuclear-power capacity reported for the Carbon value/Breakthrough scenario is approaching the market penetration limits specified by annual maximum growth-rate of 13% for advanced and 3% for conventional plants. The total new nuclear-capacity installations in the Carbon value/Breakthrough scenario within the period 2010-2050 represent 2.6 TW_e on the global level. This would mean on the average a construction of around 54 new units (of 1.2 GW capacity each) per year, between 2010-2050, i.e., about 1 new reactor every week somewhere in the world[28]. It must be remembered that the lifetime extension of operating plants to 50-60 years would reduce this huge capacity additions by around factor of two.

Final energy and electricity consumption

Imposition of the carbon tax as specified in this exercise implies important changes on the demand side of the reference energy system. The total final energy consumption decreases by 13% in 2030, and by around 10% in 2050 under the carbon constraint relative to the Baseline. The most affected are uses of fossil fuels, i.e., coal, oil and natural gas. Demand for electricity and heat is reduced as well relative to the reference case. On the other hand, the consumption of biomass, solar-thermal energy, hydrogen and alcohol-fuels increases considerably. Figure 6.7 shows that the level of demand reduction for electricity is higher in the Carbon value/Phase-out scenario. This is explained by the higher electricity costs in the case of elimination of nuclear power from the generation mix. Reduction of natural gas final use between 2040-2050 is due to increased gas consumption for the power generation dominated by NGCC systems.

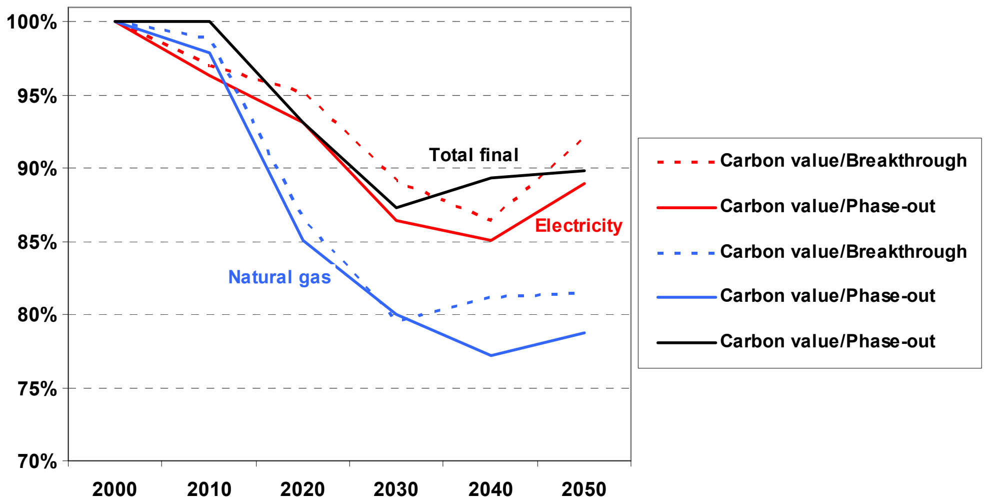


Figure 6.7 *Reductions in total final energy demand, and in global electricity and natural gas consumption over the Baseline for different carbon-constrained scenarios*

6.1.3 Consequences of a nuclear phase-out or breakthrough

Changes in carbon emissions

Change in the global CO_2 emissions relative to the Baseline for the Baseline/Breakthrough scenario and for scenarios applying carbon value is summarised in Figure 6.8. The energy-related CO_2 emissions are reduced by nearly 50% in 2050 in the scenario allowing for policies in favour of nuclear energy. Phasing-out of nuclear power under the carbon-tax regime results in 15% CO_2 emission growth in 'the end of horizon'. About 3.5% emissions drop over Baseline takes place in the Baseline/Breakthrough case, where the cost reduction of nuclear power leads to an increase in carbon-free electricity supplies.

[28] For comparison, the nuclear capacity construction rate during the early 1970s was rapid, average 30% capacity expansion per annum from 1970 to 1975 worldwide (McDonald, 2004). Past experiences in the capacity growth for the same period in the US show the average additions of about 10 reactor units per year. In 1974, which was the most active year in the US, 13 reactors were added to the grid.

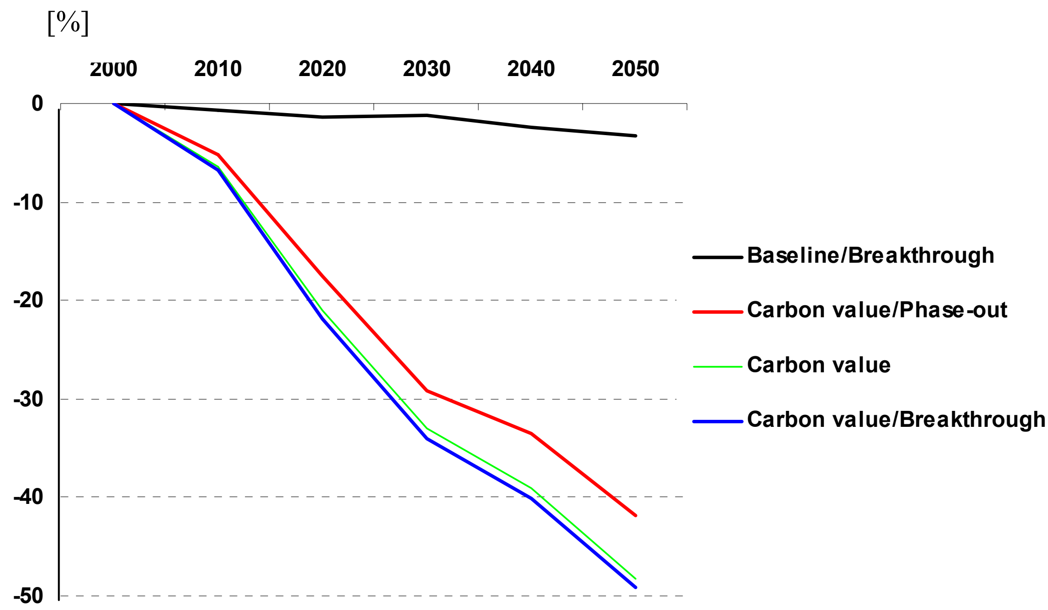


Figure 6.8 *Change in CO_2 emissions relative to the Baseline*

The importance of nuclear energy as compared to other options within the carbon mitigation strategy is illustrated in Figure 6.9, where a break down 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 Carbon value/Breakthrough scenario, the 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, as opposite to the Carbon value scenario where CO_2 capture prevails in 'the end of horizon'. Exclusion of nuclear energy from the portfolio of abatement options in the Carbon value/Phase-out scenario results in a rapid increase of the contribution of CO_2 capture (38% in 2050)[29]. 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 capital-intensive technologies, e.g., CO_2 capture or renewables, towards later decades.

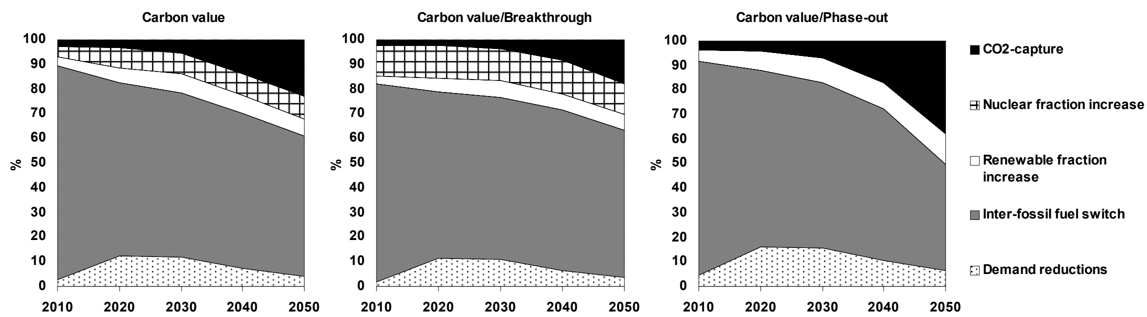


Figure 6.9 *Break-down of CO_2 reduction components*

Another implication of the large-scale utilisation of nuclear energy is the production of spent nuclear fuel and radioactive wastes containing long-lived isotopes. Table 6.4 provides rough estimates of the amount of spent fuel that would be produced under the levels of nuclear power

29 In the Phase-out scenario, the cumulative amount of CO_2 captured and stored in the period 2010-2050 is 36 GtC. This corresponds to about 13% of the global cumulative storage-potentials in depleted oil and gas fields estimated by IEA (2004).

generation projected for the Baseline, and for the scenarios Carbon value/Breakthrough and Carbon value/Phase-out. In addition, amounts of plutonium and minor actinides contained in the spent fuel are indicated for respective scenarios based on USDOE (2004) and Dones (2003). Reprocessing of spent fuel to recover Pu-239 for the MOX fuel production is not assumed in the calculations herein.

Table 6.4 *Estimates of cumulative production of nuclear spent fuel and other radioactive materials*

Cumulative production 2000-2050 (t)	Baseline	Carbon value/ Breakthrough	Carbon value/ Phase-out
Spent fuel	840,000	1,660,000	310,000
Plutonium	8,400	16,600	3,100
Actinides	1,027	2,032	378

Impacts on the total system costs

Changes in the total discounted energy-system cost invoked by an imposition of a stringent carbon constraint consist of two components: carbon tax revenues, and costs due to technology changes, i.e., fuel-switch, abatement technology investments or demand losses. Figure 6.10a indicates, that the total system cost under the carbon tax value of 100€/tCO_2 increases substantially and varies between 32-35% relative to the Baseline. About one fifth of this cost increase is attributed to the technology changes. The Carbon value/Breakthrough scenario emerges as the cheapest one among the cases with carbon constraint. The total cost rises by 9% less than in the scenario phasing-out the nuclear energy by 2050. Figure 6.10b illustrates the total system cost changes for the two nuclear technology breakthrough scenarios over the Baseline and over the CO_2 tax-regime reference, i.e., the Carbon value scenario. Reduction in capital cost of nuclear plants invokes a decrease in total system cost in both cases, while the reduction is more pronounced under the tax regime. At the same time, phasing out nuclear power under the carbon tax regime increases the total system cost by 1.6% over the reference Carbon value case.

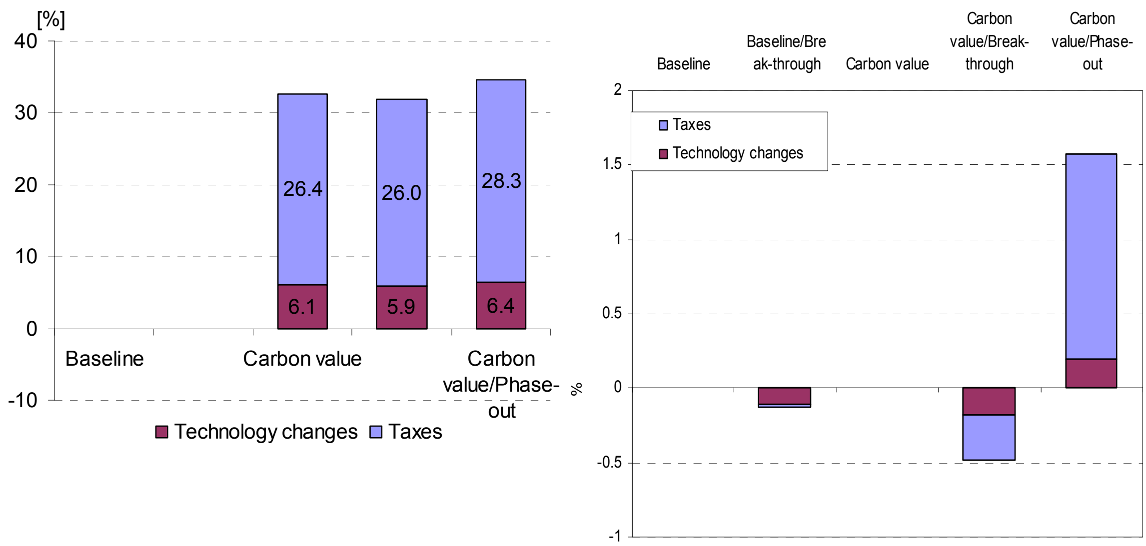


Figure 6.10*Left (a): Change in the total discounted system cost relative to the Baseline. Right (b): Change in the total discounted system cost relative to the Baseline and to the top of figure*

