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The effect of a nuclear energy expansion strategy in Europe on health damages from air pollution

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Foreword

Nuclear energy is back on the political agenda. This report studies the impacts of nuclear energy expansion on a European scale. The future of nuclear power is controversial, and despite the challenges it faces, it is one of the options for Europe to meet future energy needs without emitting carbon dioxide (CO_2) and other atmospheric pollutants. Other options such as increased efficiency, renewables, and carbon dioxide sequestration are of course considered as well. Nuclear power will only be optional if the technology performs better in economics, improved safety, successful waste management, permanent disposal facilities, low proliferation risk, and if public policies place a significant value on electricity production that does not produce air pollutants. This study identifies the issues facing nuclear power with the objective of adding scientific information to the debate and was carried out by the Netherlands Environmental Assessment Agency (MNP). The authors would like to thank Bob van der Zwaan (ECN) and Benno Jimmink (MNP) for their contributions to the report. The authors gratefully acknowledge the useful suggestions and comments from colleagues and the members of the feedback group. Specifically, they wish to thank Joop Oude Lohuis, Leo Meyer, Corjan Brink, Bert de Vries, Jan-Anne Annema, Bart Wesselink for their comments on earlier versions of this report. Finally, the authors also greatly appreciate the comments made by Wim Turkenburg, Jan-Paul van Soest, and Tim van der Hagen.

Abstract

The effect of a nuclear energy expansion strategy in Europe on health damages from air pollution

The capacity of nuclear energy to generate carbon-free electricity has put it back on the agenda despite the objections against nuclear energy, of which the main ones are the risks of accidents, proliferation, and long-term waste disposal. In June 2006, the Social and Economic Council of the Netherlands (SER) issued an advisory report “Naar een kansrijk en duurzaam energiebeleid” (06/10) (On to a successful and sustainable energy policy) containing recommendations for a sustainable energy system in the Netherlands. A sequel report is planned for the end of 2007 on the potential role of nuclear energy. Our report aims to contribute to this discussion by adding a new element to the debate within the SER, and analyzes the impacts of a nuclear expansion in Europe for health damages from air pollution. If the nuclear capacity in the EU is extended, this will likely reduce the demand for fossil energy (and not biomass or wind and solar energy). This analysis shows that the benefits of nuclear energy in terms of reduced climate change and air pollution amount to 0.5 cent per kWh. This 0.5 cent per KWh equals approximately 10% of the electricity production price with nuclear power. There are no sound estimates of the costs covering the long term nuclear waste disposal and proliferation. Current expenses on waste management amount to 0.1 cent per KWh. This study suggests there is room for investment in long term waste disposal, if solutions emerge. However, this is not a full scale cost-benefit analysis and we doubt whether aspects like proliferation and long term waste disposal can be quantified. Hence, ultimately a political decision on nuclear energy cannot solely be based on a full or partial cost-benefit analysis.

Keywords:

Nuclear power, air pollution, climate change, damage costs, cost-benefit analysis

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Rapport in het kort

Mogelijke baten in de luchtkwaliteit van Europa door kernenergie

Dit rapport analyseert de gevolgen van het opheffen van nationale beperkingen op het toepassen van kernenergie, en de gevolgen daarvan op het Europese energiesysteem, Momenteel is het kernenergie beleid in Europa sterk gedifferentieerd, variërend van stimulerend beleid (Frankrijk) tot verbod/geen verdere groei (Duitsland, Nederland). De gevolgen van het opheffen van nationale beperkingen op het gebruik van kernenergie in Europa worden gerapporteerd voor zowel de publieke als de private sector. Als referentie is een bestaand scenario genomen, gepubliceerd door het Europees Milieu Agentschap, waarbij Europa doorgaat met klimaatbeleid. Ten opzichte van dit basispad neemt de elektriciteitsproductie van kernenergie in de EU, indien nationale beperkingen worden losgelaten, toe met 45% in 2030. Vooral de toenemende emissieprijs voor CO_2 (oplopend tot 65 euro/ton CO_2 in 2030) en de toenemende kosten voor de bestrijding van luchtverontreiniging door fossiele brandstoffen maken de toepassing van kernenergie interessant voor de stroomproducent.

De vermindering van het aantal kolencentrales leidt tot een daling van de gezondheidsschade door luchtverontreiniging als gevolg van de uitbreiding van kernenergie. Deze daling van de gezondheidsschade wordt in dit rapport gemonetariseerd. Over de levensduur van de centrale bedragen de verdisconteerde externe baten (gezondheidswinst door verbeterde luchtkwaliteit) van een uitbreiding van kernenergie in Europa mogelijk 0,5 cent per KWh.

Er bestaan geen betrouwbare kostenschattingen die rechtdoen aan de belangrijkste zorgen over kernenergie, zoals het permanent, duurzaam opslaan van kernafval, en het gevaar voor proliferatie. De huidige uitgaven aan opslag van kernafval bedragen ≅0,1 cent per kWh. Dit rapport laat zien dat de mogelijke baten van kernenergie door verminderde emissies naar de lucht ongeveer 0,5 cent per KWh bedragen (≅10% van de productieprijs). Deze studie geeft dus aan dat er extra ruimte is voor investeringen in de langdurige opslag van kernafval, indien hiervoor een oplossing wordt gevonden. Aangezien een formele kosten-batenanalyse nog niet mogelijk is zal een politiek besluit over kernenergie niet alleen op basis hiervan kunnen worden genomen.

Trefwoorden: nucleaire energie, luchtvervuiling, klimaatverandering, schade, kosten-baten analyse

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Samenvatting

Acceptatie kernenergie verschillend in EU-lidstaten

Momenteel is het kernenergie beleid in Europa sterk gedifferentieerd, variërend van stimulerend beleid (Frankrijk) tot verbod/geen verdere groei (Duitsland, Nederland). Dit rapport analyseert de mogelijke gevolgen van het opheffen van nationale beperkingen op het gebruik van kernenergie in Europa, zowel vanuit het oogpunt van publieke en private sector. Als uitgangspunt is een bestaand scenario gekozen, gepubliceerd door het Europees Milieu Agentschap, waarbij in Europa klimaatbeleid gevoerd wordt, rekening houdend met nationale regelgeving op het gebied van kernenergie. Met behulp van het Europees energiemodel PRIMES zijn de consequenties voor Europa tot 2030 doorgerekend.

Private sector krijgt meer investeringsruimte door hoge CO_2-prijs

In de nucleaire variant zijn de nationale beperkingen op kernenergie losgelaten, en de gevolgen daarvan op het Europese energiesysteem doorgerekend. Ten opzichte van het basispad neemt de elektriciteitsproductie van kernenergie in de EU toe met 45% in 2030. Vooral de toenemende emissieprijs voor CO_2 (oplopend tot 65 euro/ton CO_2 in 2030) en de toenemende kosten voor de bestrijding van luchtverontreiniging door fossiele brandstoffen maken de toepassing van kernenergie interessant voor de stroomproducent.

Kernenergie een dilemma in het duurzaamheiddebat

Er bestaan geen betrouwbare kostenschattingen die rechtdoen aan de belangrijkste zorgen over kernenergie, zoals het permanent, duurzaam opslaan van kernafval, het gevaar voor proliferatie en de acceptatie door de maatschappij. Deze analyse geeft aan dat de mogelijke baten van kernenergie door verminderde emissies naar de lucht ongeveer 0.5 cent per KWh bedragen (≅10% van de productieprijs). De huidige uitgaven aan opslag van kernafval bedragen ca. 0.1 cent per kWh. Deze studie geeft aan dat er ruimte is voor investeringen in de langdurige opslag van kernafval, indien hiervoor een oplossing wordt gevonden. Aangezien een formele kosten-batenanalyse nog niet mogelijk is zal een politiek besluit over kernenergie niet alleen op basis hiervan kunnen worden gemaakt.

Door verbeterde luchtkwaliteit draagt kernenergie significant bij aan de gezondheidswinst

Dit rapport analyseert de gezondheidseffecten van de uitbreiding van kernenergie. Waar mogelijk zijn de effecten gemonetariseerd. Over de levensduur van de centrale bedragen de verdisconteerde externe baten (gezondheidswinst door verbeterde luchtkwaliteit) van een uitbreiding van kernenergie in Europa mogelijk 0.5 cent per KWh.

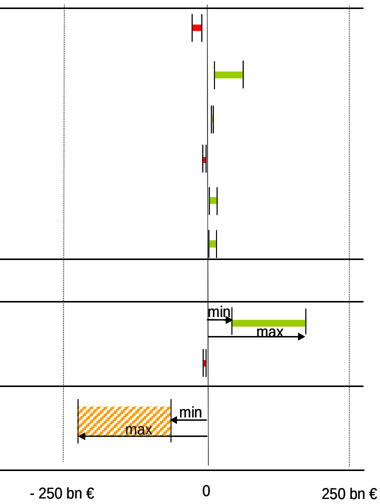
Extensive Summary

The capacity of nuclear energy to generate carbon-free electricity has put it back on the agenda despite the objections against nuclear energy, of which the main ones are the risks of accidents, proliferation, and long-term waste disposal. In June 2006, the Social and Economic Council of the Netherlands (SER) issued an advisory report “Naar een kansrijk en duurzaam energiebeleid” (06/10) containing recommendations for a sustainable energy system in the Netherlands. A sequel report is planned for 2007 on the potential role of nuclear energy. This report aims to contribute to this discussion by adding a new element. If the nuclear capacity in the EU is extended, this will likely reduce the demand for fossil energy, and consequently reduce Europe’s emissions of air pollutants, resulting in improvements in human health.

Analysis not an integrated cost-benefit assessment but a quantifier of health impacts

The table below summarizes the consequences of lifting the restrictions on a potential expansion of the nuclear capacity in Europe. In the climate-action/nuclear expansion scenario (projecting a 45% nuclear expansion by 2030) we neglected the (possibly high) transaction costs for raising public confidence in the use of nuclear power. These costs are difficult to estimate, because incidents may shift public opinion against nuclear energy and have serious repercussions on these costs. The impacts of the nuclear expansion are either presented in physical terms or plotted in monetary terms. The physical results are either cumulated over the entire lifetime of nuclear power stations or restricted to the year 2030 (energy mix and imports), while the monetary impacts capture the cumulated annual discounted impact flows over future years. These impacts are discounted at 2.5%.

Cumulated impacts of a 45% nuclear expansion by 2030 (costs = red, gains = green)

	Physical Indicators	% change from the baseline	CBA Discounted monetarized impacts
Medium term			
Nuclear Electricity generation	in 2030: TWh	+45%	
CO_2 emissions	In 2030: Gton CO_2	-3.5%	
Gas Imports	in 2030: Mtoe	-6.4%	
Uranium Imports	in 2030: Kton Uranium	+40%	
Bronchitis	In 2030: number of people	-3.0%	
Restricted Activity Days	In 2030: number of days	-2.5%	
Long Term			
$PM_{2.5}$ Deaths	Number of people	-1.9%	
Deaths from accidents (expected)	Number of people	+0.5%	
Waste	Kg Hm in Europe	+60%	
Risks of Proliferation	Nuclear installations world	+4%	

The major assumption of the Baseline concerns the DGTREN 2005 scenario with optimistic economic growth assumptions and median cost estimates for all energy technologies. The PRIMES model, is employed to estimate future pathways for all energy markets. Despite the uncertainties involved in developing scenarios for future energy markets, we find the median estimate assumptions reasonable, as this Baseline scenario has been reviewed by national energy experts of all EU member states. In addition, this scenario assumes the CO_2 emissions price to increase to 65 euro/tCO_2 in 2030, and the air pollution targets to be in line with the EU's Air Quality strategy for 2010.The figure above illustrates the impacts, as in the following:

1. Private sector benefits from nuclear power with high CO_2 prices. The nuclear expansion scenario calculates a 45% increase of the EU capacity of nuclear power in the next 25 years under moderate climate policies assumptions and no national restrictions on the production of nuclear energy.

2. The 45% expansion of nuclear energy involves the generation of 13 PWh electricity, while the discounted business costs will be around 18 bn euro. These costs, including current practices with respect to waste management techniques, come from increased investments, but are more than compensated by lower CO_2 emissions, and thus lower permit imports at global emission. The discounted gain from reduced permit imports will be equal to 30-34 bn euro. Thus, power production companies would have the economic incentive to invest in this program if the climate policy is pursued as described above. The minimal permit price should be 10 euro/t CO_2 so as to have a positive balance for nuclear power (given the costs of current waste management practices).

3. There will also be a reduction in fossil fuel, mainly coal, leading to a reduction in the background concentration of particulate matter (PM) in Europe. This will, in turn, lower the chronic exposure to PM, and result in a lower number of cases of chronic bronchitis and restricted activity days. According to the monetary valuation procedures of the Clean Air For Europe (CAFE) program, this leads to a gain equal to 30-97 bn euro (median estimate equals 36 bn euro). This represents an external impact not directly affecting economic growth, but certainly affecting the welfare of EU citizens. The benefits might be underestimated as positive health (and landscape) effects from reduced coal mining have not been quantified.

4. The "Chernobyl accident" served as an example of a small risk with large consequences. This kind of accident might even occur in the future, and if it does, it will impact on health due to radiation, and environmental degradation due to contamination of soil, air, and water. The nuclear expansion project analyzed in this report concerns Generation III types of nuclear power stations, with Generation III reactors that are expected to be safer than the current power stations. The nuclear expansion scenario will add an estimated mortality risk of approximately five persons per billion inhabitants per year. These types of risks tend to be very small compared to the risks in the nineties connected to the

Chernobyl type of nuclear power stations in Central Europe (loss estimated at 2 bn euro). It should be noted here that risks and consequences on ecosystems are not included.

5. Less exposure to PM will also reduce the number of premature deaths from air pollution by 240,000 at the most (equal to 1.9% of all the PM-related premature deaths). According to the monetary valuation procedures of the Clean Air For Europe (CAFE) program this leads to avoided environmental damages equal to 2-462 bn euro (median estimate 129 bn euro).

6. Aggregating these impacts leads to a net welfare gain equal to 50-510 bn euro (median estimate 171 bn euro). But, there are longer term impacts, which are much more difficult to quantify, i.e. the production and long-term disposal of waste and risks involved in proliferation. Here we indicate the physical impact if possible and show that the costs for handling proliferation and waste impacts, based on external benefits, may increase up to 50-510 bn euro (median estimate 171 bn euro) before a break-even point is reached.

7. Risks and costs associated with proliferation cannot be quantified, as there is little to no sound empirical data. The civil use of nuclear energy inherently involves threats due to 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 are, on the one hand, the use of enrichment facilities and, on the other the production of fissile materials during reactor operation that remain embedded in nuclear waste. All nuclear reactors, however new in design 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. And, given the modest expansion of nuclear energy in the EU compared with the increasing capacities in the rest of the world, the additional risks from the EU's nuclear expansion on proliferation are relatively small. 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 is phased out entirely.

