The contribution of nuclear energy to a sustainable energy system

Policy brief in the CASCADE MINTS project

M.A. Uyterlinde (ECN)
G.H. Martinus (ECN)
H. Rösler (ECN)
B.C.C. van der Zwaan (ECN)
L. Szabo, P. Russ (IPTS)
L. Mantzos M. Zeka-Paschou (NTUA)
M. Blesl, I. Ellersdorfer, U. Fahl (IER)
C. Böhringer, A. Löschel (ZEW)
F. Pratlong, P. Le Mouel (Erasme)
I. Hayhow (NRCan)
A.S. Kydes, L. Martin (EIA)
P. Rafaj, S. Kypreos (PSI)
F. Sano, K. Akimoto, T. Homma, T. Tomoda (RITE)

The CASCADE MINTS project is funded by the EU under the Scientific Support to Policies priority of the Sixth RTD Framework Programme

ECN-C--05-085 March 2006

Preface

The CASCADE MINTS project on 'CAse Study Comparisons And Development of Energy Models for INtegrated Technology Systems' is partially funded by the EU under the Scientific Support to Policies priority of the Sixth RTD Framework Programme. The project is registered at ECN under nr. 77596. More information on the project can be found on www.e3mlab.ntua.gr/cascade.html.

The following partners are involved in Part 2 of the Cascade Mints project:

- 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.
- Paul Scherrer Institute (PSI) (Switzerland); GMM model.
- 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.
- ERASME-Équipe de Recherche en Analyse des Systèmes et Modélisation Économiques, University of Paris (France); NEMESIS model.
- International Energy Agency (France); ETP model.
- U.S. DOE/EIA Energy Information Administration of the U.S. Department of Energy (USA); NEMS model.
- Research Institute of Innovative Technology for the Earth (Japan); DNE21+ model.
- National Institute for Environmental Studies (Japan); AIM model.
- Natural Resources Canada (Canada); MAPLE model.

For more information, please contact: Ms. Martine A. Uyterlinde, uyterlinde@ecn.nl, Energy research Centre of the Netherlands, Policy Studies department.

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.

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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.

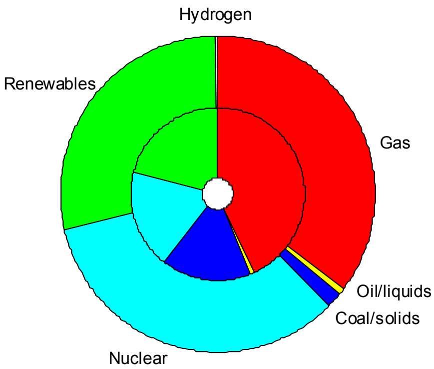

Figure P.1 *Electricity generation mix in the EU-25 in 2030; baseline (inner circle) compared to Renaissance & Carbon value case (outer circle)*
Source: PRIMES.

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.

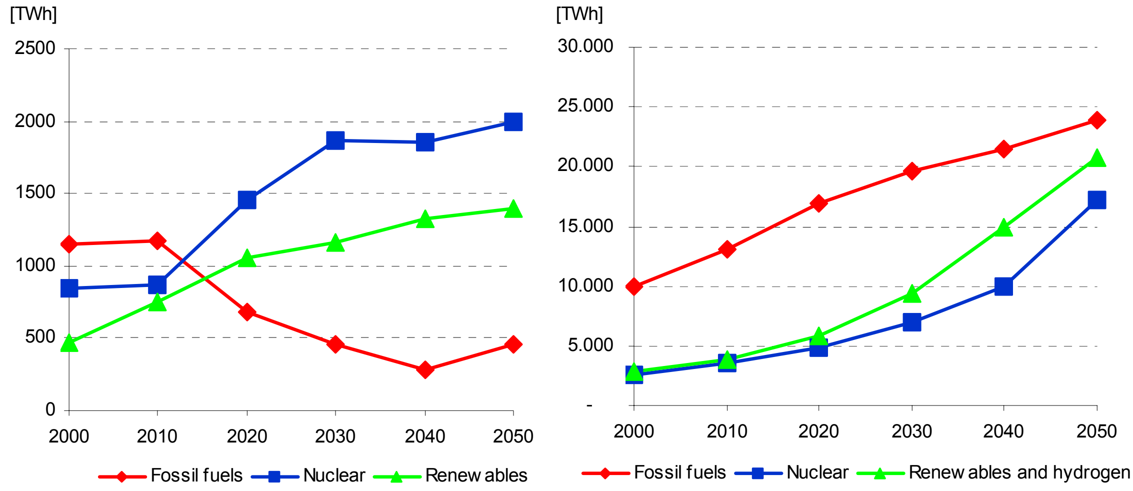

Figure P.2 *Electricity generation by fuel for Europe and the world for the Renaissance & Carbon value case*
Source: MARKAL and GMM.

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.

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 ex-

[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).

pensive 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.

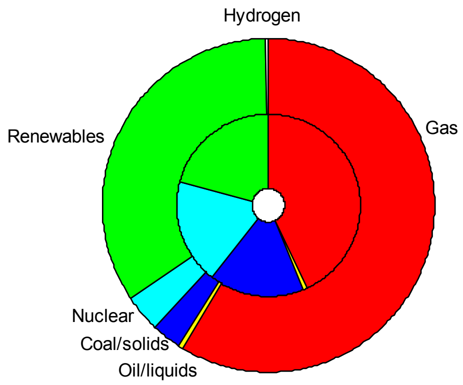

Figure P.3 *Electricity generation mix in the EU-25 in 2030; baseline (inner circle) compared to Phase-out & Carbon value case (outer circle)*
Source: PRIMES.