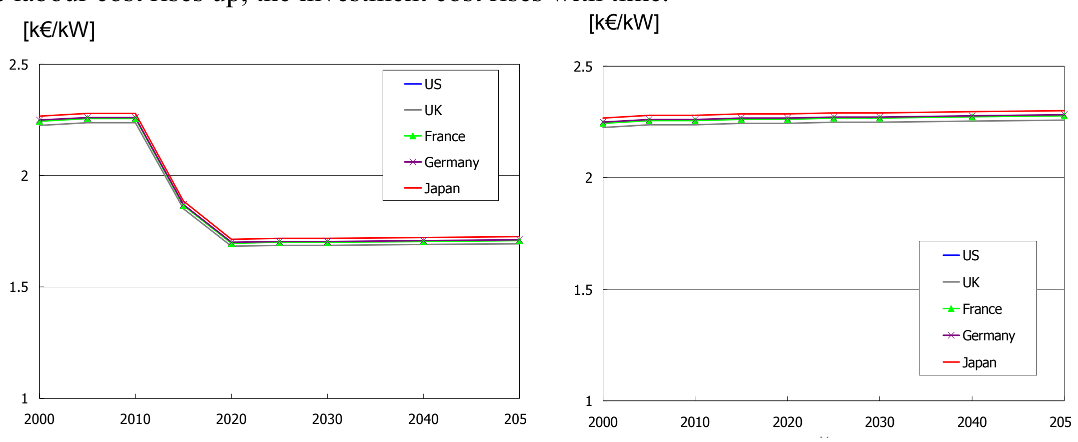
6.1.4 Conclusions and recommendations

- Utilization of nuclear energy is an important component of the portfolio of carbon mitigation strategies.
- The contribution of nuclear energy to reach CO_2 reduction targets is accelerated by policies in favour of cost and performance improvements of advanced nuclear reactors.
- The policies supporting nuclear power can postpone the need for investments in other competing capital-intensive, low-carbon technologies, e.g., CO_2 capture or renewables, towards later decades.
- The rate at which nuclear power can increase its market penetration has to be assessed carefully in order to avoid unrealistic projections of nuclear capacity additions.
- Substantial increase in nuclear energy use does not represent an acute threat from the cumulative uranium resources scarcity point of view for the time horizon of the analysis if the speculative resources are considered. However, the cost of nuclear fuel supplies might increase without improvements in technology used, particularly for costs related the 'back-end' of the nuclear fuel cycle.
- Technology improvements that can be foreseen in order to increase competitiveness of nuclear power comprise: higher burn-up rates of nuclear fuel, life time extension of existing and future reactor units, construction time reduction, utilisation of unconventional fissile materials, and advanced fuel cycles that deal with the growing waste problem(s).
- Co-Production of hydrogen and district-heat from nuclear energy, although not analysed explicitly in this study, could contribute to the longer-term sustainability goals.
- Additional obstacles that are associated with competitiveness of nuclear energy are the technology acceptance, spent fuel and radioactive waste disposal, proliferation, and risks of severe accidents. These aspects cannot be addressed by bottom-up energy models; however, they belong to factors that will determine the future position of nuclear technology in the global energy supplies.

6.2 DNE21+

6.2.1 Introduction

The following assumptions were set up for the nuclear case. Only a conventional type is treated in DNE21+ model. The lifetime is assumed 40 years. The variable cost is 24 €/MWh and common to all regions and time points. The investment cost depends on regions and time points. The cost data of some regions for the breakthrough case and other cases (the specific reference case and the phase-out case) are shown in Figure 6.11. In Figure 6.11(b), because it is assumed that the labour cost rises up, the investment cost rises with time.



(a) breakthrough case (b) other cases

Figure 6.11 *Investment costs of nuclear power plant (selected some regions)*

The maximum utilization rate of nuclear power plant is assumed to be 85%. The maximum share of nuclear electricity generation in total electricity generation is 50% for each region except for regions where the current share is above 50%, e.g., France.

The specific reference case, the phase-out case and the breakthrough case are calculated. Common scheme of carbon value (10-50-100 €/tCO_2 in 2010-2020-2030) is assumed for these cases. Furthermore, CO_2 emission path as in the phase-out case is applied as the upper limit of CO_2 emission for the breakthrough case.

DNE21+ model has a vintage structure and adopts the common lifetime of nuclear power plant. So, the nuclear power plant capacity in each time point does not exactly keep up with the given phase-out scenario, although the transition of that capacity that was obtained by model runs is similar to the given scenario.

6.2.2 Results

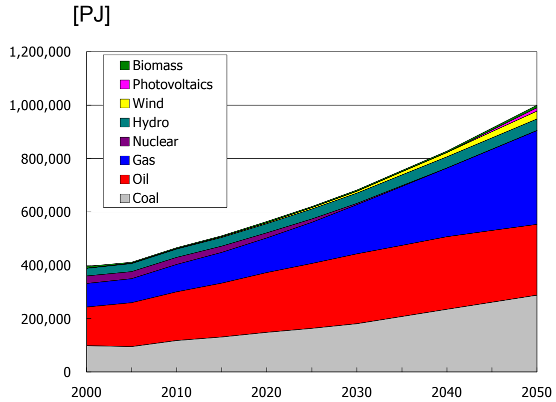
Primary energy consumption

The world primary energy consumption for each case is shown in Figure 6.12. Nuclear and renewables are expressed in primary equivalent by using conversion factor of 0.33. Compared with Base case, the increases in gas and renewables are achieved for the specific reference case by the imposition of the carbon value. In 2050, gas and renewables consumption amounts to 390 EJ and 293 EJ, respectively. Those increases relative to those for the base case are 41EJ (increase ratio: 12%) and 200EJ (increase ratio: 212%). On the other hand, the amount of nuclear for the specific reference case is relatively small and similar to that for the base case.

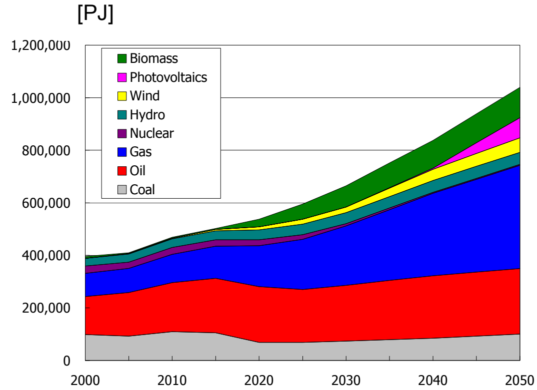
The world primary energy consumption for the phase-out case is very similar to that for the specific reference case. Because nuclear is also phased out for the specific reference case, a large change from the specific reference case does not occur for the phase-out case.

For the breakthrough case, the nuclear consumption is clearly larger than that for other cases. The amount of nuclear consumption is 147 EJ in 2050 and that increase relative to the specific reference case is 143 EJ. The achieved share in the total primary energy consumption is 14% in 2050. As a result, the decrease in other sources consumption relative to the specific reference case is shown. In 2050, the decreases in coal and oil are relatively large and those amounts are 335 EJ (decrease ratio: 33%) and 340EJ (decrease ratio: 14%), respectively.

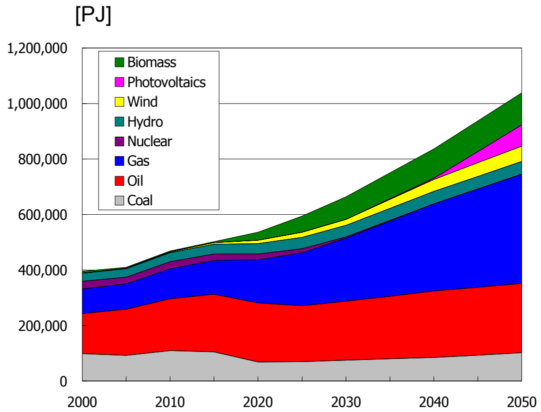
Figure 6.13 and Figure 6.14 show the primary energy consumption for EU-15 and EU-30, respectively. The consumption of gas and biomass particularly increases under the carbon value. The difference between the specific reference case and the phase-out case is very small and this feature is similar to that of the world total. For the breakthrough case, the amounts of nuclear for EU-15 and EU-30 are 8.2 EJ and 8.3 EJ, respectively. The nuclear consumption for other EU-15 countries in EU-30 is relatively smaller than that for EU-15. As a result, the achieved shares in the total primary energy consumption are 13% for EU-15 and 7% for EU-30 in 2050.



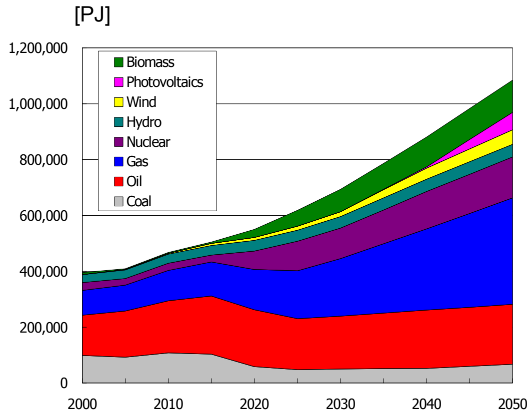
(a) Base case



(b) Specific Reference case

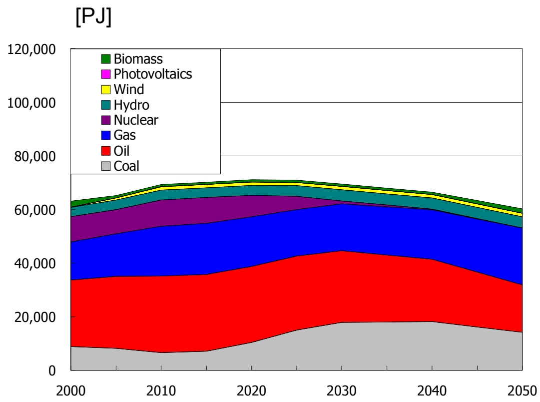


(c) Phase-out case

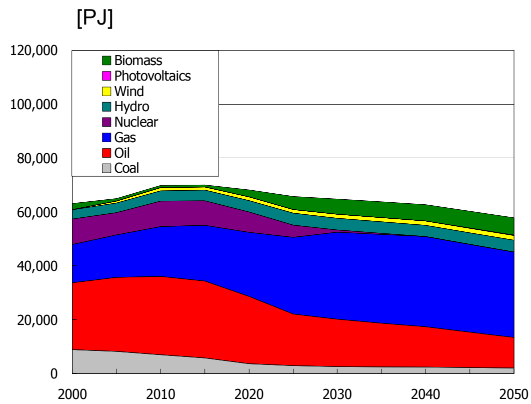


(d) Breakthrough case

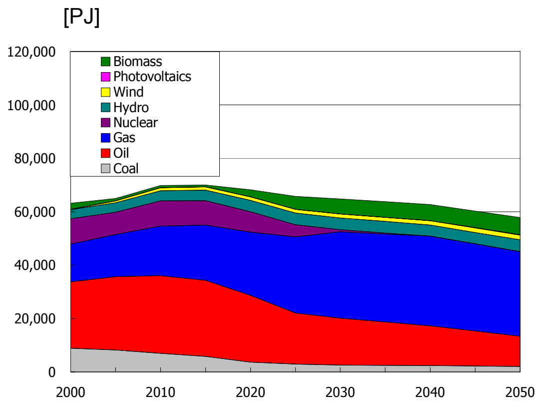
Figure 6.12 *Primary energy consumption (World total)*