8. It can be seen that in Europe the amount of nuclear waste produced from this nuclear expansion project will ultimately raise the cumulated stock by 60%. The net present economic value of a project is the sum of discounted monetary flows (with positive discount rates). Hence, little is done to bring the interests of future, burdened, generations to the fore, assuming a technical solution can be found for handling the nuclear waste in the very long term.

9. The current waste management efforts cost less than 0.1 cent per KWh. The cost–benefit analysis theoretically allows the costs of waste management and proliferation to increase up to 0.5 cent per KWh, which can be shown to be equal to the median estimate of the discounted benefits of 171 bn euro. This break-even price may be even higher if lower discount rates are employed or if a higher (but still reasonable) discounted monetary

estimate for avoided premature deaths applies. In all cases there seems to be scope for intensified waste management and prevention of the risks associated with proliferation, i.e. with welfare benefits outweighing the costs.

10. The nuclear expansion could prove to be a less profitable strategy when the global coordination of climate policies fails, and there is not sufficient willingness of countries to combat climate change. In this case local air pollution benefits still provide substantial positive effects for the expansion of nuclear power, at least from a welfare point of view, but the direct gains to electricity producers diminish (when the climate price will be higher than 10 euro per tonne CO_2).

As the European air quality and climate targets become more stringent, the context for fossil-free energy production changes and, in turn, so does for the nuclear energy context. There are clear economic incentives to expand nuclear power in Europe in the context of the ambitions on climate change. Even if the climate policies fail, the potential air pollution benefits will remain as the cost-benefit ratio of current air pollution policies is still well below one. As long as there is no full accounting for the air pollution externality in commodity prices, an EU-wide strategy for nuclear power enables welfare gains due to lower damages to public health (also the case for some renewables). There are also clear drawbacks, although there seems to be scope for governments to act on long-term aspects of waste management and proliferation.

Finally, the findings of a recent survey, conducted among 18,000 citizens of 18 countries representing the major regions in the world, show that 62% believe that existing nuclear reactors should continue to be used, while 59% are against new nuclear plants. This shows that public opinion on nuclear energy is quite divided. Any nuclear incident or rumours of the possible use of nuclear weapons by terrorists will shift the balance and lead to a higher valuation of the disadvantages of nuclear energy.

1 Introduction

It is very difficult to predict with any confidence what the 21st century will hold for nuclear power. However, the factors that will shape its future are less unclear. Still the debate on nuclear energy is very difficult because of the different magnitudes of different impacts and risks involved (including the heterogeneous perspectives on these risks by different stakeholders). Whereas some European countries (like Austria and Italy) today have no plans to build nuclear power capacity, and others (such as Germany and Sweden) are officially committed to gradually phase out domestic nuclear energy supply, recent policy directions in other countries (including the Netherlands and the United Kingdom) show that nuclear energy is reappearing on the political agenda, while some governments (e.g. Finland and France) decisively continue to keep a significant part for nuclear energy in their national electricity generation.

The aim of this report is to analyse the possible contribution of nuclear energy to the establishment of sustainable development in Europe on the basis of a concise inspection of the main driving forces involved. Arguments concerning radioactive waste, nuclear proliferation, reactor accidents, economic competitiveness, and public opinion continue to create concerns, and thereby influence nuclear energy policy making. The issues of energy supply security, local air pollution, and global climate change provide growing reasons to reassess its future desirable share in European power production. Recently, a MNP/ECN study (2006) concluded from a cost-effectiveness analysis that an expansion of nuclear energy in the Netherlands is a necessary factor, if nuclear energy is disregarded as an option when sticking to these deep cuts in emissions, then the costs of compliance in 2020 will increase by 0.3% of GDP. This report takes a broader perspective, and will, from a Cost-Benefit Analysis (CBA) perspective, try to sketch the possibilities for comparing different kinds of impacts from more nuclear power in Europe.

The report is set up as follows. First, an overview will be given of the main changes in elements relevant for the discussion on nuclear energy. What has changed the discussion on nuclear energy since the 1970s? The CBA approach will be used to analyze the expansion of nuclear energy. Chapter 3 summarizes the methodological aspects when applying this methodology, and also provides an overview of the disadvantages or limitations of the chosen approach.

2 What has changed in the discussion on nuclear energy since the 1970s?

From 1970 onwards, nuclear energy has been a controversial subject. At the country level, the main question was to whether to expand or reduce the number of nuclear power stations. After the Harrisburg accident people's approval of nuclear energy dropped, while elsewhere – in the Netherlands, for example –the government decided to build three new power plants. Still, nuclear capacities hardly increased at the European level; after the Chernobyl accident the acceptance of nuclear declined significantly, and led to a stagnation of further expansion nuclear power. In the policy debate arguments on nuclear energy concern radioactive waste, reactor accidents, and nuclear proliferation, but also economic competitiveness, resource availability, and public opinion. Especially the issues of climate change and supply security have provided a new rationale for the reappearance of nuclear energy on the international political agenda. Because nuclear energy currently faces stagnation, it is unrealistic to consider it a serious option for significantly reducing carbon emissions in the short term. On the other hand, we cannot automatically dismiss the nuclear option, as it is a form of energy that can contribute to decreasing emissions of greenhouse gases in the longer term.

Whether or not nuclear energy will play a role of significance in the long-term, all energy technologies – including nuclear ones – ought to be considered in terms of their potential to contribute to goals of sustainable development. These include, in general, aspects related to environmental, economic, and social risks, and, in particular, climate change prevention and supply security support. This document 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 (see also Turkenburg, 2003, 2006).

Sustainability indicators for any energy option are placed in three categories: environmental, economic and social. Addressing the role of nuclear energy in establishing sustainable energy paths involves especially aspects of radioactive waste, reactor accidents, nuclear proliferation, market competitiveness, climate change, energy security, resource availability, and public opinion. Radioactive waste, reactor accidents, and climate change mostly belong to *environmental* indicators for the sustainability of nuclear energy. Its market competitiveness, natural resource availability, and role in contributing to ascertaining energy security have a predominantly *economic* dimension. The characteristics of nuclear energy in terms of nuclear proliferation and public opinion are mainly *social* indicators.

These eight aspects will be examined below, in separate sections. First, the three most technical aspects – radioactive waste, reactor accidents, and nuclear proliferation – are examined concisely and qualitatively in terms of the potential risks they involve. In the following sections, the five remaining less technical aspects – market competitiveness, climate change, energy security, resource availability, and public opinion – are dealt with in consecutive sections.

2.1 Climate change and air pollution

Although less pronounced than in other parts of the world and notably developing countries, energy and electricity consumption in Europe are expected to continue increasing over the foreseeable future, at least until 2030, and most likely beyond (IEA, 2006; IIASA/WEC, 1998). With the current predominance of fossil fuels in our energy system, accounting globally for almost 90% of commercial primary energy supply, this growth in energy consumption will lead, in a business-as-usual scenario, to a gradual but steady increase in the level of greenhouse gas (GHG) emissions (IPCC, 2000). Essentially, nuclear power does not emit such GHGs. Even when the complete nuclear fuel chain is considered, including especially the mining of uranium (Mudd and Diesendorf, 2007) and the construction of the power plant, nuclear energy emits typically no more than a few percent of GHGs per unit of generated electricity[1] in comparison to coal, oil, or even natural gas-based power production, and around the same order of magnitude of GHGs (as renewables such as wind or solar power (see Table 2.1)

As the mitigation of climate change is increasingly being recognized as one of the largest present global challenges, nuclear energy is receiving renewed consideration. If nuclear power is kept in the energy mix for reasons of achieving GHG emission reductions, it can only contribute to addressing the problem of climate change when it is expanded significantly on a global scale (Sailor et al., 2000). If nuclear energy were expanded 10-fold, it could contribute to reducing annual CO_2 emissions in the 2^{nd} half of the 21^{st} century by about 30% (Van der Zwaan, 2002). Hence, under such a challenging scenario, nuclear energy can still at best only be part of the solution, and should be complemented by drastic fossil fuel decarbonisation efforts e.g. through the application of CO_2 capture and storage (CCS), a massive development of renewables, and/or far-reaching efficiency measures, in order to attain a CO_2 emissions reduction down to about one-third of the present level by the end of the century. Such a CO_2 emission profile would preclude reaching a doubling of the atmospheric CO_2 concentration, corresponding to an increase in the average atmospheric temperature of typically a few degrees Celsius.

[1] The Life Cycle Energy Requirements for the Nuclear Power Plant for Uranium by centrifuge enrichment (the most common technology) is approximately 1.7%, and by diffusion enrichment technology 5.7%, (WNA, 2006)

Table 2.1: Lifecycle analysis (LCA) for electricity generation (2000)

Emission in g/kWh$_{electric}$		
Electricity from:	CO_2-eq	CO_2
Wind Park offshore	**23**	**22**
Wind Park onshore	**24**	**23**
Nuclear (uranium, import-mix)	***32***	***31***
Hydropower	**40**	**39**
Biogas (CHP)	**49**	**5**
Solar (photovoltaic)	**101**	**89**
Gas (electricity)	**428**	**398**
Import-Coal (electricity)	**949**	**897**

Source: Oeko et al., 2007

In Europe too, it is evident that nuclear energy can be no panacea with respect to the desired reduction in GHG emission levels. If climate change control ambitions of some countries remain as high as their current intentions to cut down CO_2 emissions by 50% around the middle of the century, nuclear energy could significantly reduce emissions. Given that Europe has 137 GWe installed nuclear capacity (one-third of the EU's electricity use being produced by nuclear power), compared to the global figure of around 370 GWe worldwide and the largest nuclear energy region (see Figure 2.1), it is, in principle, in a good position to increase the role of nuclear energy for climate change management. As the development of nuclear energy in Europe currently faces stagnation, and because both the planning and construction of new nuclear power plants involve long lead times, nuclear power can contribute significantly to realizing further CO_2 emission reductions in only a few decades from now. The required expansion of nuclear capacity installed for GHG emission reduction purposes would simultaneously contribute to mitigating several environmental and health problems of local and regional air pollution, as nuclear power does not generate emissions of SO_2, NO_x, Hg, or particulates, unlike its fossil counterpart, coal-based power. However, it will increase the release of radioactive effluents (notably krypton-85) into the atmosphere.

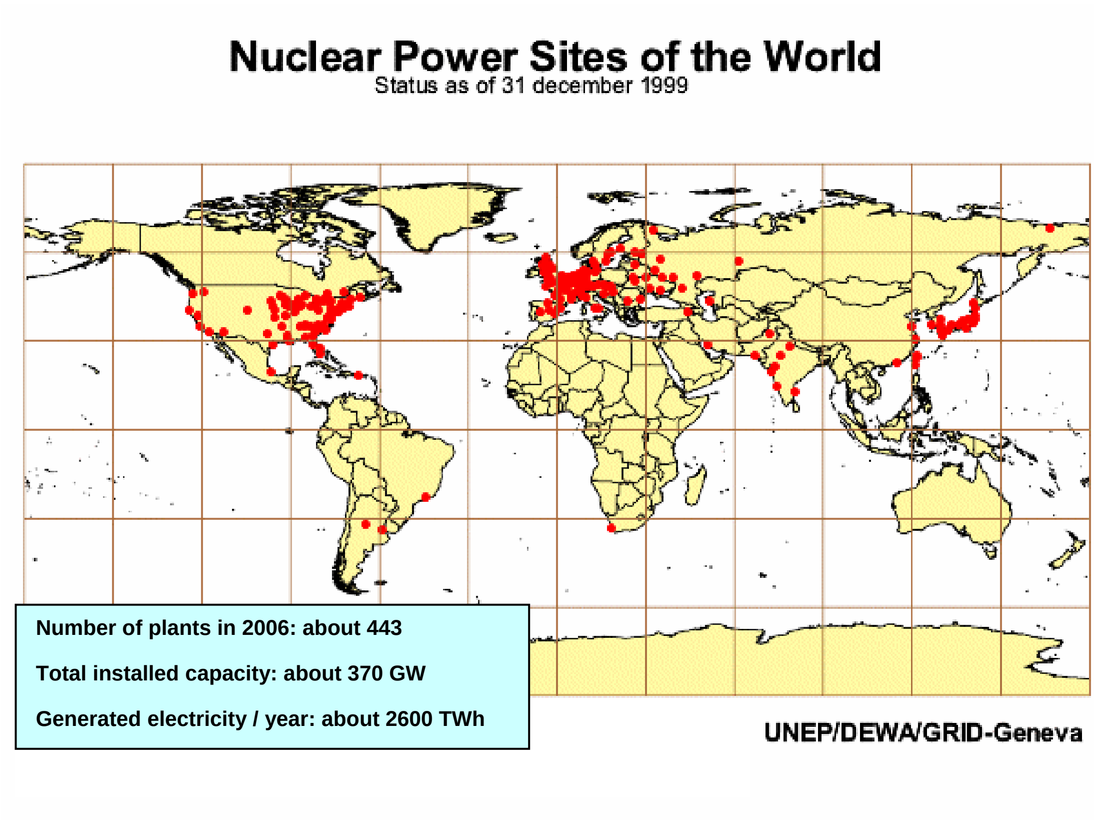


Figure 2.1: Nuclear power sites of the world (Source: Turkenburg, 2006).

2.2 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 ways. The attitude to the former is that of "concentration and protection": radioactive contamination of the external environment from spent fuel storage minimized through several layers of physical containment. The principle of "dilution and exposure" is applied mainly to the latter, which means that 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.

2.2.1 Accumulation of radionuclides in the biosphere

The emission of radionuclides into the biosphere may result in an accumulation of these nuclides in time and in parts of the biosphere, depending on physical, chemical, and biological properties of these nuclides. Due to accumulation, the emissions may cause health damage on the longer term and influence the functioning of natural systems negatively. Therefore this aspect should be considered, especially when assuming a nuclear system with a globally installed capacity of 1700 GWe or more by 2030.

One of the radionuclides deserving specific attention is krypton-85, a gaseous fission product (with a half-life of 10.5 years) that is emitted during the reprocessing of spent fuel. It accumulates in the atmosphere. The Kr-85 activity in air showed a regular increase in the last decades (see Figure 2.2, Wingera et al., 2005). The ground level reached at Jungfraujoch in the year 2001 was about 1.3 Bq/m^3. Kr-85 dominates present-day artificial radioactivity in air (Satorius et al., 2002). The sink of Kr-85 is the radioactive decay in the atmosphere, with a half-life of 10.5 years. The present-day Kr-85 activity in the atmosphere is released mainly from reprocessing plants, for example, in La Hague, France, and Sellafield, United Kingdom. A yearly global release rate of about $5 \cdot 10^{17}$ Bq is estimated from the measured global activity.