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.

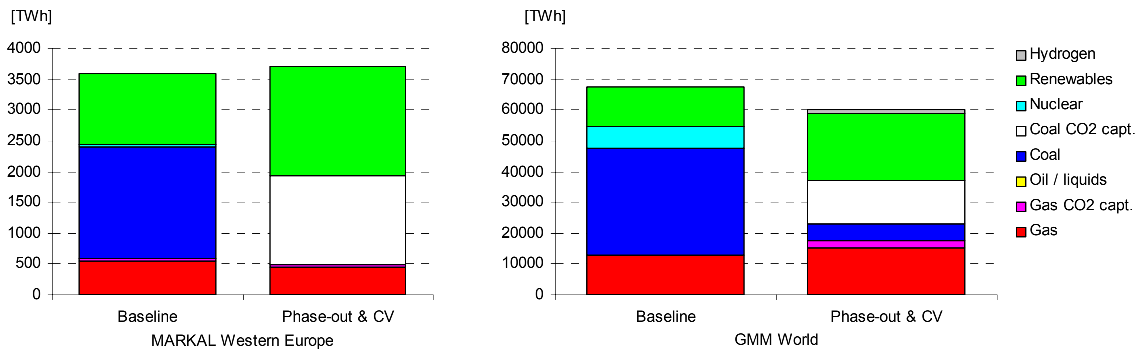

Figure P.4 *European and global power generation mix in 2050; Phase-out & CV case*
Source: MARKAL and GMM.

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.

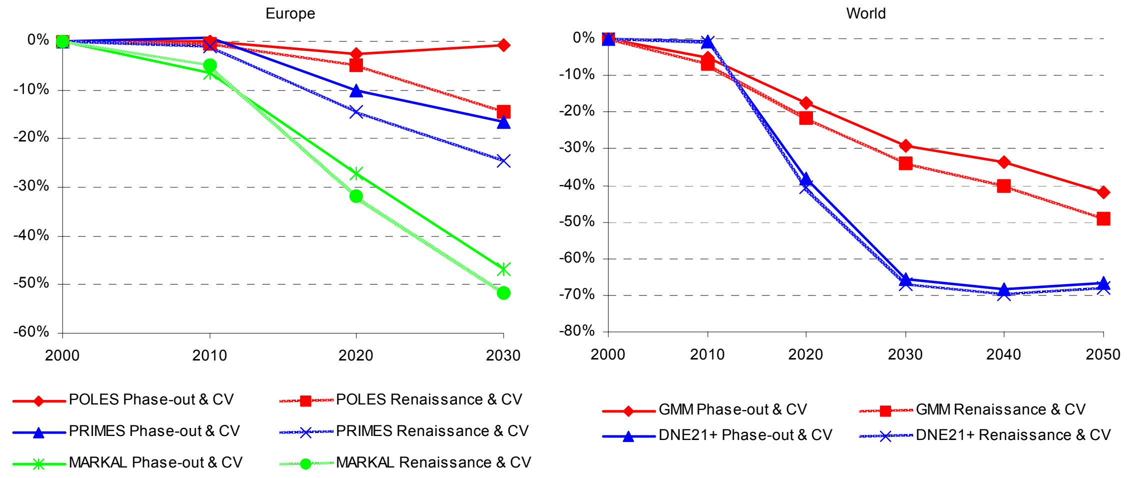

Figure P.5 *Change in CO_2 emissions relative to the Baseline*

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.

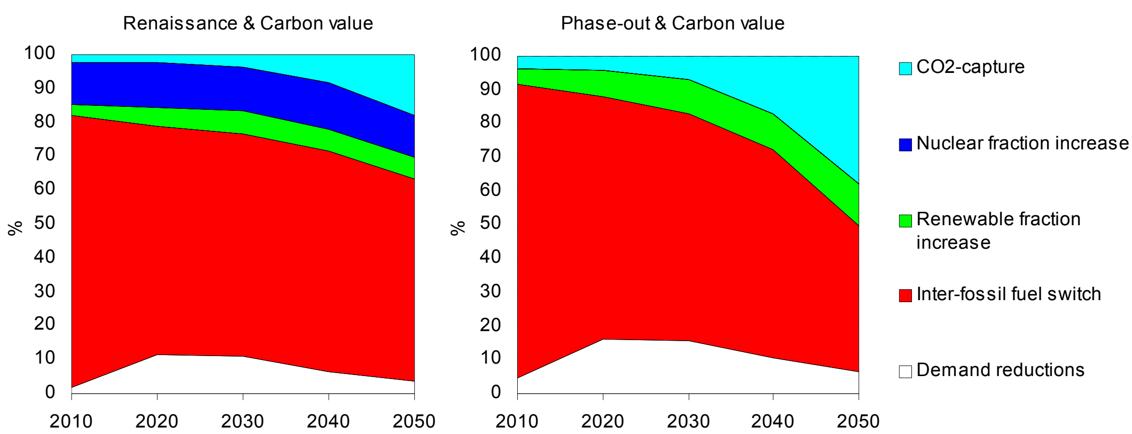

Figure P.6 *Breakdown of CO_2 reduction components*
Source: GMM.

[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.