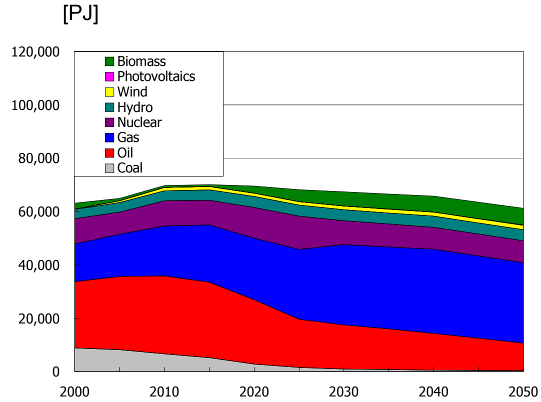
(a) Base case



(b) Specific Reference case

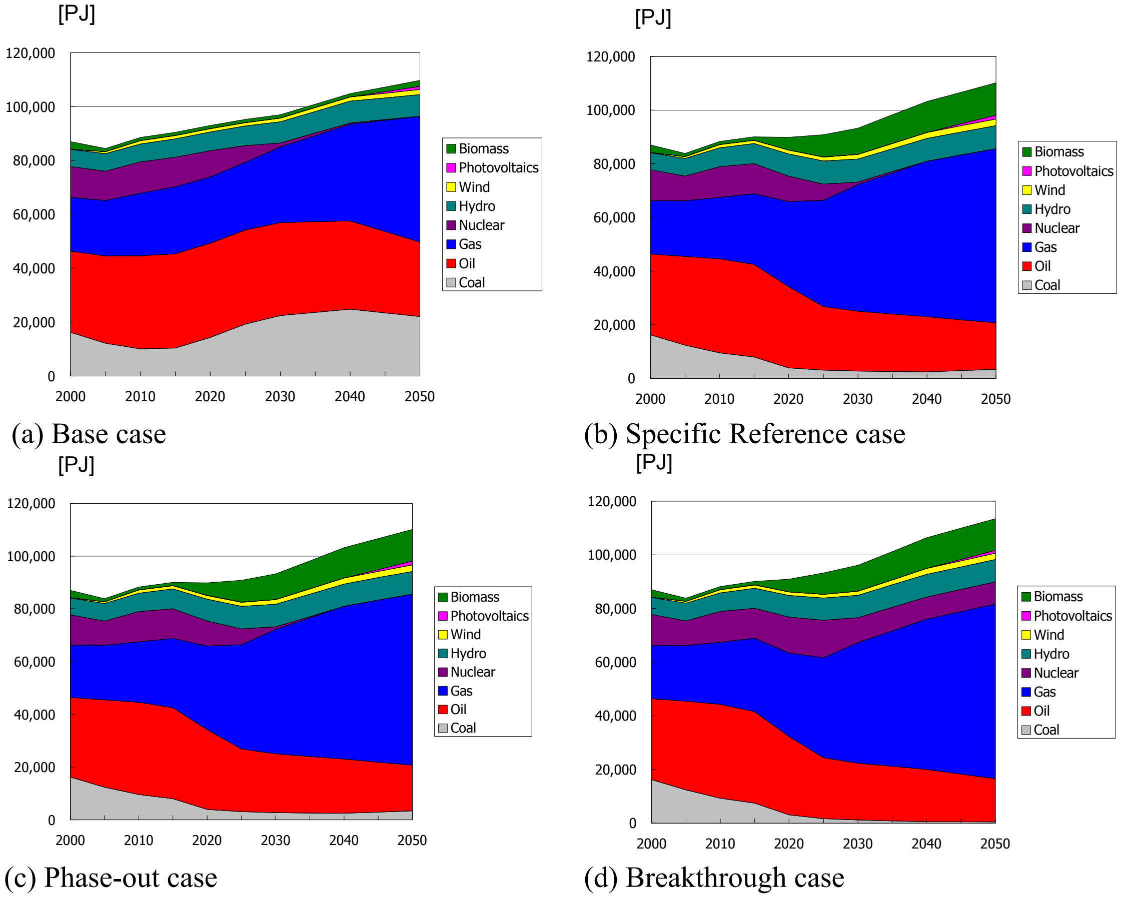


(c) Phase-out case



(d) Breakthrough case

Figure 6.13 *Primary energy consumption (EU-15)*



(a) Base case

(b) Specific Reference case

(c) Phase-out case

(d) Breakthrough case

Figure 6.14 *Primary energy consumption (EU-30)*

Figure 6.15 shows the increase in nuclear for the breakthrough case relative to the specific reference case by region. A large increase is shown in North America, China and other Asia. In 2050, the nuclear increases in those regions are 34 EJ, 31 EJ and 23 EJ, respectively. On the other hand, for the regions where there is no nuclear power plant in 2000, e.g. Oceania, the nuclear power is not introduced. It can be said that the nuclear cannot compete with other sources for these regions even in the breakthrough case.

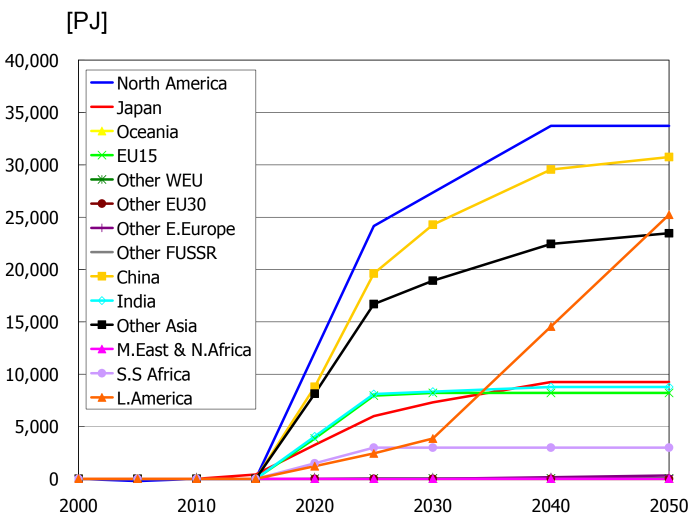


Figure 6.15 *Increase in nuclear by region (Breakthrough case - specific reference case)*

6.2.3 Consequences of a nuclear phase-out or breakthrough

CO_2 emissions

Figure 6.16 shows the net CO_2 emission of world for each case. The CO_2 emission is reduced from that for the base case after 2010 under the assumed carbon value. The amount of reduction is approximately 40 $GtCO_2$/Year in 2050. The phase-out of nuclear power does not affect CO_2 emission, because the difference in primary energy consumption between the specific reference case and the phase-out case is very small as mentioned in Section 6.2.2.

Figure 6.17 shows the CO_2 reduction by region. In 2050, relatively large reduction is shown in Latin America, North America and other Asia. Those amounts are 9.0, 6.4 and 4.4 $GtCO_2$/year, respectively. For the reduction ratio, that in Oceania is largest (99%) among the regions.

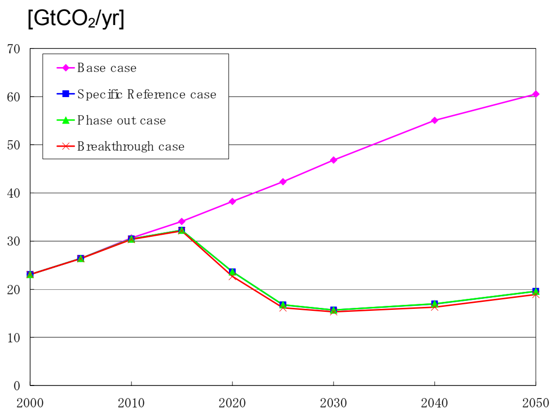
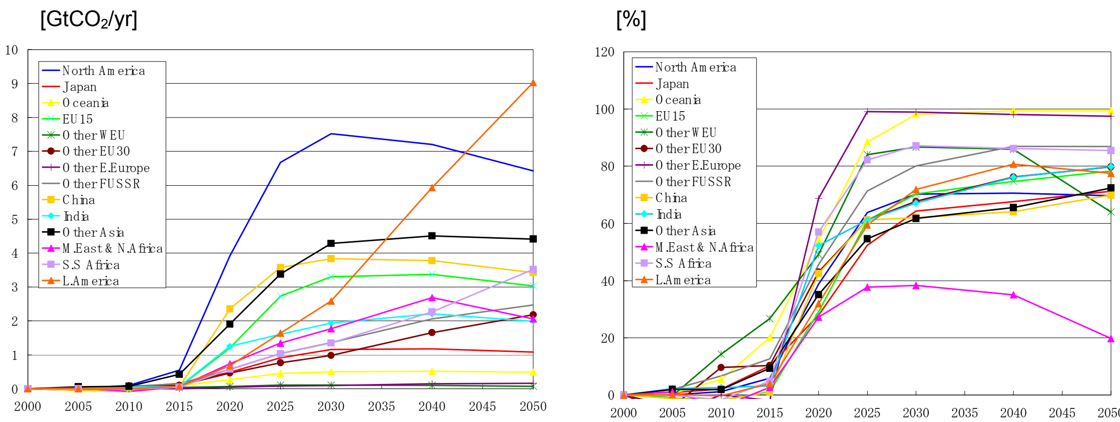


Figure 6.16 *Net CO_2 emission (World total)*



(a) Amount (b) Percentage

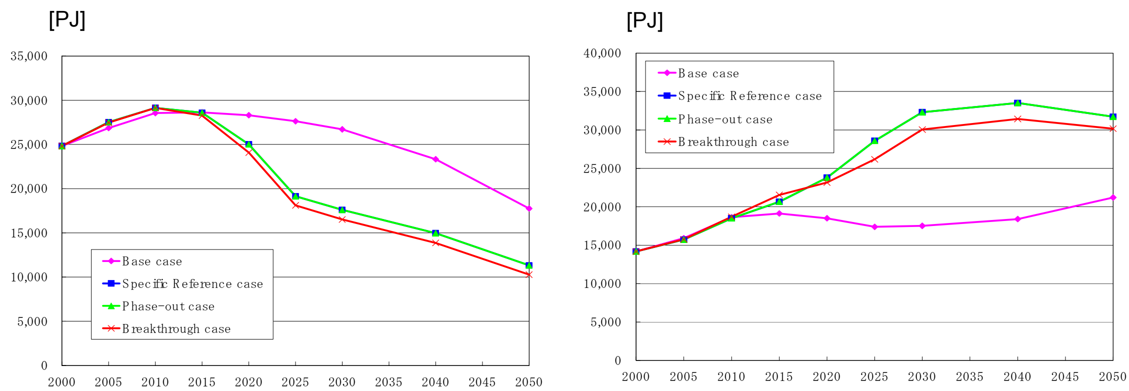
Figure 6.17 *CO_2 reduction by region (Base case - Specific reference case)*

Import dependency of EU-15

In this section, the import dependency of oil and gas of EU-15 is discussed. Figure 6.18 and Figure 6.19 show the primary energy consumption and production of oil and gas, respectively. For all the cases, oil consumption decreases after around 2015 and the decrease is accelerated for the three carbon value cases. The main reason for this acceleration is the diffusion of FCV (Fuel Cell Vehicle) and gas fuelled CHP for the three cases. FCV substitutes hydrogen for gasoline and the model run result indicates the hydrogen is produced from biomass. Light oil consumption for heating demand decreases due to the diffusion of gas fuelled CHP. The gas consumption for all the cases increases with time. The conspicuous trend of the increase is observed especially for the specific reference case and the phase-out case.

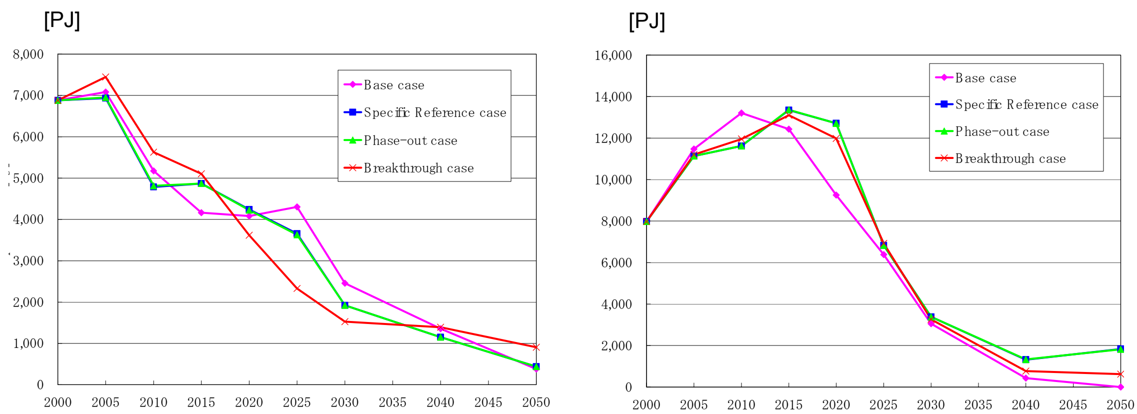
In Figure 6.19, the oil production decreases with time and the decrease ratio relative to the amount in the year 2000 is much larger than that of the oil consumption. The difference in the time-series trend among the cases is not clear. For the total production of 50 years, that for the base case is largest and that it is about 104% relative to that for other three cases. For the gas production, the productions for every case decrease after the peak year (2010 for the base case and 2015 for other three cases). In contrast to the oil production, the gas production for 50 years for the base case is smallest among that for all cases. Here, the greater part of the assumed potentials of conventional oil and gas in EU-15 is consumed in the base case. Furthermore, a part of unconventional gas in EU-15 is consumed in the other three cases.