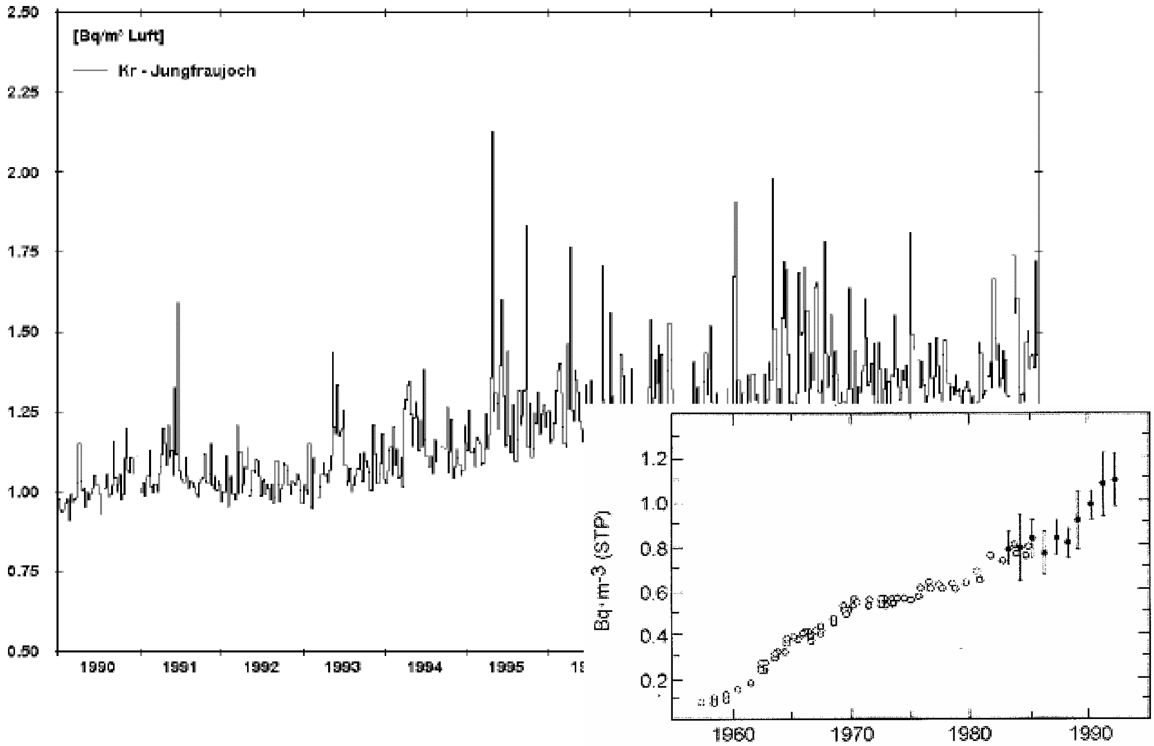


Figure 2.2: Kr-85 measurements at Jungfraujoch, 1990-2001 (Source: Satorius et al., 2002).

From a sustainable, precautionary principle, further accumulation of Kr-85 should be limited (see for some concerns Textbox 1), by limiting the quantity of radionuclides be emitted from waste processing plants, which can be dependent on the growth of nuclear waste removal capacity.

Attention should also be given to the accumulation of other radionuclides that may cause damage. Examples are tritium (H-3), jodium-129 (J-129) and carbon-14 (C-14, life-time: 5730 years.

Textbox 1: Krypton-85 accumulation in the atmosphere

Krypton-85 is a long-lived radioactive isotope which is naturally released into the atmosphere in small quantities (Harrison and Apsimon, 1994), approximately 5.2 10^{13} Bq/yr and, in larger quantities artificially (10^{17}-10^{18} Bq/yr). It has steadily accumulated in the atmosphere since 1945 (from <0.2 Bg/m^3), when anthropogenic nuclear activities started, and reaches 1.3 Bq/m^3 nowadays.

Ion production

The principal concern with krypton-85 release is not a radiological/medical one, as population doses are small (Boeck, 1976), but the possible disturbance of the global electrical system (Legasov et al, 1984, Tertyshnik et al., 1977). It is known from nuclear weapon testing (Huzita, 1966) that atmospheric radioactivity increases air's natural conductivity.

The conductivity of air is proportional to the (small) ion concentration. These ions are formed naturally in atmospheric air at a rate (near the surface) of about 10 ion-pairs cm^{-3} s^{-1} (Chalmers, 1967). There are three major sources of these ions: airborne alpha radiation, cosmic rays and terrestrial gamma radiation. Near the Earth's surface, gamma radiation from the soil is the chief source of ionization, due to the nuclear decay in the Earth's crust. This accounts for about 80% of the ionization near the surface. The remaining ionization is caused by cosmic rays, whose intensity increases greatly with height. Ionization over the oceans is considerably lower, since there is no gamma contribution and a greatly reduced amount of airborne alpha radiation.

Removal

The removal of ions can take place through two mechanisms: ion-ion recombination and ion-aerosol attachment. In the last case the particles become electrically charged (Fuchs, 1963). In the steady state, the bipolar ion production rate q per unit volume and the ion loss rates are balanced, given by (Harrison and Apsimon, 1994):

$$q-\alpha n^2-\beta nZ=0 \qquad (1)$$

Where α is defined as the ion-ion recombination coefficient (1.6,10^{-6} cm^3.s^{-1}, e.g. Gringel et al, 1978) and β is the attachment coefficient between an ion and aerosol particle. β depends on the aerosol particle radius and charge (Gunn, 1954). Z is aerosol particle number concentration per unit volume, and n is the average ion number concentration. At higher aerosol concentration (i.e. 10 μg/m^3 with 0.2 μm radius particles) n is dominated by aerosol-ion attachments. From the formula it becomes clear that a change in conductivity can occur due to an increase in the production rate q (by, for example the additional ionization caused by krypton-85) or a change in aerosol concentration (increase will decrease conductivity).

Change in conductivity by krypton-85

The amount of extra ionization caused by the beta radiation can be found by using the average beta energy (0.249 MeV) for krypton-85. For a krypton-85 concentration of C_{kr} Bq/m^3 the ionization rate is:

$$q_{kr}=(2.49.10^5/35).C_{kr}. \qquad (2)$$

Assuming a surface ionization rate q_o of 10 ion-pairs cm^{-3}.s^{-1} the change in ion production is:

$$dq/q_0 = 7.11.10^{-4}\ C_{kr}. \qquad (3)$$

Over the oceans, where q_0 is about one-fifth of its continental value, the fractional change will be corresponding larger. The concentration of krypton falls with density (height) of air:

$$C_{kr(z)}= c(0)e^{-z/8561}\text{, where c(0) is the surface concentration.} \quad (4)$$

Combining ion production from the crust and cosmic ray, a maximum share of krypton-85 ion production can be expected at a height of 500-1500m, about twice the value at the surface and at a surface concentration of 1.3 Bq/m^3 , a change of 2‰ in ion concentration at 1000 m can be expected . Locally, near a nuclear waste processing plant, the share can increase to approximately 20% (Clarke, 1979). Note that the conductivity above mountainous (remote) areas (Antarctic, Himalaya, determines the Earths resistance and interaction with the ionsphere.

Consequence for the atmospheric system

- It is generally assumed, although surrounded with some uncertainty and controversial (Illingworth and Latham, 1975), that thunderstorms provide the earth with a small negative charge. The slight conductivity of the atmosphere (see above) creates a small, opposite "fair weather current" (E= + 100 V.m^{-1}, J ~2 pA.m^{-2} at the surface). Considering the earth as a spherical capacitor (with C_t ~2.8 Farads) it would lose it's charge (τ ~667 s) in about an hour. The earth needs therefore continuously be charged by approximately 2000 thunderstorms (Schonland, 1953). A change of 0.1% could therefore be compared with the equivalent of two continually active thunderstorms. The interaction between an increasing conductivity and thunderstorms remains unclear although there are suggestions (Spangler and Rosenkilde, 1979) that it would weaken thunderstorm lighting.
- Recently there have been some suggestions that charged ions can, even at small concentrations, can have a (substantial?) effect on the formation of certain type's of clouds (Marsh and Svensmark; 2000, Harrison, 2000; Carslaw et al., 2002) . If confirmed this would imply that a changing concentration of krypton-85 could affect to some extent the earth's climate.

2.2.2 Solid radioactive waste

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 for 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 de-commissioning nuclear power plants.[2] 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 lose much of their radioactivity in short periods of time.

Various means for management types (NEA, 2007) are considered for each of the main irradiated fuel constituents discharged from LWRs – uranium, plutonium, actinides and fission products:

- Uranium: constitutes about 96% of the fuel unloaded from commercial power reactors. In the case of light water reactors, the most widespread type of reactor in Europe and in the world, the spent fuel on discharge still contains 0.90% enriched in the fissile isotope 235, whereas natural uranium contains only 0.7% of this isotope.

- Plutonium: constitutes of about 1% of the weight of discharged fuel; it is a fissile material which can be used as fuel in present and future commercial reactors.

- Minor actinides constitute about 0.1% of the weight of discharged fuel. They consist of about 50% neptunium, 47% americium and 3% curium, which are very radiotoxic;

- Fission products (iodine, technetium, neodymium, zirconium, molybdenum, cerium, cesium, ruthenium, palladium, etc.) constitute about 2.9% of the weight of discharged fuel. At the present stage of knowledge and technological capacity, they are considered as the final waste form of nuclear power production, unless a specific use is found for the non-radioactive platinum metals.

As illustration, a typical 1000-MWe PWR unit operating at 75% load factor generates about 21 tons of spent fuel at a burn-up of 43 GWd/t; this contains about 20t of enriched U; 230 kg Pu; 23 kg minor actinides; 750 kg fission products.

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[2] The terms "radioactive emissions" and "spent fuel" categorize the waste produced according to the state in which it is generated. On the other hand, the terms HLW and LLW form a categorization 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 categorization (as it is not emitted into the environment). The distinction between HLW and LLW is sometimes refined by adding ILW (intermediate-level waste).

The management of irradiated fuel should ensure that the biosphere is protected and the public must be convinced of the effectiveness of the methods. Since the spent fuel contains very long-lived radionuclides, some protection is required for at least 100,000 years. Two means are possible:

- Society can wait for the natural decay of the radioactive elements by isolating them physically from the biosphere through installation of successive barriers at a suitable depth in the ground. This strategy leads to deep geological disposal.

- Society can make use of nuclear reactions that will transmute the very long-lived wastes into less radioactive or shorter-lived products.

Whatever the solution chosen for highly radioactive wastes, deep geological repository disposal will always be necessary. Tests are in progress to try to reduce the volume of these wastes, but there is still a lower threshold below which technology cannot reasonably go.

For society, the risks of a waste storage site depend on its radiotoxicity and the possibility of transfer to the biosphere. This transfer can occur after failure of the barriers and subsequent migration of the elements into the surrounding geosphere. International studies (Pagis, PACOMA) suggests that these phenomena are very slow, so that no activity would be noticeable for at least 400,000 years. Uncertainties regarding the transfer mechanisms, however, as well as the possibility of the waste coming into contact with the biosphere following a geological upheaval or accidental intrusion, have prevented the choice of certain location to date.

Different irradiated fuel management approaches can be envisaged:

- Deep geological disposal of irradiated fuel without reprocessing. The fuel is encapsulated after an interim storage time period varying from 10 years (planned for in the USA) to 40 years (planned for in Sweden) to allow sufficient decay of the residual power. This solution may be the least expensive and requires the least handling. On the other hand, it implies some waste of energy, the formation of which are in fact uranium and plutonium mines.

- The alternative strategy of reprocessing of the spent fuel followed by deep geological disposal of wastes has been chosen by France, United Kingdom, Japan and other countries. Uranium and plutonium are quantitatively separated from the other nuclides with yields ranging from 99.7 to 99.9%. The recovered uranium is re-enriched and recycled in LWRs. The minor actinides and highly radioactive fission products are embedded in glass and are meant for placement at the proper time into deep geologically sealed repositories. Their radiotoxicity decreases by a factor of 10 to 100 in 10,000 years. While the recycling of plutonium in LWRs decreases the growth rate of plutonium stocks, only the use of Fast Reactors specially designed to burn plutonium can decrease the plutonium inventory of spent fuel.

- Advanced Reprocessing involves the separation, not only of uranium and plutonium, but also that of the so-called "Minor Actinides" (neptunium, americium and curium) and some long-lived fission products into single element or element-group packages with similar nuclear and/or chemical properties. In this way, suitable solutions can be designed to improve conditioning or to set up transmutation scenarios. Transmutation of plutonium and minor actinides will reduce the radiotoxic potential of high-level waste but has little effect on the release rate of the radioactivity to the environment, since the very low solubility of the actinides is the controlling transfer factor to the biosphere. Further R&D is required to investigate all the aspects of this way of waste management, so as to be able to truly assess its benefits or consequences for the fuel cycle. Among the problems to be solved are the high-efficiency partitioning of hazardous materials and their subsequent transmutation.

- To this date, however, no country has 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, USA is planned to open and receive its first nuclear waste in 2010 at the earliest. On the basis of studies performed between 1991 and 2005, the French government will, in 2006, initiate a debate with the French Parliament on the choices of long-term disposal of HLW. 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. No uncertainties on either geological or container integrity exist for short term storage (e.g. centuries). A remaining fear though is that canisters, as a result of corrosion, may start to leak after thousands of years, and consequently contaminate groundwater.

The role of public opinion, in the form of local opposition (NIMBY)[3], in a governments' decisions on burying waste underground is a determinant factor here. The European Commission is preparing legislation (EU, 2007) that will create incentives and a regulatory framework for EU states to set up timetables and stimulate action to develop permanent (underground or above-ground) disposal facilities for high-level nuclear waste.

2.3 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

[3] Not In My Back Yard

designed in the former Soviet Union, particularly those of the Chernobyl-type power plant, the present generation of nuclear reactors has an improved safety record. The fact, however, that severe accidents *can* still occur, provides insufficient safety guarantees for the future, since the consequences of a serious accident, if it occurs, can be large. The potentially pervasive scale of reactor meltdown accidents was experienced during 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. Furthermore, an estimated aggregate of many thousands of people have already developed, or may develop, a fatal cancer as a result of radiation exposure.

Since 1986, however, much has changed, both regarding the probability of accidents occurring, and in terms of controlling potential consequences. In addition to many improvements in the technologies and materials used for reactor operation worldwide, all power plants today are, basically, 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, human–machine interactions in reactor operation have also been considerably improved. One of the additional measures that has contributed to establishing better safety 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 Pressurized Water Reactor (EPR) and pebble-bed High Temperature Reactor (HTR). As in the field of waste disposal, the EU is in the process of creating new directives (ie. EU, 2007) for reactor safety in order to improve security here and orchestrate this largely national issue on a European level. In particular, among the issues addressed are the ascertainment of sufficient funds for decommissioning nuclear power plants, the exchange of best practices in enhancing safety of nuclear installations, and provision of greater transparency and information for citizens.