Figure 6.20 shows the import dependency of oil and gas. The import dependency is defined as the imported oil or gas per primary consumption of oil or gas in EU-15. For all cases, the import dependencies of oil rise because the decrease ratios in the production relative to the amount in the year 2000 are larger than those in the consumption. In the year 2050, the import dependencies are 98% for the base case, 96% for the specific reference case and the phase-out case and 91% for the breakthrough case. For the gas, the import dependency in the latter half of the 50 years are considerably higher than that in the first half of the 50 years because of the increase in the consumption and the decrease in the production. The import dependencies are 100% for the base case, 94% for the specific reference case and the phase-out case and 98% for the breakthrough case, respectively.



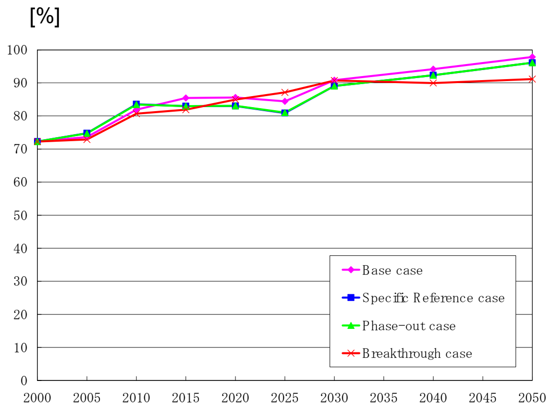
(a) Oil (b) Gas

Figure 6.18 *Oil and gas consumption (EU-15)*

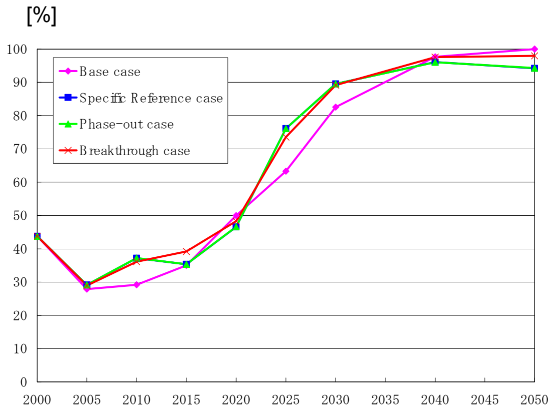


(a) Oil (b) Gas

Figure 6.19 *Oil and gas production (EU-15)*



(a) Oil

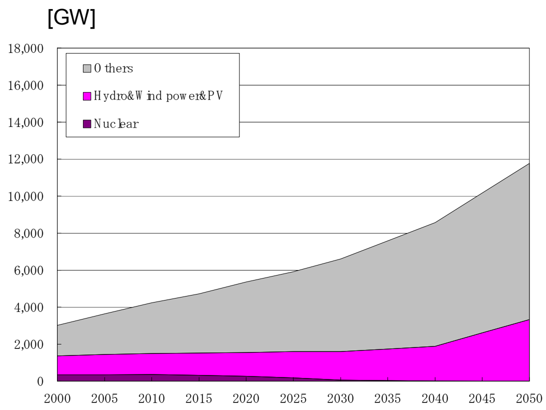


(b) Gas

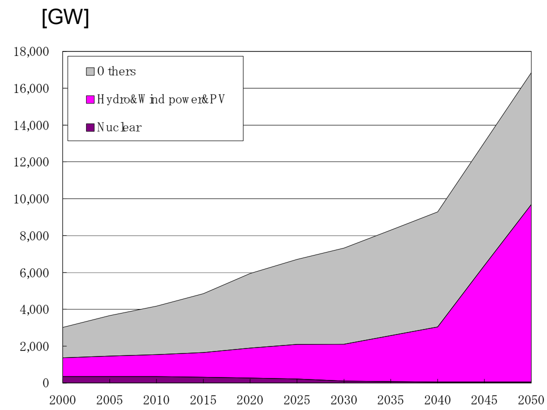
Figure 6.20 *Import dependency (EU-15)*

Generation capacity

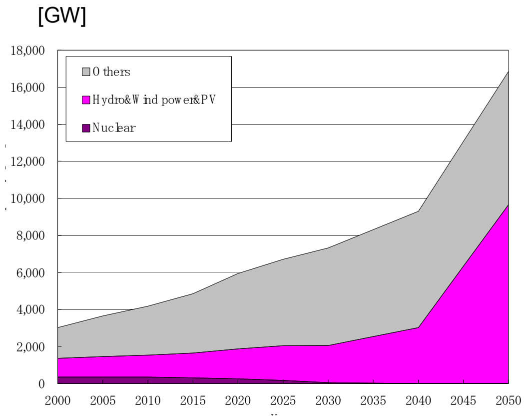
Figure 6.21 shows the generation capacity of nuclear and others for each case. In DNE21+ model, the capacity vintages of hydroelectric, wind power and PV are not treated explicitly. So, those capacities were calculated based on those electricity generations that were obtained through model-runs and the assumed utilization rates. The assumed utilization rates are 30% for hydroelectric, 42% for wind power and 12% for PV, respectively. The total generation capacity for the base case is smaller than that for other three cases, especially for the latter half of the 50 years. As shown in Figure 6.22, increases in hydroelectric, wind power and PV relative to the base case are achieved for the other three cases because of the imposition of the carbon value. The utilization rates of those are low and the total generation capacities for other three cases become larger than that for the base case. The difference in the generation capacities between the specific reference case and the phase-out case is small and it is similar to the above-mentioned results. The nuclear generation for the breakthrough case rises after the year 2015 as known in Figure 6.12. The capacity in the year 2050 is 1,800 GW and the percentage of it in the total generation capacity is about 11%. According to the increase, the generation capacity in the year 2050 of hydroelectric, wind power and PV decreases 1,300 GW and the decrease in that of others is 1,450 GW compared with the specific reference case.



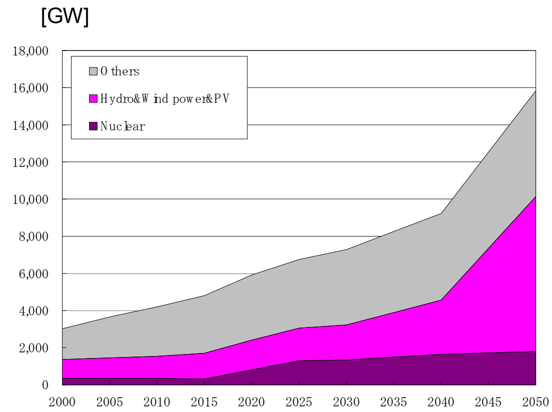
(a) Base case



(b) Specific Reference case



(c) Phase-out case

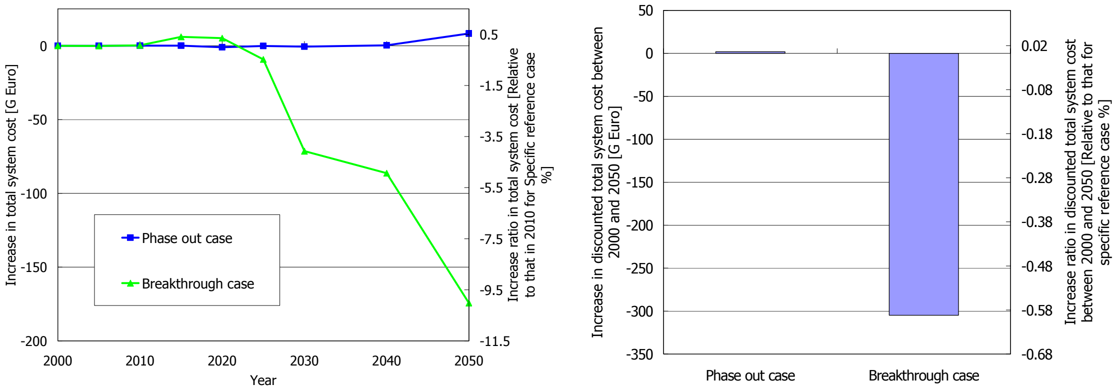


(d) Breakthrough case

Figure 6.21 *Generation capacity of nuclear and others (World total)*

Cost

Figure 6.22 shows the time series data of increase in total energy system cost and discounted total energy system cost between the years 2000 and 2050. A discount rate of 5% per year is used. As mentioned above, the difference between the phase-out case and the specific reference case is small and the increase in discounted total system cost is 2G€ (increase ratio: 0.004%). For the breakthrough case, an increase is observed between the years 2010 and 2020, because many power plants are reconstructed in the period. The increase in discounted total energy system cost is minus 305 G€ (increase ratio: -0.6%). Here, the total energy system cost for the breakthrough case does not include the cost for reducing the capital costs of nuclear power plants. Although the amount of R&D investment for nuclear power plant should be taken into account, that investment has the potential to reduce total energy system cost. Therefore, it is important to invest in nuclear power plants, effectively.



(a) Time series (b) Discounted between 2000 and 2050

Figure 6.22 *Increase in total system cost (Relative to cost for Specific reference case)*

6.2.4 Conclusions and recommendations

Three case studies (Specific reference, phase-out and breakthrough) were analysed by using DNE21+ model. The results are summarized as follows.

- The amounts of gas and renewables increase under the assumed carbon value. Those increases relative to those for the base case are 41EJ (increase ratio: 12%) and 200EJ (increase ratio: 212%) in 2050.
- The difference between the specific reference case and the phase-out case is very small.
- For the breakthrough case, the relatively large use of nuclear power is achieved. The amount of nuclear consumption is 147EJ (share: 14%) in 2050.
- By region, large increases are observed in North America, China and other Asia. On the other hand, nuclear cannot compete with other sources in the regions that do not have nuclear power plants at present.
- The world net CO_2 emission has reduced by 40 $GtCO_2$/year (reduction ratio: 67%) by the imposition of the carbon value.
- The import dependency of oil and gas of EU-15 increase with time for all cases. For the oil, although the consumption decreases with time especially for the cases with the carbon value, the production in EU-15 decreases and the import dependency is not improved compared with that in the year 2000. Although it depends on the time point, the import dependencies in 2050 for the cases with the carbon value are improved relative to that for the base case.
- The nuclear capacity for the breakthrough case increase with time and it is 1,800 GW (percentage in the total generation capacity: 11%) in 2050. According to the increase, the generation capacity in the year 2050 of hydroelectric, wind power and PV decreases 1,300 GW and the decrease in that of others is 1,450GW compared with the specific reference case.
- The discounted world total energy system cost is reduced by 305 G€ (reduction ratio: 0.6%). R&D investment for reducing the capital cost is important.

7. Synthesis: long term perspective of hedging with nuclear technologies

7.1 Introduction

The impacts of costs reduction of nuclear technologies as well as the phasing-out of nuclear technologies are likely to have clear global and long-term implications. On the one hand, it is highly unlikely that the rest of the world will refrain from using cheap nuclear technologies as such technologies become available for the present day industrialized world. On the other hand, phasing out in Europe, or indeed the industrialized world, will only be acceptable if the rest of the world follows suit. Both sides of the nuclear spectrum will have severe impacts on the global energy system, and it is the aim of this chapter to provide an analysis of the required adaptations, in terms of technological and economic impacts.

7.2 Would a technology breakthrough lead to a nuclear renaissance?

The nuclear technology breakthrough (BT) is reflected by a reduction in investment costs for new nuclear technology design with 25% compared to the Baseline scenario beyond 2010. In addition, the improved safety characteristics of this technology compared to conventional nuclear technology are assumed to lead to the re-evaluation of declared nuclear phase-out policies in several EU-25 Member States and to a broader acceptance of nuclear energy. Most models have assumed that all EU-25 Member States would accept nuclear power in this scenario (although not all countries might actually install it). Only TIMES-EE and NEMESIS have differentiated their assumptions on country level.

A rather strong CO_2 policy (‘carbon value’ or CV) is assumed in the central case for the breakthrough scenario, reflected in a CO_2 price rising to 100 € per tonne of CO_2 from 2030 onwards. When analysing the impact of the nuclear breakthrough, the message from such changes will be clouded by the impact of such a strong CO_2 policy change. The models involved have chosen different ways to circumvent this. Most of them have calculated a ‘CV-only’ scenario for comparison. Some models have also analysed the nuclear breakthrough in a ‘BT-only’ scenario where no reinforced policy is assumed, i.e. the CO_2 value stays at 10 €/tCO_2 (as in the baseline) for the entire time horizon.

7.2.1 Nuclear renaissance in Europe - mainly at the expense of coal

The conventions used for calculating primary energy equivalents of nuclear and renewables may obscure the comparison of total primary consumption among the scenarios. The nuclear fuel is accounted for with a conversion factor of 0.33 and the corresponding electricity generation efficiency of the (fossil) technologies is in general at least 40%. Consequently, 3 PJ of primary consumption of nuclear fuel replaces at most 2.5 PJ of fossil fuels, leading to a seemingly increasing demand while the demand for the final useful product may actually be decreasing. Therefore the most useful measure of the effect of the nuclear scenarios is the change in fossil fuel consumption. As a result of the nuclear breakthrough and carbon tax, the amount of fossil fuels consumed drops with 11% (POLES), 20% (PRIMES) and 34% (MARKAL). Likewise, the contribution of renewables increases in all models, by 7% (POLES), 22% (PRIMES) and 14% (MARKAL) respectively. Summarising, the share of fossil fuels in primary energy consumption in 2030 drops from some 70-75% in the baseline to approximately 65% (PRIMES and POLES), or 55% (MARKAL).

Nuclear being a power generation option, the BT-CV scenario induces significant shifts in the electricity generation mix. Figure 7.1 shows that the share of nuclear power could increase up to 50% (MARKAL and TIMES-EE) while PRIMES and POLES show less strong increases to approximately 30% of total power generation. Although the large growth in MARKAL at first sight might seem optimistic, as MARKAL is not taking into account country-specific preferences. The feasibility of such a growth is confirmed by TIMES, which has a larger country coverage and has such preferences included, arrives at a comparable amount of electricity produced from nuclear. PACE (not included in the graph) also arrives at a 50% contribution of nuclear, even in 2020, but admits that the lack of data for capacity limits for nuclear power extension nor adjustment costs for increasing the installed capacities may lead to an overestimation.

Comparing the effect of the BT-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. In the PRIMES CV-only case, for instance, the amount of natural gas-based power generation is comparable to the baseline, while this is substituted by nuclear power in the BT-CV case. The PACE results also suggest, that the breakthrough assumptions are decisive in the competition between renewables and nuclear. While in the CV case both gain significantly compared to the baseline, the breakthrough assumptions make nuclear the more attractive solution. However, MARKAL shows that in 2050, the share of nuclear in a 'CV-only' case approaches that in the BT-CV case, indicating that in the longer run a high carbon tax alone can already induce a large share of nuclear in the power generation mix. This obviously would require an acceptance or reduction of the risks related to nuclear power.

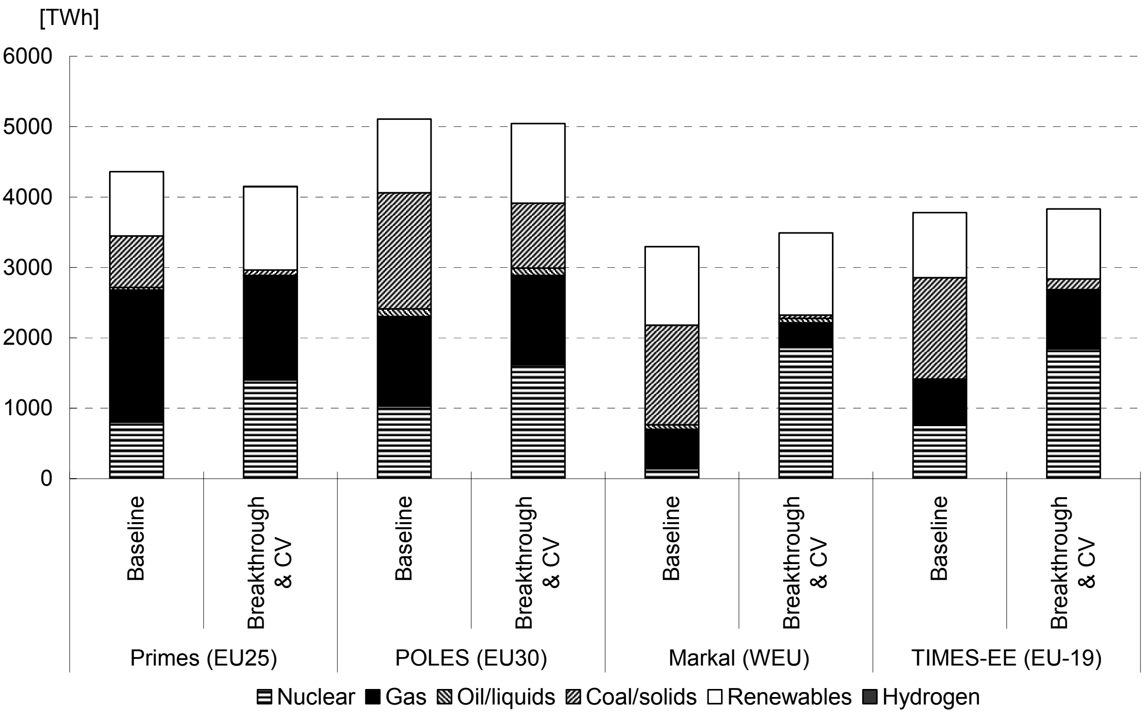


Figure 7.1 *Electricity generation by fuel in 2030; baseline and nuclear breakthrough*[30]

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 solid fuels more than natural gas. Similarly, the high carbon value provides an incentive to renewables, which gain in all models. Comparable shifts are shown for the US by the NEMS model.

[30] For explanation of the regions involved, see Appendix C.

The models are not uniform in their projections of the total electricity generation - some expect a higher production than in the baseline while others project a lower production, as in PRIMES, for instance, mainly due to the carbon value. On the other hand, in TIMES-EE the assumption that not all countries are able to build nuclear power plants lead to an increase of electricity trade and grid losses and therefore a slightly higher total net electricity generation compared to the baseline. Also in PACE, the effects of a reduction in capital costs overcompensates the effects of the carbon penalty on total electricity production: in 2020 electricity production increases by almost 3% compared to the baseline, while it would decrease with 5.5% in a CV-only case.

A related question is whether the investment cost reduction of new nuclear power plants could cause a breakthrough in a world without ambitious Post Kyoto policies. Several models have analysed this 'BT-only' scenario, and have shown that the cost reduction still provides a large incentive to nuclear power, as illustrated in Table 7.1.

Table 7.1 *Net electricity generation capacities based on nuclear power plants, year 2030*

	Baseline [GW]	BT-CV [GW]	BT only [GW]
PRIMES (EU25)	114	235	226
POLES (EU-30)	133	218	193
TIMES-EE (EU19)	88	224	208

Figure 7.2. shows installed nuclear capacities for separate EU Member States. This graph reflects the differentiated assumptions on nuclear policies by country, as summarised in Table 3.10. France is expected to expand its current large nuclear capacity already in the baseline, and to find the main driver for yet further expansion in the carbon value. For most other countries, the technology breakthrough and the related public acceptance of nuclear lead to an increase in installed capacity. The TIMES-EE model has assumed that countries in which no nuclear power plants have been built to date will not do so in the future. Consequently, Austria, Denmark, Greece, Ireland, Italy, Luxembourg, Portugal, and Norway are not shown in the graph.

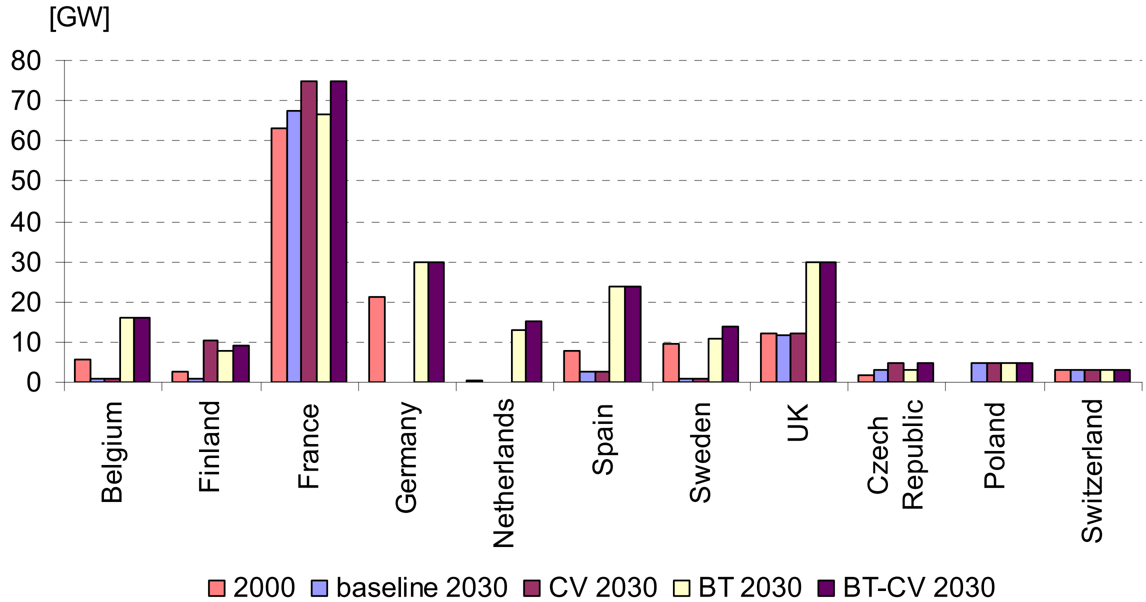


Figure 7.2 *Installed nuclear capacity by country in 2030.*
Source: TIMES-EE.

7.2.2 World models: nuclear substitutes gas (and possibly coal)

The breakthrough case sees a considerable increase of deployment of nuclear technologies in both world models. This is by and large a result of the cost decrease of the technology. In DNE21+, this is clear from the comparison with the 'CV-only' case, where the deployment of nuclear technologies gradually fades out. In GMM, comparing the BT-only case to the baseline gives rise to a similar conclusion.

The overall conclusions for both models are roughly on par, and by 2050 the primary energy use of nuclear fuel is between 147 EJ (DNE21+) and 188 EJ (GMM). The onset of this massive use of nuclear technologies differ somewhat, however, as is illustrated in Figure 7.3. While in DNE21+ the major increase takes place in the first decades, to gradually flatten off towards the end of our time horizon, GMM shows an increasing uptake of the capacity. This is closely related to the parametrisation of the technology: in DNE21+ the costs are exogenously specified while in GMM the nuclear technologies are learning by doing, and hence see increasing cost advantages.

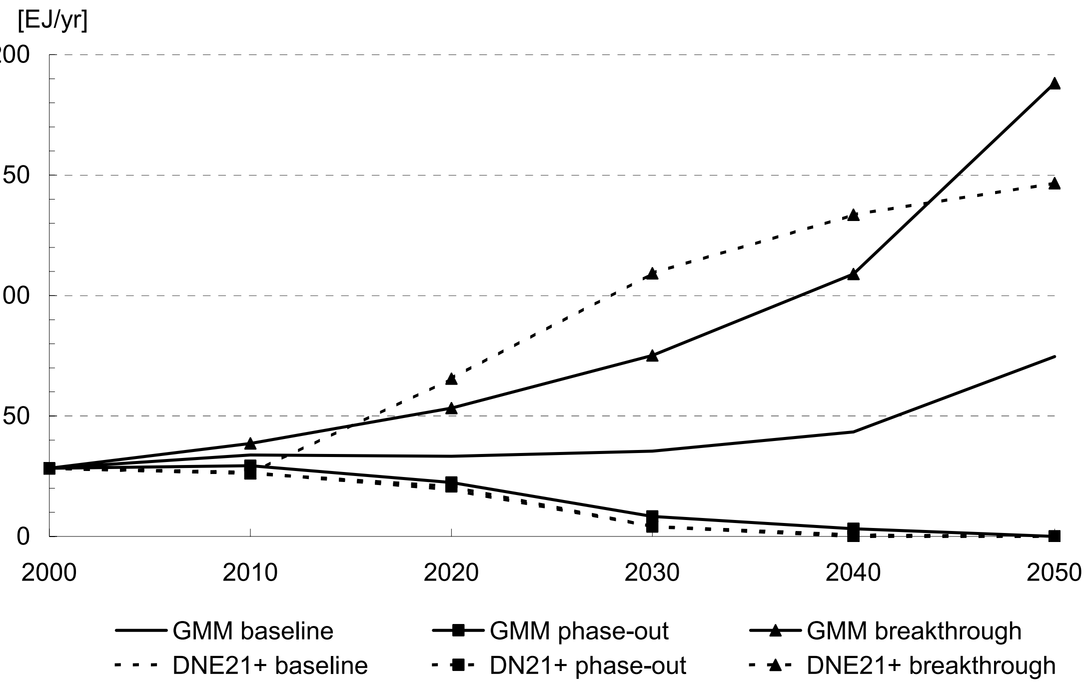


Figure 7.3 *Global consumption of primary nuclear energy according to the two global models, using a conversion factor 0.33*

As the breakthrough cases principally contain a strong carbon policy, it comes at no surprise that the advancement of nuclear technologies goes mostly at the expense of low-carbon technologies. However, as the comparison to the other scenarios show, both models are rather univocal that this does not imply a decreased use of renewable sources. Instead, DNE21+ shows a strong substitution of natural gas. To some extent, this also occurs in GMM, but there also the use of clean coal technologies is replaced by nuclear.