2.4 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, 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 in possession of enrichment technologies, or organized terrorists with HEU, may use these for military or terrorist purposes, respectively.

Every year more than 50 tons of plutonium are produced by the current global nuclear arsenal 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 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 spent fuel standard is reasonably protected from diversion for weapon use – because of the highly radioactive materials in which it is embedded – its separation in a 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 the 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 to be phased out entirely.

2.5 Resource availability and energy security

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 considered to be widely available, economically acquirable and easy to store. Arguments of energy supply security will continue to motivate countries to maintain, expand and/or develop domestic nuclear power facilities, not only in the industrialized world (including notably countries in the EU, the ex-Soviet republics, Japan, and the USA), but also those in the developing world with presently modest or absent shares of nuclear energy in electricity production (including China and India). In a business-as-usual scenario, the EU's dependency on imported energy is seen to increase from 50% today to about 70% in 2030. Concerns regarding energy supply security drove the investments in nuclear power in Europe during the oil crises of the 1970s, even though Europe does not possess large domestic uranium resources. Similar events in the future could well again lead to an invigorated interest in nuclear energy, and an associated impulse to the construction of new nuclear power plants.

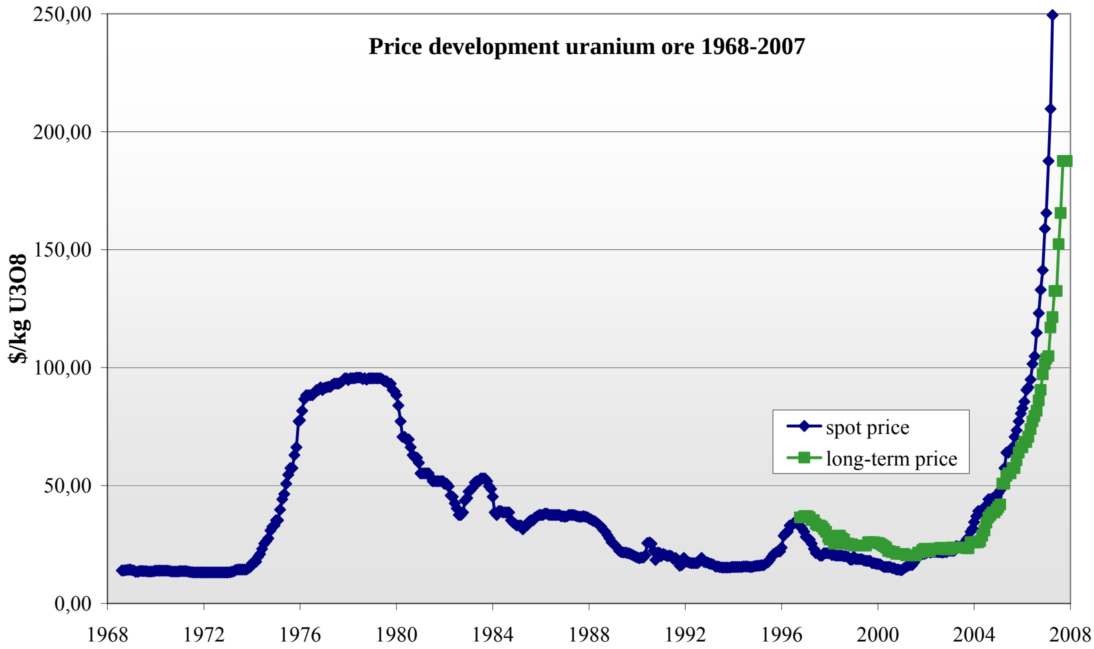

Figure 2.3: Price development of uranium ore (spot prices and long-term contracts) 1968-2007
(Source: TradeTech, http://uranium.info/prices/enr_spot.html).

A diverse roster of stable uranium producers exists globally, and the small storage space required implies that strategic reserves can be easily built. Furthermore, nuclear power is hardly sensitive to fluctuations in the price of uranium, so that price shocks and market volatilities, as experienced recently (see Figure 2.3), influence the generation price marginally (see Figure 2.4).

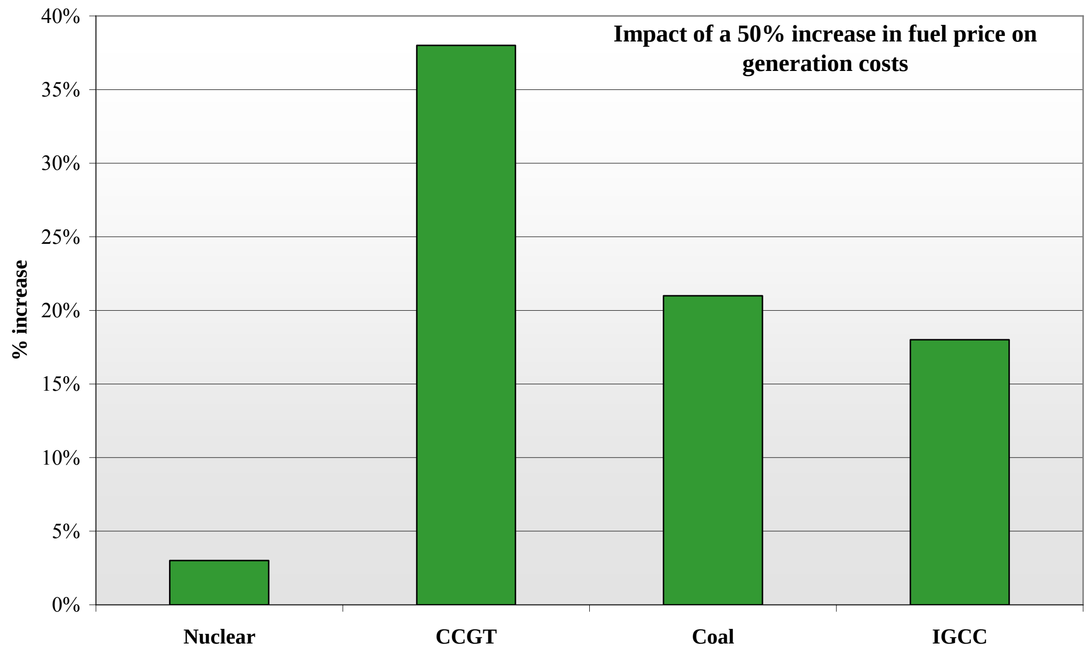

Figure 2.4: Impact of a 50% increase (compared to Baseline) in fuel price on generation costs
(Source: IEAE, 2006).

Still, concerns are sometimes expressed about the estimates of the global amount of uranium ultimately recoverable at a given price, and the comparison to scenarios of uranium consumption this century. A doubling of the uranium price has typically only an effect at the percentage level on the production cost of electricity. Therefore, while large quantities of uranium are still recoverable at the current price of \$40- \$50/kg U3O8, uranium reserves are often quoted at higher prices, e.g. \$130/kg U3O8. The Nuclear Energy Agency (NEA) estimates that total world conventional uranium resources, available at less than \$130/kg U, amount to about 17 Mt U3O8 (NEA, 2002).

This estimate may be conservative for several reasons.

- First, approximately 300-3000 Mt U3O8 can be recovered from the oceans at estimated prices of approximately \$200-300/kg U3O8.

- Second, the estimate of 17 Mt U is limited to conventional resources, i.e. deposits in which the uranium ore is rich enough to justify mining at the indicated price, and does not take into account cases where uranium can be produced as by-product.

- Third, low uranium prices and released military stocks over the last two decades have virtually eliminated incentives for supplementary uranium exploration, so that large quantities of undiscovered uranium, not yet included in the NEA estimates, are still likely to exist, particularly in the higher-cost categories. Hence, there is a high probability that the amount of uranium that will ultimately prove recoverable at or below \$130/kg U is significantly greater than 17 Mt U.

2.6 Solid radioactive waste

Whereas the current debates on climate change and energy supply security have a positive influence on the public attitude towards nuclear energy, for the moment support for new nuclear power plants remains tentative. Findings of a recent survey, conducted among 18,000 citizens of 18 countries representing the major regions in the world, show that 62% believe that existing nuclear reactors should continue to be used, but 59% are not in favor of building new nuclear plants (Globescan, 2005). As the impacts of climate change and the vulnerability of the European economy to foreign fuel imports become more evident, it is likely that the shift in public opinion of the last decade will further develop in favor of nuclear energy. The Chernobyl accident has dramatically demonstrated that a single event may abruptly modify the public acceptance of a technology. Inversely, a catastrophe associated with climate change, or a long-lasting rupture in the supply of oil or natural gas as a result of geopolitical tensions, may lead to a step-change in the support of nuclear power, both in Europe and elsewhere. Public opinion - on a time scale of decades appearing constant – may, in the longer run, be subject to significant variability.

As pointed out by Van der Zwaan (2007), the controversy over nuclear energy has mostly been related to the problems of waste, safety, and proliferation. Progress on these drivers of public skepticism towards nuclear power will likely positively influence support for the nuclear industry. Any severe incident related to these aspects, such as another major accident, or terrorists' use of a simple atomic bomb or radiological device will, likewise, imply a major setback in the acceptance of nuclear energy.

3 Methodological issues

This chapter will describe the major assumptions of the applied CBA modelling framework. It will also highlight the advantages and limits of the applied analysis.

3.1 Introduction

This study aims to shed some light on the costs and benefits involved to accommodate a nuclear expansion in Europe of almost 50% in the course of the next 25 years under the restriction of the EU target for renewable energy (Mantzos et al., 2004). The impacts of these variants of baseline scenarios are reported for the years 20230 and 2030. This is also the time horizon used for our calculations. Still, some impacts will continue beyond 2030. The assumption made is that all impacts occurring in 2030 are depreciated in 60 years (the average life-time of nuclear power stations).

In a cost-benefit analysis (CBA), all effects of an investment project are recorded and, wherever possible, given a monetary value. CBA is a well-founded tool based on the economic welfare theory. In the Netherlands CBA is used mainly for transport infrastructure projects. A special CBA guide has been developed to support this Dutch CBA practice (Eijgenraam et al., 2000).

The aim of a CBA is to express all effects in monetary terms and to sum them. However, this is not possible for all impacts. Some non-priced effects of investment projects can be reliably expressed in monetary terms, for example, journey time profits (in the case of transport investment projects) and some environmental effects. Other effects cannot be objectively expressed in monetary terms. This is also the case for this nuclear expansion described in this CBA. Impacts like “fear” for nuclear disasters (although the objectively calculated risks may be very low) and for proliferation of nuclear technology cannot be expressed in monetary terms. Therefore it was chosen in this CBA to express all effects in their own units – for example, investment costs in euros, emission reduction of Particulate Matter in kilograms, etcetera. These impacts (expressed in their own units) can be used for a Multi Criteria Analysis (MCA).

3.2 Scenarios, base case, discount rate and time period

A CBA compares a project alternative with a base case. The base case describes a possible future development of the “world without nuclear expansion”. It is recommended in the CBA guide to use two or more base-case scenarios. By doing so, the impact on CBA outcome of some important uncertainties in future developments (oil price, economic growth) can be analyzed. In this nuclear expansion project, only one base case is taken into account. However, a sensitivity analysis is carried out to give insight into some of the major uncertainties, with the sensitivity assumptions referring to higher oil prices, the willingness of regions to combat climate change, and other valuations.

The project alternative involves nuclear expansion in Europe by almost 50% in the course of the next 25 years, under the restriction of the EU target for renewable energy. The costs and benefits will be reported in net present values for the year 2000, against prices in the year 2000. Scenarios indicate to what extent the return of a project depends on specific and general external factors. Scenarios give a qualitative picture of the risks of a project, but do not provide a quantitative measure for risks (Eijgenraam et al., 2000). For valuing risks the “Commissie Risiscowaardering” (Advisory group on risk valuation) recommends a risk-free discount rate for a cash flow of 4% (in real terms) with a risk premium of 3% for market-related macro economic risks. As in the CBA for wind energy (Verrips et al.., 2005), a discount rate of 7% is used in this study. However, this 7% discount rate will be not be used in the cash flow for all cost and benefit categories. External effects of power plants like emissions of particulate matter, nitrogen and sulfur oxides (to the extent that these impacts are not internalized by emission charging or trading schemes) are not correlated with macro economic risks, so for these impacts, a discount rate of 4% is used.

Although the impacts of emissions on the end-points are modeled at the sectoral level for each country, we will only present results for the aggregate EU-25 region, so as to minimize the information presented in this report.

How to value direct costs and benefits for the longer term beyond 2030

The nuclear expansion strategy will be partially realized in 2020, and fully implemented in 2030. Subsequently, the nuclear energy power will be maintained by replacement investments up to 2040. The effects of the nuclear expansion project compared to the base case are estimated for the period of 2010 – 2030. However, it is likely that the built-up nuclear energy plants will continue to exist beyond this time frame. For this reason, the costs and benefits of the project are estimated for an infinite time frame by extending the calculated costs and benefits of the project for 2020 and 2030 periods. For the years beyond 2030, we assume that the undiscounted impacts in 2030 are depreciated by 0.02% per year (based on a 60-year lifetime of the nuclear facilities deployed in 2030). The discount rates as described above are also applied with respect to these depreciated impacts.

3.3 Impact calculation for 2030

We will focus on the following elements of costs and benefits. For the **direct economic impacts** we will rely on the calculations based on PRIMES. This is a bottom-up model, distinguishing many EU countries and sectors, which minimizes the costs of energy options to meet a prescribed exogenous final energy demand.

PRIMES energy system

The development of the PRIMES energy system model has been supported by a series of research programmes of the European Commission. In the 1998-1999 period, the model PRIMES was used to prepare the European Union Energy and Emissions Outlook for the Shared Analysis project of the European Commission, DG XVII. More recently, PRIMES has been used for DG Environment and applied at the government level in the EU.

PRIMES is a modeling system that simulates a market equilibrium solution for energy supply and demand in the European Union (EU) member states. The model determines the equilibrium by finding the prices of each energy form so that the producers find the best match for the demand of the consumers. The equilibrium is static (within each time period) but repeated in a time-forward path under dynamic relationships.

The model is behavioral but also represents, in an explicit and detailed way, the available energy demand and supply technologies, and pollution abatement technologies. The system reflects considerations on market economics, industry structure, energy/environmental policies, and regulation. These are conceived so as to influence market behavior of energy system agents. The modular structure of PRIMES reflects a distribution of decision making among agents that decide individually about their supply, demand, combined supply and demand, and prices. The market integrating part of PRIMES then simulates market clearing.

PRIMES is a general purpose model, and can support policy analysis in the following fields: Policies related to energy and the environment, (standards on) technologies (including new technologies and renewable sources, energy efficiency in the demand side, alternative fuels), energy trade, conversion, decentralization, electricity market liberalization, and finally, gas distribution and refineries.

By removing some of the restrictions that limit the expansion of nuclear energy, we can use the model to calculate the benefits in terms of the reduction of investments and costs involved in the expansion of nuclear energy. When simulating the nuclear expansion, this hardly alters the carbon price on a global permit market. Carbon price is assumed to remain fixed at baseline level. Thus any reduction of compliance costs regarding climate policies does not feed back into the decisions to be taken on energy markets. Emission reductions lead to less imports of permits by the EU-25, and hence the cost reductions involved are partial but of first-order importance.

On the national level, **energy security** is a qualitative measure indicating the extent to which a country is able to provide itself with the means to satisfy its internal energy requirements. We distinguish security aspects here on different time scales, which we refer to as “short term” (days to weeks), “medium term” (months to years), and “long term” (decades, or more). Increasing nuclear energy involves especially **baseload** energy demand and reduces the demand for coal, gas, and renewables. This means less reliance on the imports of **gas** from Russia (**medium term**), and less depletion of the EU’s gas resources (**long-term**). Secondly there will be less demand for the EU’s coal resources, and to some extent the resources outside Europe. In the case of renewables there will be less wind and solar, and to some extent also biofuel imports. Overall, the nuclear expansion wil,l especially in the longer term, (beyond 2040), increase Europe’s self-reliance on their energy sources. But changes on import dependency will be small and therefore beyond the scope of this CBA.

Learning is beyond the scope of this analysis; still exogenously declining costs of the different energy potions will serve as good approximation of the costs involved in applying the options in electricity supply.

The macro economic impacts are also beyond the scope of this analysis. Since this involves employment changes in the electricity sector, it will be limited.

The external effects include Local Air Pollution (LAP), Radiation, Waste, Proliferation, and Land use. As will be argued further on, we will focus in this report on the largest monetary benefits and disregard the rest, at least with respect to air pollution, though these may turn out to be important when being assessed in a MCA assessment. The largest benefits with respect to LAP concern Chronic Mortality, Infant Mortality, Chronic Bronchitis, and lastly, Restricted Activity Days.

Break-even point price of non-monetizable impacts (also long -term)

In this study some externalities are difficult to quantify. These long-term externalities concern proliferation risks and waste disposal. The monetarization of these impacts is even more difficult, and the literature provides little guidance. However, both externalities are closely linked to the cumulative production of nuclear energy. Therefore these impacts can be approached as a break-even point issue, i.e. adding up all known monetary impacts, and calculating the net value of the strategy. The break-even price of long-term externalities (per unit of Kwh) equals the costs up to which the expansion project can be interpreted as a no-regret strategy.

4 The nuclear expansion project

This chapter describes the characteristics of the nuclear expansion project. The focus of this analysis is Europe and the time frame, the 2010-2030 period. This restricts the nuclear options, which will be described in the first section of this chapter. But as time evolves, future economic circumstances will change in Europe, and hence may influence the potential penetration of nuclear energy in future electricity markets. This chapter will present an overview of the major assumptions underlying the changes of future energy markets. These concern future growth of the economy, and changes to prices and demand for energy. As the results of the analysis depend highly on its environmental outcomes, this chapter will also present the assumptions and changes of emissions spurring climate change (mainly CO_2) and air pollution (SO_2, NO_x , NH_3, and $PM_{2.5}$). The chapter concludes with the definition of the baseline nuclear project, as analyzed throughout the remainder of this report.

4.1 Nuclear options

Table 4.1 shows the currently deployed nuclear reactors in Europe, and the optional reactor types applicable to short, medium and long term. Still, the expansion strategy is formulated in terms of impacts for the years 2020 and 2030. Hence we restrict our analysis to two types of reactors, reflecting new technology: the EPR reactor, jointly developed by Areva and Siemens and selected for the planned new Finnish nuclear plant, and the AP600 reactor, developed by Westinghouse. Both reactor types are based on simplified and passive plant systems to enhance plant safety and operations (see below).

4.1.1 EPR reactor

The design of the EPR reactor is based on experience gained by France and Germany, which initiated the project. In this way, most of the components and equipment of the EPR are the direct result of technologies already used in the most recent reactors built in France and Germany. From the operational point of view, the new features adopted in the EPR to reduce costs principally concern fuel and maintenance. The core design will allow the reactor to operate with a fuel which is slightly less enriched than that used in current reactors. Refueling operations will be less frequent, with cycles of between 18 and 24 months. Apart from conventional uranium fuel, the core will also take MOX mixtures (uranium oxide and plutonium), allowing the plutonium to be recycled. The operating lifetime of the reactor will be 60 years (as against a lifetime of around 40 years for current reactors) due to reinforced protection of the pressure vessel against neutron radiation. From the safety point of view, one of EPR's innovations makes it possible for core meltdown to be taken fully into account in the design stage. The systems allocated to safety operations (safety inspection, emergency steam generator supply, component cooling, and emergency electrical supply) are divided into four independent networks and geographically separated. In this way they can be individually powered by a diesel generating set allocated to each network. Finally, although the design of the primary and secondary systems follows that of existing reactors, the size of the main components (vessel, pressurizer, and steam generator) has been increased. This gives the whole system an increased inertia and provides the operator a longer time to intervene should any operating problem arise.

Table 4.1. Nuclear reactor types in Europe currently deployed (with reactor numbers - in brackets), deployable in the short to medium term (non-exhaustive), and possibly developed in the long term (speculative).

	Today	Short to medium term	Long term
Generation	I and II	III	IV
	PWR (92)	**EPR (PWR)**	GFR
	WWER (22)	**AP600 (PWR)**	LFR
Reactor type	BWR (19)	AP1000 (PWR)	MSR
	AGR (14)	WWER (PWR)	SFR
	GCR (8)	ABWR (BWR)	SCWR
	LWGR (1)	ESBWR (BWR)	VHTR
	PHWR (1)	HTR (pebble bed)	
	FBR (1)		

Source: Van der Zwaan (2007)

4.1.2 AP600 reactor

The Westinghouse AP600 is a 600 MWe reactor utilizing passive safety features that, once actuated, depend only on natural forces such as gravity and natural circulation to perform all required safety functions. These passive safety systems result in increased plant safety and can also significantly simplify plant systems, equipment, and operation. The AP600's major components are also based on years of reliable operating experience. The canned motor reactor coolant pumps have been in use by the US Navy for decades. The passive safety systems are an extension of the technology used previously, since Westinghouse-supplied PWRs have had accumulators for injection of core cooling water without the use of pumps for many years. The main features of the AP600 passive safety systems include passive safety injection, passive residual heat removal, and passive containment cooling.

4.1.3 Costs and economic competitiveness[4]

Nuclear energy is, in economic terms, able to compete with its two main counterparts in the electricity sector, and coal and natural gas-based power generation. Figure 4.1 depicts the range of total levelized electricity production costs for coal, natural gas, and nuclear power plants for two values of the discount (i.e. interest) rate. The more investment-intensive the option, the more sensitive the levelized costs to the value of the discount rate. The investment part of these costs may be twice as high for coals as for natural gas, and for nuclear power three times higher (OECD, 2005). Still, as a result of the low fuel-cost component for nuclear energy with respect to both coal, and especially natural gas-based power in terms of overall levelized costs, the former generally constitutes a good competitor of the last two. There is a dependency for all three alternatives with respect to where and under what operational conditions the electricity is produced. The ranges indicated by the bars in the three plots reflect mostly the dependency on in the (OECD) country in which the power is generated. If one takes the average of these uncertainty ranges as a measure of comparison, nuclear power shows marginal proof of offering the most competitive option, with total levelized costs of about 30 US$/MWh with a 5% discount rate, and a little over 40 US$/MWh with a discount rate of 10%.

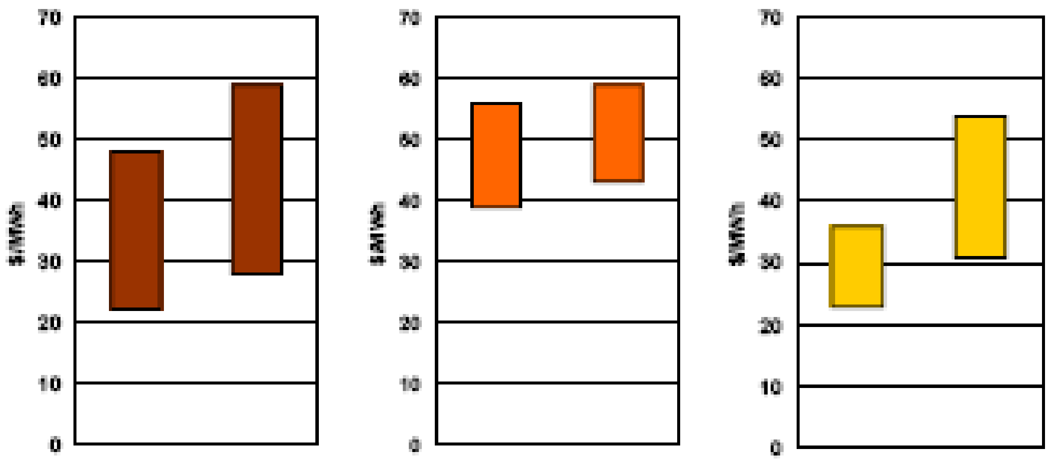

Figure 4.1: Range of total levelized electricity generation costs (in US$/MWh) for (a) coal, (b) natural gas, and (c) nuclear power plants for two values of discount rate (left bar: 5 %, and right bar: 10%) (Data from OECD, 2005).

The high capital cost necessary for the construction of a nuclear power plant nevertheless forms an impediment for the sector to invest in nuclear energy. Regulatory, legal, and political incertitude often exacerbates the hesitation of potential investors. In each of the European countries in which nuclear energy has been developed, an active role of government has been indispensable in addressing these uncertainties. The ongoing process of electricity market

[4] This section is taken from Van der Zwaan (2007).

liberalization and deregulation in Europe, seems to discourage (see IJGEI Special Issue) new investments in nuclear energy. Still, the recent cases of Finland and France demonstrate that it is possible to build new nuclear power plants in this modified economic environment.

If climate change concerns are seriously addressed and if, consequently, CO_2 abatement gets a price in economic terms, nuclear energy and renewable resources will eventually profit from their low levels of GHG emissions. In some cases nuclear energy may be the preferred climate-friendly option for base-load power production, depending particularly on the availability and affordability of the renewables in the locality considered. Considering climate control, if coal or natural gas-based power production is complemented with CCS – supposing that CCS develops into the attractive and realizable innovation it presently promises to become – the capital intensity difference between this decarbonized fossil electricity generation and nuclear power will be reduced, which will benefit nuclear power. Carbon dioxide emission credits, enacted since January 2005 in the 25 present EU countries through the Emissions Trading System (ETS), already give nuclear energy, in principle, a cost advantage relative to fossil-fueled power production. In the longer term, a sustained and stable ETS may lead to renewed investments in the construction of nuclear power plants.

4.2 Assumptions of the Baseline, climate action and nuclear expansion scenarios

In the context of the “Long Range Energy Modelling” framework contract, ICCS/NTUA has developed a new medium term (up to 2030) Baseline scenario for DG-TREN. This baseline projection has also been selected by the DG Environment for the CAFE (Clean Air For Europe) project and EEA for their 2005 forecast (EEA, 2005). The “Long Range Energy Modelling” (LREM) scenario is based on quantitative analysis, with the use of the PRIMES model, and on a process of communication with and feedback from a number of energy experts and organizations. A detailed analysis of assumptions and results for this scenario can be found in “European Energy and Transport – Trends to 2030” (EU, 2003). While results for EU Member States are identical to those of the “Long Range Energy Modelling” framework contract, there are small differences that relate to acceding countries, given that results provided are the output of the PRIMES model (developed in the meantime for those countries). Based on the economic/population assumptions of the Baseline, a Climate Action scenario was developed by EEA (EEA, 2005). This scenario describes the effects of introducing a carbon tax (increasing to 65 euro/t CO_2 by 2030) on the energy system. Nuclear capacity growth was restricted due to phase-out policies (current legislation) in various European countries. In the nuclear expansion scenario current restrictions on nuclear capacity growth was released for European countries with existing nuclear capacity. The following overview was based mainly on a technical paper from EEA (EEA, 2004).

4.2.1 Assumptions of growth in the economy and the population

Global level

Spurred by further globalization, economic growth at the global level is relatively fast in this scenario, although not as sharp as assumed in the IPCC A1b scenario (IMAGE-team, 2001; Nakicenovic et al., 2000). Economic growth can therefore be described as medium (per capita yearly growth rate of 2 to 3%) in almost all regions. As growth is greater in low-income regions than in high-income regions, the relative gap between the regions will be reduced. However, for economic growth to occur, regions will need to have a sufficient level of institutional development and stability. In the scenario it is assumed that in the first 2-3 decades, these conditions will not be met in Sub-Saharan Africa; as a result this region will clearly lag behind in terms of income growth. However, the current barriers to economic development are gradually reduced in this same period – and from 2025/2035 onwards, the region "takes off" in terms of its development, similar to what we have seen for Asian countries in the past.

European level

Europe (EU27 plus EFTA and Turkey) population is projected to exhibit a limited growth peaking in 2030 at some 587 million inhabitants. However, significant divergences occur among the different regions, with population in the new EU countries (EU10) declining by some 5.6 million people in 2030 compared to 2000 levels, whereas in candidate countries (e.g Turkey) an increase of 0.8% per year is expected to take place in the same period.

Rising life expectancy, combined with declining birth rates and changes in societal and economic conditions, are the main drivers for a significant decline in average household size (i.e. the number of persons per household), in Europe-30. Average household size in Europe-30 amounts to 2.2 persons per household in 2030 compared to 2.6 in 2000, with the projected decline giving rise to significant growth in the number of households (+0.6% per year in 2000-2030) despite the rather stable evolution of population (see Table 4.2). Growth in the number of households is one of the key drivers of energy demand in the residential sector.

The economic outlook of Europe-30 is dominated by the evolution of the current EU economy. This is because the contribution of acceding countries, despite their much faster growth over the projection period (+3.5% per year in 2000-2030 compared to +2.3% per year in EU-15), remains rather limited in terms of overall Europe-30 GDP (see Table 4.3). By 2030, EU10 GDP reaches 5.6% of Europe-30 economic activity compared to 4.1% in 2000[5] .

Table 4.2. Population assumptions

	Million inhabitants					Average annual growth rate				
	1990	2000	2010	2020	2030	90/00	00/10	10/20	20/30	00/30
EU15	366	379	388	390	389	0.3	0.2	0.1	0.0	0.1
NMS	75	75	73	72	69	-0.1	-0.2	-0.2	-0.4	-0.3
EU-25	441	453	461	462	458	0.3	0.2	0.0	-0.1	0.0

Source: DGTREN (2004)

The GDP projections for Europe-30 Member States are based on Economic and Financial Affairs DG forecasts of April 2002 for the short term (2001-2003), and on macroeconomic forecasts from WEFA (now DRI-WEFA), adjusted to reflect recent developments, for the horizon up to 2030.