7.2.3 Consequences of a nuclear renaissance

A technological breakthrough in nuclear technologies will have a severe impact on the deployment of such technologies, particularly in a world with a high carbon value. Under such circumstances, the two global models indicate a possible increase in nuclear installations of almost one 1200 MW installation every week on average, in the period 2010 to 2050. For the GMM model, the growth is close to the maximum annual increase in market penetration of 13% for advanced nuclear technologies, and 3% for conventional ones. If one compares this to the maximum in the historical growth rates, it equals annual increases in global capacity of the order of 30% in the early seventies (McDonald, 2004). Even although in terms of number of installations the growth seems rather high, assuming that part of the increase is due to lifetime extensions of existing plants, resulting in a halving of the need for new capacity puts the growth in line with historically observed growth rates.

As a consequence of the increase in nuclear installations, there will also be a considerable increase in the demand for adequately trained personnel. This implies the need for sufficient investment in knowledge infrastructure, starting with renewed investments in training facilities. As in many OECD countries there is decreasing interest in the fundamental research into the nuclear sciences, the major challenge could be to establish such training facilities on a commercial basis. Both such a shift to a more commercial approach as well as the spread over the world regions furthermore require the acceptance of a more even spread of technological know-how over the developed and undeveloped world.

7.2.4 Costs of the nuclear renaissance

Generally the models report on lower total system costs for the BT-CV case than for the case where the carbon value is imposed without the availability of a cheap nuclear technology. This was to be expected with the assumption of an investment cost reduction in the BT case. However, it implies an underlying assumption that the technological improvement that causes the investment cost reduction is 'for free'. To investigate the effect of this implicit assumption, one of the general equilibrium models, NEWAGE-W has calculated the impacts of viewing the costs of the nuclear breakthrough as a subsidy. Then the advancement of the nuclear technology would go at the expense of the income of the representative household.

When taking into account the additional costs of an e.g. R&D induced increase of power plant efficiency or subsidized capacity investments, weakening impact on economic indicators can be expected. Due to the negative effects on household expenditure, related to the financial aspect of the subsidy, one has to revaluate the results of the technology breakthrough scenario slightly. Considering the same carbon price up to 2030, the costs of subsidizing the nuclear electricity generation capacities lead to a lower GDP in Western Europe by approximately 0.03% in 2015, 0.04% in 2020 and 0.02% in 2030 compared to the Nuclear Breakthrough ('for free') scenario. This slight decrease in GDP can be led back on the negative effects on household income due the subsidy. The financing of the subsidy changes the household's disposable budget for consumption and investment plans comparable to a negative tax revenue. However, compared to the positive GDP effect of 2% in the breakthrough case (see also Section 7.4.5 in this chapter), the 0.02% is negligible.

Different models show different impacts of the investment cost reduction related to their technology characterisation. For instance, the TIMES-EE model shows that the EPR type reactor with 5% discount rate might hardly need any additional cost reduction, while MARKAL shows that applying the cost reduction to the conventional LWR type leads to a high penetration when an 8% discount rate is used. If a higher discount rate of 12% is assumed to reflect the investment decisions of suppliers in a liberalised market, most of the cost reduction is cancelled out.

Electricity and fuel prices

POLES reports on changes in the oil and natural gas prices within a +/- 5% range. The breakthrough case reduces the price of these fuels as a consequence of the reduced demand for fossil fuels. However, the impact is limited, because oil and gas are traded on global markets, and by 2030 the demand from the developing word (e.g. China, India and Brazil) is a significant driver of the global demand. Since coal markets are modelled in POLES as national markets, the impacts on coal prices are stronger, and the breakthrough case leads on average to a 15% reduction compared to the baseline, although most of this reduction should be attributed to the carbon tax.

Impacts on electricity prices have been analysed by several models. Generally, the nuclear technology breakthrough has a favourable impact. It compensates some of the increased costs due to the carbon tax, e.g. the electricity price increase is less than in the CV-only case. In PACE, for instance, electricity production costs are reduced by 4% in the BT-CV case (2020), and counterbalancing a 6% increase due to the carbon value. Moreover, NEWAGE shows that the breakthrough more than compensates the effect of the carbon value. While the carbon tax causes a 20% increase in electricity prices compared to the baseline, the technology breakthrough causes a 2% decrease in electricity prices compared to the baseline. The size of the impact on country level largely depends on the composition of the electricity generating mix, as illustrated by POLES.

Global models
The cost reduction of nuclear technologies in both global models shows room for saving on energy spending. Here, the picture is quite consistent between the two models, as the savings are of the order of -0.5% of total discounted system costs. GMM provides a split between costs due to shifts in technology, and savings due to lower tax expenditures, with taxes now responsible for some two-thirds of the saving.

7.2.5 Fuel availability, waste management and proliferation

In the breakthrough case studies in this report, 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 tonnes 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 proven reserves and additional resources amount to 8.4 million tones. A further 12.1 million tonnes of speculative resources (undiscovered to date) might come in use in the long run. However, there is no cost estimate for these speculative resources and therefore it is not clear whether these might be utilized at acceptable costs.

For Western Europe, the MARKAL model indicates that such a large growth of the nuclear power generating capacity as in the Breakthrough case would imply that in Western Europe in 2020-2030, each year ten new plants are built. This would require an amount of 187 kton uranium. With the current assumptions on proven reserves, this is not implausible.

A secondary 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 breakthrough case may amount to a doubling of the cumulative waste production by 2050 as compared to the baseline. For Europe, the MARKAL Breakthrough case shows that the amount of waste for which storage is required will increase from 30 kton in 2000 to 190 kton in 2050. The annual storage costs in 2050 would be some € 47 million, and would continue for an indefinite period of time. TIMES-EE indicates a more modest increase of the total amount of nuclear waste with some 50% 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 breakthrough 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.

All three issues raised here might 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 involve either further basic research or addressing of public concern. If such advances are not made, the results presented here are likely to be somewhat optimistic, as the need to find solutions for resource and waste problems will deteriorate the competitiveness of nuclear energy.

7.3 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 no new nuclear plants are built, and that existing plants are decommissioned after their lifetime. This scenario was examined under the same carbon value as in the breakthrough case, of 50 €/tonne CO_2 in 2020, increasing to 100 €/tonne CO_2 in 2030 and further.

7.3.1 Nuclear phase-out: the return to gas, renewables and clean coal

In the phase-out, the carbon policy plays an essential role. Figure 7.4 shows the shifts in the power generation mix due to the combination of a high carbon tax and the nuclear phase-out for European models. The amount of power generation from coal is substantially reduced (except in POLES), and is compensated by an increased contribution from renewables and natural gas. Renewables have a share of 25-45% in electricity production in 2030. Savings on electricity consumption could also play a role, as all models show a lower electricity production than in the baseline. MARKAL is the only European model where coal plants equipped with CO_2 capture contribute to a carbon constrained generation mix without nuclear power. NEMS reports on shifts in the US electricity generation that renewables gain most from the nuclear phase-out in presence of a carbon value, while in the reference case coal would be the main substitute to nuclear power.

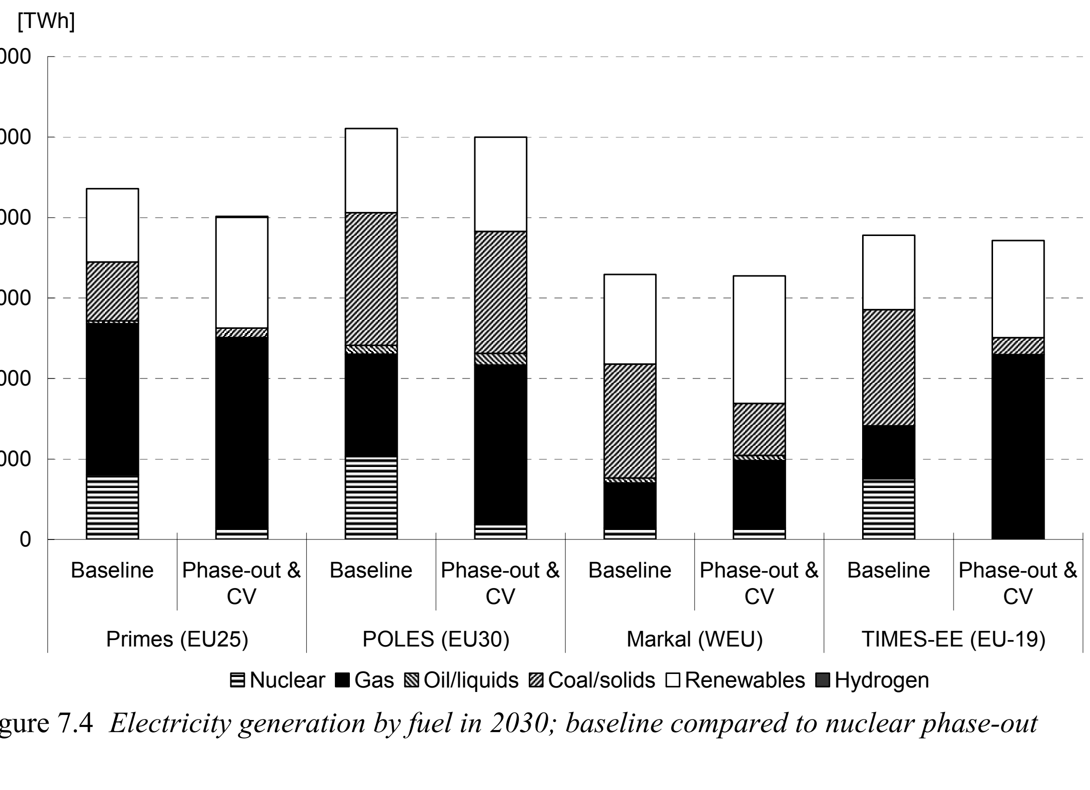


Figure 7.4 *Electricity generation by fuel in 2030; baseline compared to nuclear phase-out*

The world models GMM and DNE21+ also show that the carbon value enhances the deployment of relatively low-carbon technologies such as natural gas and clean coal technologies. While the first of these is the preferred option in the early periods, the combination of coal gasification and carbon capture gives rise to a considerable increase in the use of coal beyond 2030.

7.3.2 Costs of a nuclear phase-out

The assessment of the costs associated to the phase-out of nuclear technologies depends strongly on the view on the current and future market potential, as is illustrated by the difference between the baselines of the two global models. While DNE21+ sees an autonomous phase-out even under a severe climate policy, GMM indicates that nuclear power will play a role in the future energy system, particularly in case of a severe carbon policy. As a consequence, the costs of a phase-out may range between almost zero, using the DNE21+ assessment, up to 1.6% of total discounted system costs according to the GMM model. In this case the additional costs to a large extent are connected to additional tax expenditures (close to ninety percent).

For the European models, the phase-out in a carbon-constrained future generally leads to higher costs than a scenario with only the carbon tax. MARKAL reports that the investments in alternative power generation are considerable, as in the phase-out, investments in the period 2020-2050 are on average 1.7 times that in the baseline. However, the differences in total system cost without taxes between the scenarios are very small. In the phase-out case, the total system costs are maximal 2% higher than in the Baseline. TIMES reports that the total costs for the electricity sector of a nuclear phase-out in Western Europe will amount approx. € 224 billion.