Table 4.3. GDP assumptions

	2000 Euros (x thousand)					Average annual growth rate				
	1990	2000	2010	2020	2030	90/00	00/10	10/20	20/30	00/30
EU15	6982	8545	10859	13641	16920	2.0	2.4	2.3	2.2	2.3
NMS	333	394	574	821	1100	1.7	3.8	3.6	3.0	3.5
EU-25	7315	8939	11433	14462	18020	2.0	2.5	2.4	2.2	2.4

The baseline assumptions for economic growth reflect the long established trend of structural changes in developed economies, away from the primary and secondary sectors and towards services and high value-added products (less material and energy-intensive products), However, the pace of change is expected to decelerate in the long term. Services and value-added increases over the projection period at rates above average, implying a continuous increase of market share

[5] The validity of GDP estimates based on market exchange rates for Central and Eastern European countries is under debate as they generally underestimate the level of GDP. If GDP expressed in purchasing power standards is used, the contribution of the new EU and candidate countries economies in Europe-30 GDP would reach 13% of economic activity in 2000.

in total economic activity (70% in 2030 compared to 68% in 2000). This increase in market share of services occurs to the detriment of all other sectors of the economy. The market share, industrial activity, which grows at rates slightly below average, declines by 1.3 percentage points over the projection period (from 21% in 2000 to 20% in 2030). The lowest economic growth is projected for agriculture (+1.5% per year in 2000-2030), while the energy branch and construction sectors are also projected to exhibit a significant decline in terms of market shares, growing by 1.6% per year and 2% per year, respectively, to 2030.

The Baseline scenario includes existing trends and the effects of policies in place and of those in the process of being implemented by the end of 2001. These include the further development of the liberalized electricity and gas markets in the EU, but also in EU10 and candidate countries, policies in place due to the use of nuclear energy by a country, further improvement of energy technologies in both the demand and supply sides, the continuation of support of renewable energy forms and co-generation, the extension of natural gas supply infrastructure, and stringent regulation of acid rain pollutants. For analytical reasons the Baseline scenario excludes all additional policies and measures that aim at further reductions of CO_2 emissions to comply with the Kyoto emission commitments.

4.2.2 Assumptions for energy

The primary energy prices assumed here reflect the view that no structural major supply constraints are likely to be felt, at least in the period up to 2030. These assumptions on primary energy prices follow an optimistic view of future discoveries of new oil and gas fields and on further advances in extraction technologies. Oil prices are assumed to decrease over the next few years from their high 2000 level. The 2010 oil price is projected at 20US$(2000); from here it grows gradually to reach 28US$(2000) by 2030. Natural gas prices are assumed to reach 17US$(2000) per barrel of oil equivalent in 2010, which is higher than their 2000 level. This means a medium term decrease in the oil–gas price gap. With increasing gas-to-gas competition gas prices are decoupled from oil prices in the second part of the projection period. Coal prices remain essentially stable in real terms.

The evolution of the Europe-25 energy system to 2030 under baseline assumptions clearly reflects the further decoupling between energy demand and economic growth. These trends materialize in all regions. Primary energy demand is projected to grow by 25% between 2000 and 2030 (see Table 4.4), with energy needs growing slightly faster in EU-10 countries (+21%) compared to the EU-15 (+18%). By 2030 primary energy demand in EU-10 countries is projected to reach 12% of overall energy needs in Europe-30. Primary energy needs remains dominated by prevailing trends in the EU-15 energy system over the projection period.

Table 4.4. Energy demand in EU-25.

	Baseline assumptions				Climate action			Nuclear expansion	
	2000	2010	2020	2030	2010	2020	2030	2020	2030
EU25	Mtoe				difference from baseline			difference from climate action	
Solid Fuels	303	244	253	300	-27	-84	-194	-20	-20
Liquid Fuels	636	654	672	674	-10	-19	-43	0	-1
Natural Gas	376	507	598	628	-5	-32	-21	-11	-16
Nuclear	238	245	214	185	0	1	40	67	102
Electricity	2	2	2	2	0	0	0	0	0
Renewable Energy Sources	96	133	151	169	8	45	71	-4	-4
Total	1651	1784	1889	1960	-34	-89	-147	31	59

Source: DGTREN (2004), EEA (2005)

Natural gas and renewable energy forms are projected to remain the fastest growing fuels in the Europe-25 energy system (as was the case during the last decade), growing at rates 3 times faster than overall energy needs over the projection period (+2% per year in 2000-2030 for natural gas; +1.7% per year for renewable energy forms). Primary energy demand for liquid fuels exhibits a moderate growth over the projection period (+0.4% per year) though less than average.

Solid fuels, after a strong decline up to 2010, are projected to regain some market shares in the Europe-25 energy system beyond 2015 as a result of the increasing competitiveness of imported coal and also nuclear plant decommissioning. By 2030, primary energy demand for solid fuels is projected to come close to that observed in 2000. Novel energy forms, such as hydrogen and methanol, are not projected to make significant inroads in the Europe-30 energy system in the period to 2030. As regards non fossil fuels, nuclear energy accounts for 8.4% of primary energy demand in 2030 (compared to 14% in 2000). The share of renewable energy forms increases from 7% of primary energy demand in 2000 to reach 9.5% in 2030. CO_2 emissions are projected to grow over the outlook period (+0.7% per year in 2000-2030; see Table 4.5). However, even in 2030, CO_2 emissions in acceding countries remain at levels significantly below those observed in 1990 (-7.6% lower, while emissions in the EU-15 are projected to rise +19% from 1990 levels.

In the 2000-2010 period, CO_2 emissions for Europe-25 are projected to grow by 3.6%, reaching at +0.3% from 1990 levels (Table 4.5). The further changes in the fuel mix towards less carbon-intensive fuels, on both the demand and supply sides, form the main reason for this limited growth, with emission reductions in industry and in district heating largely off-setting the emissions growth projected from the transport sector. Beyond 2010, CO_2 emissions are projected to rise much faster, with the power generation sector becoming the main driver for this increase. The massive decommissioning of nuclear power plants, and the increasing competitiveness of coal in the sector, cause these higher emissions.

Table 4.5 Baseline emissions EU-25

		1990	2000	2010	2020	2030	90/ 00	00/ 10	10/ 20	20/ 30	00/ 30
CO_2	Mt CO_2	3769	3665	3757	4041	4304	-0.3	0.2	0.7	0.6	0.5
NH_3	kt NH_3	5293	4638	4727	4648	4582	-1.3	0.2	-0.2	-0.1	0.0
SO_2	kt SO_2	26724	13068	7080	4700	3239	-6.9	-5.9	-4.0	-3.7	-4.5
NO_x	kt NO_x	17899	13360	9670	6998	6674	-2.9	-3.2	-3.2	-0.5	-2.3
PM_{fine}	kt PM_{fine}	4568	2246	1616	1348	1218	-6.9	-3.2	-1.8	-1.0	-2.0

Source: DGtren and calculations authors

4.2.3 Assumptions of the Climate Action scenario

In the Climate Action scenario, the permit price for CO_2 emissions in the Europe-30-wide emission trading regime has been set at 7 euro/t CO_2 in 2005 (compared to 0 in the baseline case), 12 euro/t CO_2 in 2010, 20 euro/t CO_2 in 2015, 30 euro/t CO_2 in 2020, 50 euro/t CO_2 in 2025, and 65 euro/t CO_2 in 2030. In addition, the projected evolution of world energy prices is different in the Climate Action scenario in comparison to the Baseline scenario because of changes of primary energy needs at the global level. Thus, international fuel prices exhibit a decline from baseline levels because of the slower growth in energy requirements. The decline is insignificant for natural gas and crude oil and slightly more pronounced for hard coal. Qualitatively, the two scenarios show the same trend: steadily increasing prices for oil and natural gas, and almost constant prices for coal.

In this Climate Action scenario, the Europe-25 energy system undergoes some significant changes (see Table 4.6), all the way through to 2030 when compared to the Baseline scenario. At the aggregate level of analysis, the economic system has two means of responding to the imposition of the carbon constraint, while maintaining the same level of GDP. Either it can reduce the level of energy used per unit of GDP (the energy intensity) or it can change the fuel mix in order to reduce the carbon intensity of its energy sub-system. The division of the system's response between these two effects is an extremely important indication of where most of the flexibility in the system is to be found. A reduction in the carbon intensity of the energy system signifies that substitution opportunities among fuels are more cost-effective than substitution of energy by other goods.

Changes achieved in CO_2 emissions show the flexibility of the power and steam generation sector to respond to climate policy measures. On average, for every 1% reduction in generation output there is a multiple decline in CO_2 emissions. Thus, by reducing electricity and steam generation by just 0.5% in 2010, the generation system reduces its emissions by 7.0%. The corresponding reductions in 2020 are -1.4% versus -21% and in 2030 -4% versus -41%, reflecting the high exploitation of carbon-free options in the Europe-25 power generation system under the Climate Action scenario assumptions.

These significant gains in carbon intensity of the power generation sector are not only due to the strong increase in the use of renewable energy forms and nuclear energy – both of which exhibit a growth in absolute terms and, of course, in terms of market shares on top of baseline levels – but also because of changes in the fuel mix as regards electricity generation from fossil fuels. It is mainly the use of solid fuels that exhibits a strong decline in electricity generation (solid fuels input in power generation reaches -73% from baseline levels in 2030), while growth on top of baseline levels occurs for natural gas and biomass/waste (+7% and +180%, respectively, in 2030). The increase in the use of biomass/waste combined to the significant growth in the use of hydropower and intermittent energy sources (ranging from +2.2% in 2010 up to +21% in 2030) and to the overall decline of electricity generation, allow for a substantial growth of the market share of renewable energy forms in electricity generation. In 2010 this reaches 23% and in 2030, 32% (from 22% and 22%, respectively, at the baseline). Finally, the increase in the use of nuclear energy becomes increasingly important in the long term (+26% from baseline levels in 2030), taking into account that under the climate action scenario assumptions, countries with declared nuclear phase-out policies do not alter them. Thus, it is only for a limited number of countries that nuclear energy is available as an option for reducing CO_2 emissions in the scenario examined.

Table 4.6: Primary energy and CO_2 emissions in Europe-25 - Difference from Baseline

GIC (Mtoe)					% Difference from baseline		
	2000	**2010**	**2020**	**2030**	**2010**	**2020**	**2030**
Solid Fuels	341.8	252.3	197.3	125.2	-10.6	-32.0	-63.5
Liquid Fuels	703.2	715.0	746.0	745.8	-1.6	-2.9	-6.6
Natural Gas	411.0	551.2	633.6	710.6	-1.0	-5.7	-3.6
Nuclear	250.7	256.4	228.7	241.0	0.0	1.2	25.7
Renewable En. Sources	130.1	177.5	243.8	296.9	5.2	26.4	37.4
Total	**1837**	**1952**	**2049**	**2120**	**-1.9**	**-4.7**	**-7.3**
EU 15	1453	1547	1584	1588	-1.8	-4.4	-7.6
CCA	198	203	216	224	-2.6	-6.9	-6.8
BU, RO, TU	133	146	190	247	-2.4	-4.7	-7.1
NO, SW	53	56	59	60	-1.0	-3.0	-0.7
Mt CO2					% Difference from baseline		
	2000	**2010**	**2020**	**2030**	**2010**	**2020**	**2030**
Total	**4069**	**4048**	**4088**	**3963**	**-4.0**	**-11.4**	**-21.5**
EU 15	3118	3085	3061	2897	-3.7	-11.1	-21.0
CCA	547	521	513	454	-5.6	-14.1	-28.5
BU, RO, TU	327	357	430	531	-4.5	-10.8	-17.9
NO, SW	77	84	84	82	-2.2	-9.3	-17.1

Source: PRIMES

In the Climate Action scenario, CO_2 emissions (see Table 4.6) are projected to reach -3.7% from 1990 levels in 2010 (compared to a near stabilization in the Baseline), further decreasing to -5.7% from 1990 levels in 2030 (-2.7% in 2020; the corresponding figures in the Baseline being +9.9% in 2020 and +20% in 2030).

The imposition of allowance prices results in an increase in energy system costs, reflecting the increase in the sector's investment requirements, increased tariffs etc. It is by no means a pure economic cost, since most of the additional funds will be recycled within the overall economy. In the climate action scenario, total energy system costs for the Europe-30 energy system increase by 30 billion euro in 2010, 71 billion euro in 2020 and 102 billion euro in 2030, in comparison to the Baseline, including the cost of allowance prices.

The various economic sectors are affected differently by the imposition of the allowance prices, with costs differing among sectors depending on their energy intensity. In energy-intensive industrial sectors, the increase in the average cost of sectoral output (industrial product) ranges from 0.9% to 4.5% in 2010 and from 3.6% to 19% in 2030. The same increase in the output cost of non-energy intensive sectors ranges from 0.05% to 0.3% in 2010 and from 0.2% to 1.4% in 2030. In particular, the increase in the cost of energy for industry is higher, reaching up to 59% in energy-intensive sectors, and to 46% in non-energy-intensive ones.

Table 4.7. EU25 CO_2 emissions 2000-2030

	Baseline				**Climate action**		**Nuc. Expansion**	
	2000	2010	2020	2030	2020	2030	2020	2030
EU25	Mt CO2				dif. to baseline		dif. to climate action	
Solids	1106	884	922	1106	-337	-771	-81	-81
Liquids	1647	1685	1741	1763	-62	-132	0	-1
Gas	911	1188	1378	1435	-69	-50	-26	-38
Total	3665	3757	4041	4304	-467	-953	-108	-120

The energy cost for the service sectors increases by 2.4% in 2010 (implying a small increase in total cost of the sector), reaching +3.8% in 2030. Spending by households on energy-related costs increases by roughly 1.8% in 2010 and 3.0% in 2030 (2.9% in 2010 and 14% in 2030 for energy fuel purchases).

The energy fuel purchase costs in the transport sector also rise, ranging from +3.8% in 2010 to +9.3% in 2030 for passenger transport and from +4.3% in 2010 to +20% in 2030 for freight transport. However, the cost of transportation increases less, ranging from 0.8% in 2010 to 3.4% in 2030 for passengers, and from 0.7% to -1.4% for freight. The prevailing trend of declining costs in services, households and transport in the long term under the climate action assumptions, strongly relates to a slower adoption of high comfort standards (for example, less km traveled per capita in comparison to the baseline) and the more rational use of energy (including improvements in a building's thermal integrity). However, there is already a shift of consumers towards more efficient energy-related equipment before 2030.

The costs incurred by the power and steam generation sector relate to higher capital expenditures (more expensive plant technology), the costs induced from stranded capital, and the higher fuel purchase costs. The average power and steam generation cost increases in the Climate Action scenario from 5.9% in 2010 to 27% in 2030, compared to Baseline, while the average electricity tariff increases by 5.7% in 2010, reaching +28% in 2030. However, the increase remains significantly lower compared to the impact of permit prices on fossil fuel consumption.

4.2.4 Assumptions for health impacts of air pollution

Under current legislation assumptions for the year 2020, there will be considerable health improvements from lower levels of emissions of air pollutants (see Table 4.5). Beyond 2020 the trend in these improvements will be sustainable, although the number of premature deaths and restricted activity days will slightly increase again (see Table 4.8). The reason is the graying European society between 2020 and 2030, with higher crude death rates and hence a population more vulnerable to air pollution.

Table 4.8. Health-related impacts

		Level			Average annual growth rate		
Impact	unit	2000	2020	2030	00/20	20/30	00/30
PM_{25} concentration	ug/m3	8.3	7.5	7.3	-0.5	-0.3	-0.4
Chronic mortality	life-years (months)	6.8	7.7	7.6	0.6	-0.3	0.3
Deaths	thousands	300	305	332	0.1	0.9	0.3
Infant mortality	thousands	1.2	1.1	0.9	-0.8	-2.3	-1.3
Chronic bronchitis	per 100 adults	25	26	26	0.1	0.2	0.2
RADs	cases>27 year per adult	29	29	30	0.1	0.2	0.2

4.3 Results for energy markets and the economy

The previous section described the baseline developments; here we will explain the major assumptions of the policy shock (nuclear expansion project) that we will analyze in the remainder of this report.

The availability of new nuclear technologies and the re-evaluation of declared nuclear phase- out policies in EU-25 Member States lead to a potentially significant increase in the role of nuclear energy in power generation, especially in the long term (see Figure 4.2). Under the "nuclear expansion scenario" case assumptions, primary energy demand for nuclear energy exhibits a continuous growth over the projection period, reaching +78% higher than baseline levels in 2030. The increased use of nuclear energy occurs to the detriment of solid fuel (-16% from baseline levels in 2030) and to a lesser extent, natural gas (-3.5%). But the availability of new nuclear technologies does not have a significant impact on the use of renewable energy forms in the EU-25 energy system. Primary energy requirements for liquid fuels remain rather stable at baseline levels, clearly reflecting the insignificant role of this energy form in power generation. The higher use of nuclear power plants with an efficiency of some 33% in the EU-25 energy system involves an increase of overall primary energy requirements (+3.6% above baseline levels in 2030), given, for example, that natural gas power plants have a much higher efficiency than nuclear plants. Thus energy intensity worsens for the EU-25 energy system in the "Nuclear expansion" scenario compared to the Baseline. But the increasing share of nuclear energy in primary energy requirements (16% in 2030 compared to 9.4% in the Baseline scenario), and the limited decline of renewable energy forms (with a market share of 8.3% in 2030 compared to 8.6% in the Baseline), lead to a significant improvement of the EU-25 energy system's carbon intensity (-8.9% from baseline levels in 2030).This provides for a more favorable development in terms of CO_2 emissions.

Thus, in 2030 CO_2 emissions are projected to increase by +7.8% from 1990 levels compared to +14% in the Baseline scenario. Due to the higher exploitation of indigenous energy sources import dependency in the EU-25 energy system is projected to be lower in the long run in the "New nuclear technology accepted" case. In 2030, 62% of primary energy needs in the EU-25 energy system will have to be imported (compared to 68% in the Baseline scenario). As regards import dependency of individual fossil fuels, the dependency for solid fuels is projected to reach 63% in 2030 (-2.8 percentage points from baseline levels), with natural gas import dependency reaching 81% in 2030 (no change from the Baseline). Finally, import dependency for liquid fuels remains, as expected, unchanged from baseline levels (88% in 2030), as energy requirements for liquid fuels are not affected by the assumptions introduced in the "Nuclear expansion" scenario. Another significant finding from the "Nuclear expansion" scenario concerns the evolution of final energy demand growth in the EU-25 energy system, which is projected to remain unchanged from baseline levels over the projection period. The strong inertia of the demand side to the changes projected to occur on the supply side is largely explained by the fact that the adoption of new nuclear technology in the power sector does not lead to major changes in electricity production costs. Electricity generation costs are projected to be about -1% lower than baseline levels, both in 2020 and 2030. Thus, only limited changes in the fuel mix are projected to occur on the demand side, with electricity and also co-generated steam gaining some additional market shares to the detriment of fossil fuels. The limited importance of these changes in the fuel mix is also reflected in the evolution of CO_2 emissions from the demand side, projected to remain essentially unchanged from baseline levels over the projection period. It can also be seen that renewables expand considerably between 2000 and 2030, rising by a factor 3. This is a model outcome of PRIMES (NTUA, 2000) that is in line with the sustainable strategy as laid down by the EU in their Green Paper (2007). In the NUC+ scenario, renewable energy will only decline to a very minor extent. This decline comes mainly from a decline in biofuel consumption. The NUC+ policy is a strategy not conflicting with the renewable strategy of EU.

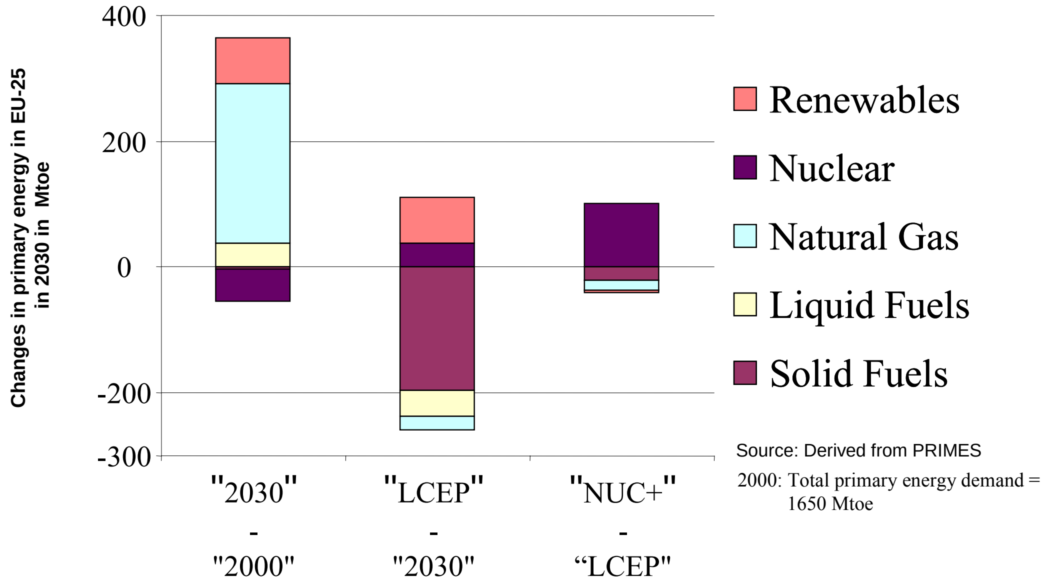

Figure 4.2: Energy changes in 2030 for two scenarios compared to the Baseline scenario.

Table 4.9. Costs in the electricity and non-energy sector for different scenarios

EU-25	**2000**	**LCEP 2030**	**Nuc+**
Electricity costs: total (billion EUR (2000))	209	381	380
Electricity: average production cost (ct/kWh)	5.3	6.8	6.7
Costs in non-energy sectors (excl. transport)			
Industry (billion EUR (2000))	157	271	273
Households (billion EUR (2000))	288	864	867
Total (billion EUR (2000))	551	1354	1359

Source: EEA, 2005

Because of different fuel inputs the total fuel costs vary considerably between the variants, from a slight decrease in the nuclear expansion scenarios to a significant increase in the renewables scenario (see Table 4.9). The increase in fuel costs, including the CO_2 costs, between Baseline and LCEP scenario, reflects the introduction of the carbon permit price. Average electricity and steam generation costs in the Nuclear expansion scenario decrease slightly in 2030, compared with those in the LCEP scenario. Still, the total costs will increase by 5 billion euro (mainly from high investments in capital-intensive nuclear power stations).

It is shown in Figure 4.3 for the world and the EU how the electricity generates cumulatively for the installed capacities and those simulated in the scenarios up to 2030. If we assume that the material intensity is constant over time and regions, then this figure also indicates the evolvement of uranium demand. Moreover, if we assume that waste production is linearly linked to the input of uranium, then this graph also indicates the waste production of all nuclear facilities. The total cumulated global electricity is indexed to 100. It can be seen that up to 2000 nuclear capacity accounts for 18% of the total electricity generated of the past and the future (up to 2030). Europe currently accounts for 40% electricity cumulatively generated and this will decrease considerably to 14% in the LCEP scenario, and rise again to 16% in the NUC+ scenario. It can be concluded that Europe's share to cumulated global waste production will likely decline considerably, whether the EU decides to keep its nuclear capacity at 2000 levels or increase it as in the nuclear expansion scenario. At the global level, the cumulative electricity generation of all nuclear power stations will be 3% higher in the nuclear expansion scenario.

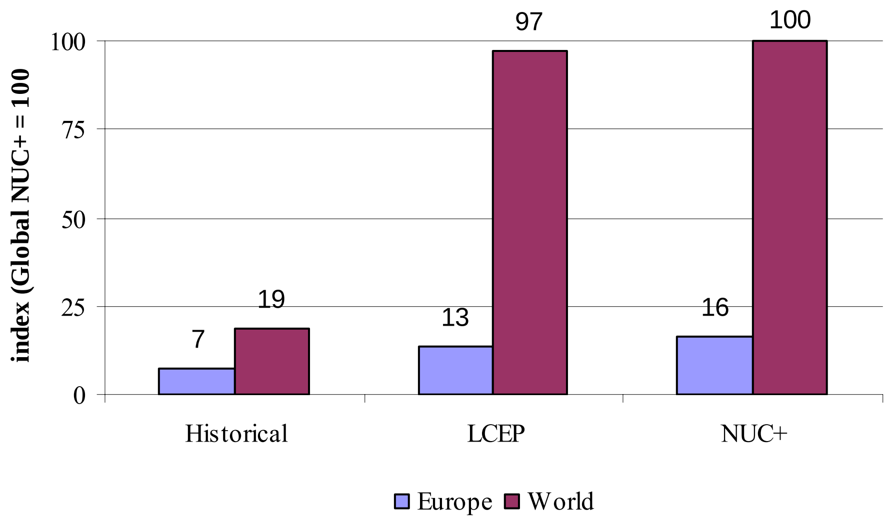

Figure 4.3: Cumulative nuclear electricity generation

Note: Authors' calculations based on historical electricity generation capacities and assumed average lifetime of 60 years

5 Externalities from Local Air Pollution

5.1 Introduction

The most important environmental externalities of the energy sector are related to air pollution and its impacts on human health (e.g. PM, ozone, NO_2, SO_2, PAHs, heavy metals), ecosystems (SO_2, NO_x, ozone) and climate (CO_2)), especially through the use of fossil fuel. Considering the impact of human health alone and using risk coefficients from a large cohort study of adults in the USA (Pope et al. 2002), IIASA (EU, 2005, Amann et al. 2005) estimated over 300,000 yearly deaths due to fine particulates[6] in Europe (with a substantial share of the electricity sector). If we monetarize the welfare loss we arrive at staggering 300 billion euro a year (assuming 1 million euro (WTP) per human life).

Including these external costs in the price of the production of electricity will undoubtedly shift the balance to low and zero emission electricity generation modes, including renewable energy from hydro, wind and solar power, and nuclear energy.

Earlier damage studies (e.g. AEA-T, 2005) already showed that over 90% of the monetarized damages come from mortality (80-90%) and morbidity (10-20%), effects due to exposure of fine particulates (PM), and ozone.

In the recently published European Union Air Quality strategy (EU, 2005), mortality impacts are differentiated by premature deaths (weeks, months) and chronic effects (up to 10 years loss of life expectancy). In monetary terms a differentiation between VOLY (Value Of a Life Year) and VSL (Value of a Statistical Life) is made.

In this study, the methodology taken from the EU Air quality strategy is used to evaluate the effects of an expanded nuclear scenario. The activity data from the

[6] Ambient particles are differentiated according to their aerodynamic diameter: coarse particles (>1µm), fine particles (0.1–1µm), and ultra fine particles (<0.1µm). Ultra fine particles constitute a small percentage of the total mass of PM, but are present in very high numbers. Because of health concerns, the ambient concentrations (mass) of both coarse and fine PM are regulated by the United States Environmental Protection Agency (EPA) through the National Ambient Air Quality Standards for PM_{10} (PM <10 µm) and $PM_{2.5}$ (PM <2.5 µm) (USEPA, 1997), and by the European Union through limit values for PM_{10}. $PM_{2.5}$, which includes only fine and ultra fine particles, is dominated by emissions from combustion processes; PM_{10}, which includes coarse as well as fine and ultra fine particles, has a much higher proportion of particles generated by mechanical processes from a variety of non-combustion sources. It is currently not clear how much particles of different sizes and composition differ in their effects on health.

PRIMES energy model (as previously explained) were used to estimate the effects on the emissions and concentration of air pollutants with the RAINS model (refer to inter page). The RAINS model was run with both the reference case and the nuclear expanded scenario. The resulting differences in PM concentration for each country was calculated and, assuming a linear relationship with the impacts, the resulting health benefits were calculated. Health effects included number of deaths (including infant mortality), life years lost, chronic bronchitis and Restricted Activity Days (RADs) for 2030 in both variants. An overview for EU-25 countries and EEA member countries can be found in the appendix for:

1. Emissions of SO_2, NO_x, NH_3, PM_f leading to PM_s (PM precursors) for 2030
2. $PM_{2.5}$ Concentrations, Chronic and Infant Mortality, Chronic Bronchitis, Restricted Activity Days in 2030 in both variants
3. Valued damages in 2030 of Health Impacts mentioned under 2
4. Valued damages for 2020 and 2030

5.2 Valuing premature deaths to chronic exposures for $PM_{2.5}$ concentration

This study provides information on the impacts of the baseline conditions, both in terms of physical impacts (see previous section) and monetary valuation. It also summarizes the change in impacts (i.e. the benefit) that will occur over time. The results are presented as annual environmental and health impacts. Furthermore, the results have been aggregated – using monetary values – so as to gain an understanding of the total damage in economic terms. The valuation methodology in this study uses similar techniques to those used in earlier cost–benefit analysis for the European Commission and US EPA, for example. The quantification of health impacts normally addresses both long-term (chronic) and short-term (acute) exposures, dealing with both mortality (i.e. deaths) and morbidity (i.e. illness). The morbidity effects that can be quantified include major effects, such as hospital admissions and the development of chronic respiratory disease, along with some less serious effects, affecting a far greater number of people. Examples of these are changes in the frequency of use of medicine to control asthma, and restrictions on normal activity. When the impact and the values are combined in the analysis, the most important health related issues relate to mortality, restricted activity days and chronic bronchitis. In this study we quantified mortality and the dominant morbidity effects in terms of valuation, the number of chronic bronchitis cases and Restricted Activity Days.