The phase-out may also lead to higher electricity production costs and therefore increased electricity prices. According to PACE, electricity production costs increase with 10% in 2020, compared to 6% in the CV-only case, while NEMESIS also shows a 15% electricity price increase in 2020, mainly due to the carbon tax. NEWAGE reports on electricity price increases of up to 28% in the phase-out case compared to the baseline, and still 7% higher than the CV-only case where nuclear power is not phased out. POLES confirms the electricity price increases of up to 30% in 2020-2030, which occur in countries with a current high share of nuclear, and which are for the main part due to the carbon tax.

7.4 Impacts on emissions and security of supply

7.4.1 Global CO_2 emissions

The central policy cases reported on in this report assume a substantial decrease of CO_2 emissions as compared to the baseline due to a severe taxation scheme. Within this perspective, the effects of the developments of the nuclear technologies play a relatively modest role. In particular, the breakthrough of nuclear technologies does little to add to CO_2 emission savings, in a world with a carbon value of 100€/tonne CO_2, as is illustrated in Figure 7.5 and Figure 7.6. And similarly, phasing out nuclear technologies causes only a limited increase in emission levels, indicating that other carbon abatement options can compensate.

There are clear differences among the scenarios in the way in which the emission reduction is achieved. According to GMM, in the breakthrough scenario, the 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, as opposite to the Carbon value scenario where CO_2 capture prevails in 'the end of horizon'. Exclusion of nuclear energy from the portfolio of abatement options in the phase-out scenario results in a rapid increase of the contribution of CO_2 capture (38% in 2050)[31]. Similarly, the fraction of renewables and demand-reductions is higher.

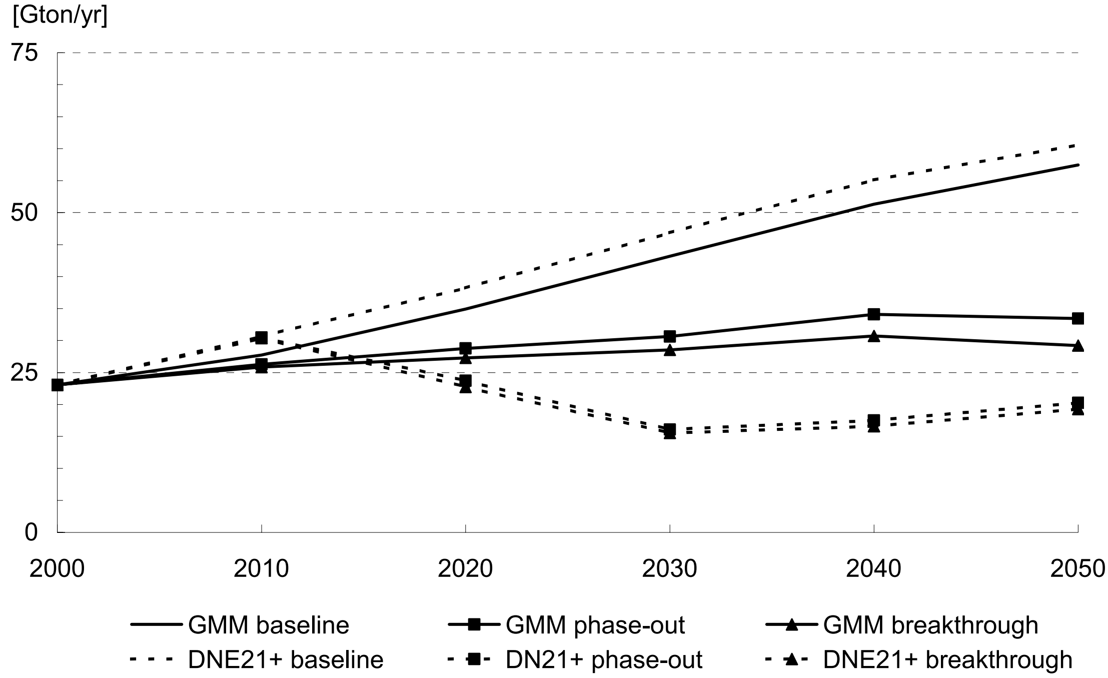


Figure 7.5 *CO_2 emission levels in GMM and DNE21+ in the baseline, without strong CO_2 policy, and nuclear phase-out and breakthrough, both with strong CO_2 policy*

7.4.2 Impacts on emissions in Europe

Both the post Kyoto policy and the nuclear scenarios have a significant impact on carbon emissions in Europe. As illustrated in Figure 7.6, the carbon value causes most of the emissions reduction. According to some of the models (PACE, MARKAL, TIMES), the increased electricity production in the breakthrough case offsets part of the emissions reduction. The nuclear phase-out, on the other hand, makes it more difficult to achieve substantial emissions reductions despite the high carbon value. This is particularly so in the POLES results, and one of the reasons is that this model does not include carbon capture and storage in its present technology database. The other models are somewhat more optimistic on the emissions reductions possible in a nuclear phase-out scenario.

[31] In the Phase-out scenario, the cumulative amount of CO_2 captured and stored in the period 2010-2050 is 36 GtC. This corresponds to about 13% of the global cumulative storage-potentials in depleted oil and gas fields estimated by IEA (2004).

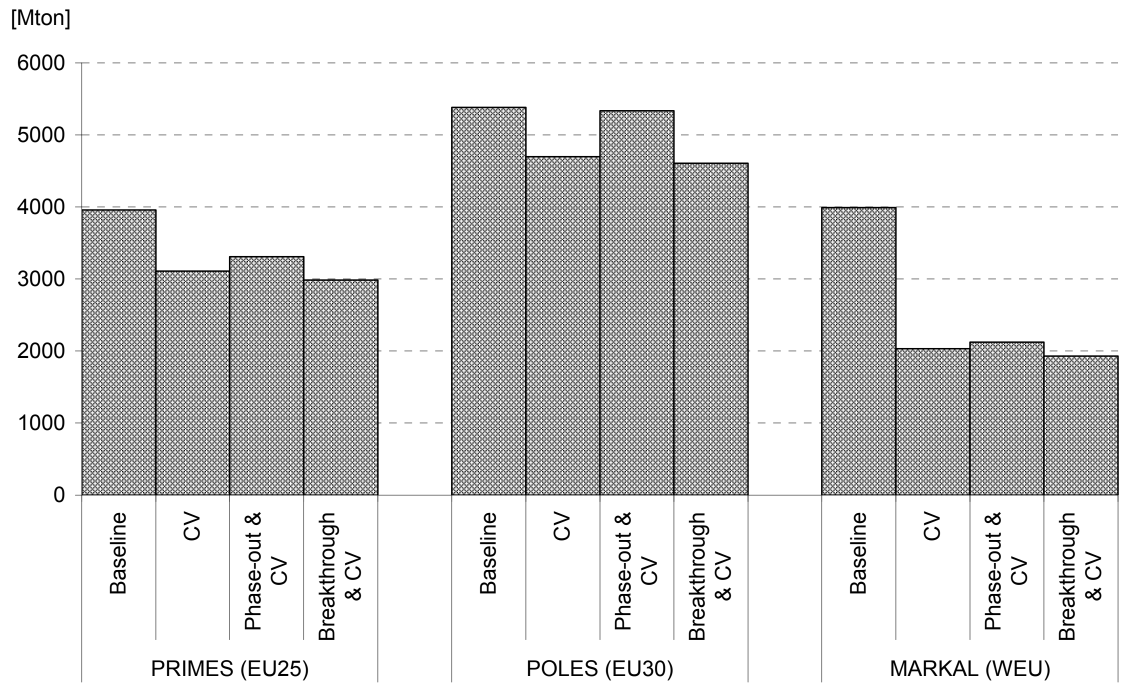


Figure 7.6 *CO_2 emissions in 2030 in different regions in Europe*

7.4.3 Security of supply

The introduction of the carbon tax causes shifts between fuels. Against these shifts, the role of nuclear technologies is relatively small, as was already indicated when discussing the CO_2 emissions. Thus, it should not come as a surprise that the effects on the indicators linked to Security of Supply show a similar independence for the specifics of the nuclear technologies. Only in the margin some effects are noticeable. For the oil import dependency, DNE21+ indicates that a breakthrough in nuclear technologies may relieve the dependence on imports somewhat, from above 95% to a little over 90%. This is a small reduction indeed, and is most likely fully counteracted by an increase in the import dependency for gas. In any case, by 2040 the import dependence for both oil and gas is higher than 90%, irrespective of whether nuclear energy sees an enhanced use.

Likewise, for European models, the shifts in power generation mix visible in the breakthrough 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.

Interestingly, PACE reports that in the phase-out case, the increase in electricity production costs triggers a decrease in electricity demand by more than 5% (and electricity supply by more than 10%) in 2020. The remaining supply-side gap is closed through increased electricity imports from outside the EU-15.

7.4.4 Impact of nuclear on renewables

As was mentioned above, the introduction of a cheap nuclear option has little impact on the global use of renewable energy sources. This feature is illustrated in Figure 7.7 for the two global models. In the figure, the contribution of renewable sources is shown for both models, in the phase-out and the breakthrough scenarios. There is a remarkable convergence towards 2050 in the overall use of renewable resource, if not in the actual mix (see also (Uyterlinde et al., 2005) for a more in-depth analysis of policies and renewable energy sources). The effect of the nuclear breakthrough is a decrease of up to 10% in the use of renewables. For the European models, differences up to 20% are found for the year 2030, implying that the impact on renewables is somewhat stronger. Thus, one may conclude that using a hedging strategy, retaining the nuclear option, has only a limited impact on renewables[32].

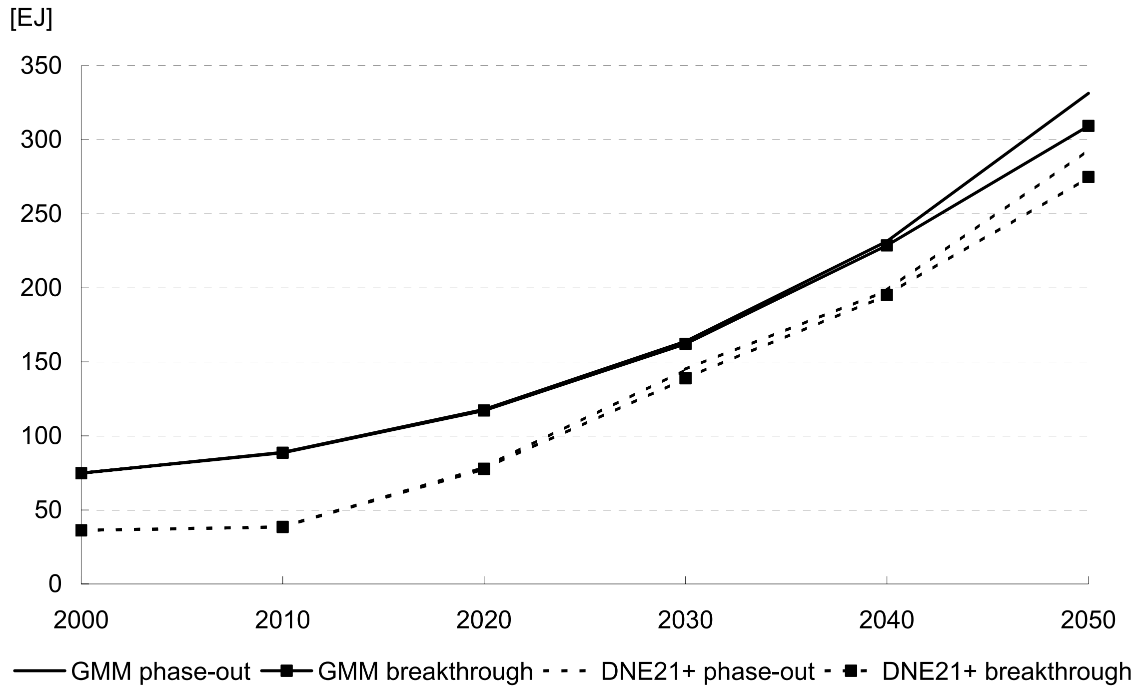


Figure 7.7 *Use of renewable resources*

7.4.5 Economic impacts

The three economic models PACE, NEWAGE-W and NEMESIS have analysed the economic impacts of the nuclear scenarios including the carbon value.

Welfare

PACE and NEWAGE-W have reported on changes in welfare in percentage *Hicksian equivalent variations in income*, which are equivalent to percentage change in real consumption with respect to the baseline, see Table 7.2. According to PACE, overall welfare losses for Europe are small and range from 0.1% to 0.3%. The welfare losses due to the CV are further accelerated in the case of a nuclear phase-out and moderated in case of a technology breakthrough. 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 breakthrough, while in PACE a negative effect on welfare remains.

[32] One must be somewhat careful here, as the analysis presented here does not incorporate the competition for research funds. Such competition may have profound impact on the changes of technologies still in the development phase.

This may be dependent on the formulation of the model (inter-temporal or recursive dynamic), and on the period; in 2020 the carbon tax is half that in 2030. Another reason may be the assumption in NEWAGE-W that revenues of the carbon tax are recycled to households, which increases their consumption.

Table 7.2 *Welfare losses in terms of Hicksian equivalent variations (versus baseline)*

	PACE (EU-15, 2020) [%]	NEWAGE-W (WEU, 2030) [%]
Breakthrough & 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. The CV-only scenario in NEWAGE-W shows a positive effect on GDP (+0.67%) for the year 2010 compared to the baseline. This impact is induced by increasing income of the households due to an increase in tax revenue. Within the first years, this positive income effect compensates the negative production effect by rising carbon taxes, i.e. rising production costs. In the year 2020 the positive effect slackens and after 2030 a negative impact on GDP could be observed. NEMESIS shows a stronger and earlier negative effect; in 2020 the GDP is reduced by approx. 1.3% in the CV-only case, due to price increases of fossil fuels and electricity with 10-40%. NEMESIS has also reported on the GDP impacts for individual Member States; ranging from -0.6% for Denmark to -2% for Greece, depending on the level of their initial dependency on fossil fuels. NEMESIS does not (yet) include carbon capture, and biofuels, limiting the flexibility in the energy system to respond to the CV. The revenue of the carbon tax is not recycled, with explains for a part the strong impact on GDP.

In NEWAGE-W, when adding a nuclear phase-out policy to the CV scenario, the positive income effect on GDP, which can be observed for 2010 as well, already slackens off in the year 2020. As of 2030 the strongest depletion in GDP of almost 2% could be seen in the phase-out scenario. This is mainly caused by an increase in electricity prices, i.e. rising input cost for electricity intensive industrial production. Opposed to the negative impact on GDP in the CV and the phase-out scenario, a technology breakthrough 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.

NEMESIS does not show any significant additional macro economic impacts for the nuclear scenarios, because these scenarios induce mostly substitutions in the power sector, with too limited impacts on the price of electricity to influence GDP growth in EU-15 countries. These scenarios nevertheless do have a direct impact on the level on CO_2 emissions through the contribution of fossil fuels to power generation. If this retroaction of nuclear capacity on the post-Kyoto's carbon constraint is taken into account, significant macroeconomic impacts for the two scenarios are found.

For example, in the breakthrough scenario, GHG emissions are reduced with about 2% in 2020, and this reduces the carbon penalty with around 5 €/tonne CO_2 for the same level of GHG emissions in 2020 in Europe. Consequently, GDP is app. 0.15% higher in the breakthrough scenario than in the CV-only scenario, with GDP gains ranging from 0.1% in Denmark to 0.2% in Greece. These GDP gains would of course be more significant at a long-term horizon. The phase-out, on the contrary, has a negative impact on GDP, leading to an increasing carbon penalty, which reaches about 52 €/tonne CO_2 in 2020 compared to 50 €/tonne CO_2 in the CV-only scenario. Here again, the change in GDP is still very limited in 2020, with a loss of GDP of -0.06% for EU-15, but it should increase importantly until 2050.

Other impacts
NEMESIS reports on the impacts of the post-Kyoto baseline with a carbon value of 50 $€_{2000}$ in 2020. This post-Kyoto baseline shows a reduction of GDP of about 1.3% in 2020, implied by the rise from 10 to 50 €/tonne CO_2 of the carbon penalty, compared to the baseline. The rise of carbon penalty increases energy prices in 2020. The inflationary impact of these increased energy prices reaches 3.5% for the GDP deflator and the impact on private consumption deflator is stronger with 4.7%, as a consequence of the importance of energy in the budget of households. This reduces real wages of about 0.75%, the fall of real wage limiting the negative impact on of GDP fall on employment level, with only 1% decrease against 1.3% for GDP.

7.5 Conclusions

The future of nuclear power is a sensitive issue in most countries. Some EU Member States have started to phase-out their existing capacities, while others are facing public pressure to limit their use. However, on the other side of the spectrum, there are Member States such as Finland who have chosen to invest in new nuclear power plants. The current CASCADE MINTS case study aims at providing insight into the possible contribution of nuclear power in a future where Post Kyoto targets are pursued. Under the assumption of a carbon tax increasing up to 100€/tonne CO_2 in 2030, a scenario where existing nuclear power plants are phased out is contrasted with a scenario where a technology breakthrough reduces the investment costs of nuclear power plants with 25%, and improved safety characteristics lead to a larger social acceptance of nuclear power.

One important issue is the almost overwhelming impact of the chosen CO_2 policy. As it is assumed that the rest of the world follows Europe's lead from 2020 onwards, the high carbon value enforces the system to exhibit severe shifts in the distribution over primary energy supply options. The impacts of nuclear advancement, be it a cost reduction or a gradual phase-out, are as expected relatively limited when compared to such a large rearrangement.

Nuclear renaissance
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 breakthrough potential may require substantial investments in R&D of which the returns are of course uncertain. However, one of the models has shown that if the investment cost reduction was attained by a direct subsidy, the GDP impacts would be negligible.

The nuclear breakthrough case is based on fairly strong assumptions, not only on the decrease in investment costs, but also on a broad public acceptance of nuclear power, due to an increased safety level, and on the ability of the nuclear industry to build a large number of advanced reactors. When these conditions are fulfilled, the nuclear breakthrough certainly has a positive impact on the energy system. It substitutes natural gas and coal-based power plants, thereby not only reducing carbon emissions, but also slightly limiting Europe's import dependency for natural gas and considerably for coal. It also has a favourable impact on electricity prices by compensating some of the increased cost incurred by the Post Kyoto targets assumed in the case study.

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.

Concluding, the uncertainty in this scenario is high, not only due to the technical nature of the issue, but also due to inherent social values, perception and attitude toward the use of nuclear power, which make the scenario ambiguous.

Nuclear phase-out
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 with up to 15% in 2030 compared to the baseline, causing Europe to be a slightly less dependent on natural gas imports until 2030. The share of renewables in electricity production ranges from 23-48% in 2030. The phase-out has negative impacts on the GDP and welfare that are slightly stronger than the impacts of the carbon value alone.

Forcing nuclear, as one of the major power generation technologies out of the market while at the same time imposing high carbon taxes is expected to lead to higher electricity generation costs and therefore also to higher input cost for electricity intensive production. 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 huge 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.

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Appendix A Nuclear phase-out scenario

Table A.1 *Phase-out path for Europe*[1]

	Installed capacities								
	1990	1995	2000	2005	2010	2015	2020	2025	2030
AU	0	0	0	0	0	0	0	0	0
BE	5794	5884	6031	6031	6031	6031	4267	2367	0
DK	0	0	0	0	0	0	0	0	0
FI	2760	3010	3357	3357	4657	4657	3277	1647	1647
FR	59110	60847	65677	65677	65677	65677	60113	33613	14288
GE	24357	23667	23667	22638	18467	13874	4240	0	0
GR	0	0	0	0	0	0	0	0	0
IR	0	0	0	0	0	0	0	0	0
IT	0	0	0	0	0	0	0	0	0
LX	0	0	0	0	0	0	0	0	0
NL	535	535	535	475	0	0	0	0	0
PO	0	0	0	0	0	0	0	0	0
SP	7800	7800	7800	7800	7640	7174	7174	3166	0
SV	10287	10287	9672	9057	9057	7965	6255	2405	0
UK	12948	14213	14213	13793	10353	7765	7145	1265	1265
BU	3760	3760	3760	2880	2000	2000	2000	2000	1000
CY	0	0	0	0	0	0	0	0	0
CZ	1760	1760	1760	3722	3722	3722	3722	3722	1962
ES	0	0	0	0	0	0	0	0	0
HU	1760	1760	1760	1760	1760	1760	1760	880	0
LA	0	0	0	0	0	0	0	0	0
LI	2500	2500	2500	1250	0	0	0	0	0
MA	0	0	0	0	0	0	0	0	0
NO	0	0	0	0	0	0	0	0	0
PD	0	0	0	0	0	0	0	0	0
RO	0	0	700	700	700	1400	1400	1400	1400
SK	1760	1760	2640	2640	1760	1760	1760	880	880
SN	664	664	664	664	664	664	664	0	0
SW	3450	3450	3450	3450	3450	3450	3450	2210	1100
TU	0	0	0	0	0	0	0	0	0

[1] Based on the decommissioning plans of the individual countries. Where this information was not available, a 40 year lifetime was assumed.

Source: NTUA.

Appendix B Reactors under construction

The following section includes the World Nuclear Association figures on the planned new nuclear reactors under construction and on the capacity expansion[33]. For the global models these reactors should be included in the database on the nuclear phase-out, but no other planned capacity should be included. The Europe data file on the phase-out (Appendix A) already includes these changes.

New Reactors under Construction

Some 31 power reactors are currently being constructed in 11 countries (see Table), notably China, the Republic of Korea and Japan. Construction is well advanced on many of them and, based on reported progress and allowing for delays in some countries, 16 with a total net capacity of over 11,000 MW_e are expected to be in operation before the end of 2004.

Table B.1 *Power reactors under construction*

Year[1]	Country	Reactor	Type	[MW_e]
2001	Czech Republic	Temelin 2	PWR	912
2002	Japan	Onagawa 3	BWR	796
2002	Korea RO	Yonggwang 5	PWR	950
2002	Korea RO	Yonggwang 6	PWR	950
2002	China National Nuclear Corporation (CNNC)	Qinshan 2	PWR	610
2002	CNNC	Lingao 1	PWR	935
2002	Argentina	Atucha 2	PHWR	692
2003	Romania	Cernavoda 2	PHWR	650
2003	Iran	Bushehr 1	PWR	950
2003	CNNC	Lingao 2	PWR	935
2003	CNNC	Qinshan 3	PWR	610
2003	CNNC	Qinshan 4	PHWR	665
2004	CNNC	Qinshan 5	PHWR	665
2004	Russia	Kalinin 3	PWR	950
2004	Russia	Kursk 5	RBMK	925
2004	Ukraine	Khmelnitski 2	PWR	950
2004	Taipower	Lungmen 1	ABWR	1350
2004	Korea RO	Ulchin 5	PWR	950
2004	CNNC	Tianwan 1	PWR	950
2005	Korea RO	Ulchin 6	PWR	950
2005	Japan	Higashidori 1	BWR	1067
2005	Japan	Hamaoka 5	ABWR	1325
2005	Taipower	Lungmen 2	ABWR	1350
2005	Russia	Rostov-2	PWR	950
2005	CNNC	Tianwan 2	PWR	950
2005	India	Tarapur 3	PHWR	450
2006	Ukraine	Rovno 4	PWR	950
2006	Japan	Shika 2	ABWR	1315
2006	India	Tarapur 4	PHWR	450
2006	Russia	Blakovo 5	PWR	950

[1] Latest announced year of proposed commercial operation. Onagawa-3 started up recently.

[33] Source: http://www.world-nuclear.org/wgs/wnasubs/energyreview[0]/.

Appendix C Regional coverage of the models involved

Model	Regional coverage
World models	
GMM	World in five regions
DNE21+	World in 21 regions
European energy models	
POLES	World, in this report focusing on the EU-30: EU-25, excluding Baltic states, but including Norway, Switzerland, Turkey, Romania, Bulgaria, Ex-Yugoslavia, Iceland and Albania.
MARKAL	EU-15, Norway, Switzerland, Iceland, denoted as Western Europe-WEU
TIMES	EU-15, Norway, Switzerland, Poland, Czech Republic, denoted as EU-19
PRIMES	EU-25
Economic models	
NEMESIS	EU-15 + Norway
PACE	EU-15
NEWAGE-W	World, in this report focusing on Western Europe
Other regions	
MAPLE	Canada
NEMS	United States