It should be noted that two approaches can be used for quantifying chronic mortality impacts: valuation of a statistical life (VSL) and years of life lost (YOLL). These are stressed as being alternative measures and hence not additive. Major advances have been made in health valuation in recent years. The latest indication of European “willingness to pay” to reduce mortality have been included in this study. Guidance from WHO, also adopted for the CAFÉ process in Europe, recommends that chronic mortality effects be expressed principally in terms of change in longevity. Following on from this, it is logical to seek value chronic mortality impacts in terms of the change in longevity aggregated across the population, necessitating use of the value-of-a-life year (VOLY) concept. For the CAFE CBA methodology, the independent external peer reviewers and several other stakeholders suggested that both the VSL and the VOLY approaches be used to show, transparently, the inherent uncertainty that is attached to these two approaches. The actual difference in mortality damage quantified using VOLY and VSL-based methods is not as great as could be derived from Table 5.1. Much of the difference between VSL and VOLY is cancelled out by the difference between the number of premature deaths quantified compared to the number of life years lost (e.g. in Europe an average of 10 life years lost is assumed, resulting in a valuation of 50% of the assumed costs for deaths attributed to $PM_{2.5}$) . In this study, we assumed the median value of a statistical life, taken from CAFE.

Table 5.1 Valuing impacts: effects of chronic exposure on mortality and morbidity

Health impact	Median (NewExt)	Mean (NewExt)
Mortality		
VSL (adults above 30)	€980,000	€2,000,000
VOLY (adults above 30)	€52,000	€120,000
VSL (infants)	€3,000,000	
Morbidity		
Chronic Bronchitus (>27 years)	€190,000	
Restricted Activity days (>27 years)	€82	
Restricted Activity days(<27 years)	€69	
Lower respiratory symptoms (LRS, adults)	€38	
Lower respiratory symptoms (LRS, children)	€13	

Comparing the baseline impacts to other studies (adapted from Holland et al.,, 2005)

Lately three studies have estimated the mortality effects of chronic exposure to fine particles:

Firstly, Ezzati et al. (2002), who contributed to the WHO Global Burden of Disease Project. Ezzati et al. report European impacts in 51 countries to be equal to 61,000 premature deaths. *Secondly*, Künzli et al. (2000) estimated that air pollution caused 40,000 premature deaths in three countries (Switzerland, Austria, and France). The Künzli et al. rate is double that of the Ezzati et al. rate when expressed per capita1 terms. *Thirdly*, the CAFE CBA health results with an estimated 348,000 premature deaths (2000 estimate) and *Last,* our study, mimicking the CAFÉ results, with an estimated 303,000 premature deaths (2005 estimate) in the EU-25.

The CAFE CBA team (Holland et al., 2005) consulted with the authors of the Ezzati et al. study to double check the numbers and to understand the differences. There appeared to be several reasons for the CAFE CBA results being higher than the Ezzati et al. results (see below):

- The population addressed by CAFE CBA (as in our study) consists of the total population (based on the advice of the WHO Task Force on Health Assessment), while Ezzati et al. included only urban air pollution in cities of more than 100,000 people. For example, for the WHO Region EUR-A, Ezzati et al. considered impacts on 80 million people, while the EU25 comprises 450 million people.
- All studies use coefficients from Pope et al. (2002). CAFE CBA and our study uses an estimate of 5.9% change in all-cause mortality hazards per 10µg/m3 $PM_{2.5}$, using the recommendations made by the working group established by WHO. On the other hand, Ezzati et al. apply cause-specific results equivalent to a 4% change in all-cause mortality.
- The conversion factor of 0.5 used by Ezzati et al. to convert PM_{10} to $PM_{2.5}$ also appears

  conservative from a European perspective. CAFE uses a factor of 0.65 where necessary, based on observations from various sources in Europe and North America. In our study we used sub-regional specific factors between 0.35 and 0.73.

There are also differences in the range over which the two studies quantify effects of particles:

- The Ezzati et al. analysis only quantifies more than 15µg/m3 PM_{10}, taken as being equivalent to 7.5 µg/m3 $PM_{2.5}$. CAFE CBA and this study do not quantify with a cut-off point. However, in the CAFE CBA the outputs include only anthropogenic contributions to $PM_{2.5}$ concentrations and excludes secondary organic aerosols. The net effect of this difference on the Ezzati et al. and CAFE CBA results is ambiguous.
- The use of an upperbound concentration of 50 $\mu g/m^3$ $PM_{2.5}$ by Ezzati et al. probably has very little effect on the comparison of results with CAFE CBA or with our study.

5.3 Results

An increase in nuclear capacity in Europe will result in a considerable reduction in coal use in power plants, as discussed in chapter 4. This chapter discusses the consequence of air emissions and air pollution health impact. Figure 5.1 presents the results for the main air pollutants for the EU25 and the three EU countries with the largest effect on air pollutant emissions. SO_2 emissions show the largest reduction, a 15% decrease in Germany and an overall 2% decrease in the EU. The effect on the NO_x reduction varies from 7% in Germany to 1.5% in the EU. Finally, we also see a reduction in particulate emissions, from 5% in Germany to 1% in Europe.

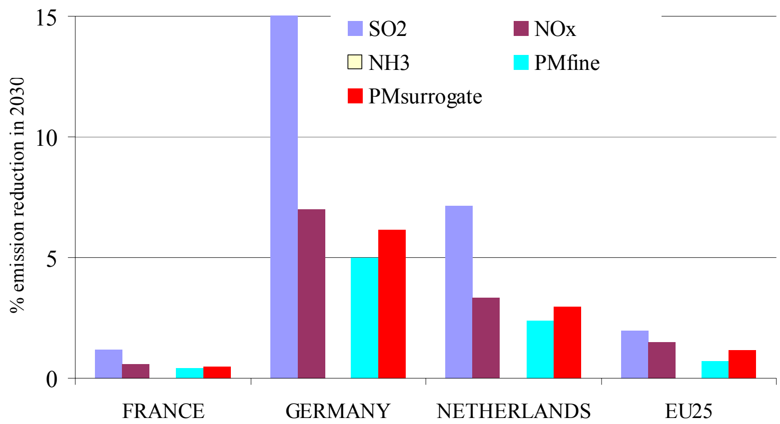

Figure 5.1: Emission reductions in 2030 in the "NUC+" scenario compared to the "CLE" scenario.

Using the RAINS model the average impact of these emission reductions on the ambient air concentration of $PM_{2.5}$ was calculated with use of the RAINS model. Due to the long lifetime (days) of $PM_{2.5}$ in the atmosphere, emission reduction in Germany will have an effect in neighbouring countries too. The results are presented in Table 5.2. The contribution of anthropogenic $PM_{2.5}$ is reduced up to 10% (Sweden). The largest reduction in premature deaths due to $PM_{2.5}$ can be found in Germany (minus 5500) and Belgium (minus 1200). Chronic bronchitis is reduced up to 4 cases per 1000 inhabitants (Germany).

Table 5.2. End points showing environmental health improvements in 2030 in the "NUC+" scenario

	CLE $PM_{2.5}$ conc. in ug/m3	NUC+ $PM_{2.5}$ conc. %red. from CLE	Change Chronic mortality Life years Lost (months)	Change Premature deaths Deaths (thousands)	Change Infant mortality deaths	Change Chronic bronchitis number per 10^5 adults	Change Restricted Activity days cases> 27 year per 1000
Belgium	19.8	8%	1.21	1.15	3.51	0.81	0.92
Finland	2.6	1%	0.02	0.01	0.06	0.01	0.01
Germany	14.1	6%	0.63	5.53	15.42	3.95	4.48
Netherlands	19.5	3%	0.49	0.67	2.22	0.51	0.58
Sweden	2.4	10%	0.17	0.15	0.39	0.11	0.13
Czech Rep.	11.5	5%	0.38	0.44	0.66	0.26	0.30
Lithuania	7.9	5%	0.18	0.10	0.39	0.06	0.07
Norway	1.5	5%	0.05	0.02	0.21	0.02	0.02

As discussed in section 5.2 we used the "Clean Air for Europe" methodology to value the above benefits in monetary terms. The results are presented in Table 5.3. In 2030 the welfare benefits can increase to almost 12 billion per year in the case of Germany.

Table 5.3. Monetized health benefits in 2030 in "NUC+" compared to "CLE" scenario

	change Premature deaths Low	**change Premature deaths High**	**change Infant mortality**	**change Chronic bronchitis**	**change Restricted Activity days**	**Change Total High**
	Billion Euro	**Billion Euro**	**Million Euro**	**Million Euro**	**Million Euro**	**Billion Euro**
Belgium	1,1	2,3	11	11	0,5	2,32
Finland	0,01	0,02	0,2	0,1	0,0	0,02
Germany	5,4	11,1	46	467	23	11,60
Netherlands	0,7	1,3	7	12	0,6	1,36
Sweden	0,1	0,3	1,2	1,3	0,1	0,30
Czech Rep.	0,4	0,9	2,0	3,4	0,2	0,89
Lithuania	0,1	0,2	1,2	0,3	0,01	0,20
Norway	0,02	0,04	0,6	0,1	0,01	0,04

6 Energy supply security, waste production, proliferation risks, and reactor accidents

This chapter deals with the externalities other than the air-related environmental problems.

6.1 Energy security

On the national level, the item *energy security* is a qualitative measure indicating the extent to which a country is able to provide itself with the means to satisfy its internal energy requirements. Energy security is a concept that also specifically refers to the certainties and uncertainties involved in a nation's efforts to guarantee or continue fulfilling its domestic energy needs. The definition of energy security can be extended geographically to a larger scale, for example, to continental level or to the political level, e.g. the European Union. It can also be applied to a smaller scale, such as the state, regional or provincial level within a given country. A challenge poorly addressed and far from resolved today is the formulation of a more precisely defined and appropriately designed measurable quantity for "energy security". Yet, a more tangible, observable and testable "formula" for energy security may have significant academic, commercial-strategic, and political benefits for science, industry, and (supra-)national authorities, respectively.

A first step towards defining such a quantitative measure is distinguishing the different time scales over which the notion of energy security may be used. We here distinguish between three different periods, as indicated in Table 6.1, which we refer to as "short term" (days to weeks), "medium term" (months to years), and "long term" (decades, or more). Indicated as well are some typical examples of cases in which energy security may be negatively affected, for each of these three time horizons. For instance, uncertainty exists in short-term energy security when there is substantial risk that, especially in times of over-demand (e.g. cold winters) when the transmission network temporarily collapses. Uncertainty exists in medium-term energy security when, in times of high oil prices or a disruption in foreign oil supply, energy consumption is negatively affected and economic growth halted or turned negative. This negative effect is due to both political instability in the country where the reserves are exploited and the fossil fuels produced and/or refined. Long-term energy security (un)certainty is intertwined with the choices of national governments to invest or not in infrastructures that contribute to the establishment of domestic energy capacity or supply systems. Governments may ascertain that energy services are needed, even under major international geopolitical changes, foreign energy reserve depletion or shifts in import patterns.

Recent examples were seen in California in 2000, the US Eastern seaboard in 2003, Netherlands in 2003, and Italy in 2004. The causes vary from under-investment in capacity and network to old equipment, lack of cooling water, heavy weather, falling trees et cetera. The costs incurred here also vary. More generally, it has been attempted to measure costs involved at large by power unavailability: see INDES project. The two oil crises (1973, 1979) are well-known cases of disruptions in medium-term energy security. The 1970s formed an era during which attitudes changed and policies were designed to avert disruptions of energy systems during longer periods of time. The costs of such crises are probably best expressed in the losses of GDP that they are thought to have engendered. Obviously, they are of a more fundamental nature than the short-term energy security disruptions and related costs mentioned above.

Table 6.1. Definition of energy security according to the relevant time scale

	Time horizon	**Examples of typical causes of disruption**
Short term	days to weeks	• Black-outs due to network failures • Absence of cooling water during hot summers
Medium term	months to years	• Temporary peak in oil prices • Political disruption of gas supplies
Long term	decades and more	• Under-capacity of domestic power production • Reliance on electricity supplied from abroad

The choice of the French government in the 1960s to develop a large nuclear power program is an example of the construction, lasting several decades, of an electricity supply system that determines domestically produced power for many decades, and constitutes a clear instance of an attempt to establish long-term energy security. Incidentally, as the French government and industry have been able to set up a program that produces cheap electricity, France has created an important source of revenues through the export of electricity to other EU countries. The French nuclear choice has also significantly influenced national R&D programmes and has led to related scientific research as well as industrial applications and expertise (such as in the medical field). Given the broad impact of choices in terms of long-term energy security, it is most challenging to express the choices related to this type of energy security in terms of economic value, or, alternatively, the costs of not investing in this kind of energy security.

How does one need to view nuclear energy in this context? In many ways, nuclear energy is no different from power produced from fossil fuels, as all of these options are dependent on the same electricity networks, and all heavily depend on large amounts of cooling water. Nuclear energy is probably of significant value in terms of medium-term energy security, given the role of fuel supply in this type of energy security. Uranium accounts for typically only a few percent of total electricity costs, so the power generated is virtually independent of even important peaks in (stock-market or contract) uranium prices. The energy content of uranium is also relatively much larger than that of fossil fuels, so strategic reserves for nuclear energy can be built much easier than for fossil fuels. As the French case has demonstrated, the value of nuclear energy in terms of guaranteeing long-term energy security may be large. But, of course, there must be a willingness to transform an energy system so radically, and to more broadly influence both research communities, and industrial and commercial activities, of a country. The size of the country is relevant in deciding whether or not an entire nuclear industry covering all aspects of the nuclear fuel cycle can be constructed.

The scenario calculations show that 62% of primary energy needs in the EU-25 energy system in 2030 will have to be imported (compared to 64% and 68% in the Climate Action the Baseline scenarios, respectively). As regards import dependency of individual fossil fuels, dependency on solid fuels is projected to reach 63% in 2030 (-2.8 percentage points from baseline levels), and no changes in dependency for gas and liquid fuels. From a CBA perspective, the nuclear expansion scenario hardly impacts the import dependency, and given the low fuel cost share of uranium in total production costs of electricity, we decided not to attach any number to the externalities resulting from energy security changes.

6.2 Proliferation

A Global issue

Nuclear weapon proliferation has been prominent in discussions on nuclear power since its earliest days. Today, the objective is to minimize the proliferation risks of nuclear fuel cycle operation through diversion (in the case of plutonium), reduction in the misuse of fuel cycle facilities, and increased control of the know-how on producing and processing plutonium. This can be achieved by strengthening the current non-proliferation regime by both technical and institutional measures with particular attention to the link between fuel cycle technology and safeguarding ability. The global expansion of nuclear power based on a once-through thermal reactor fuel cycle would sustain an acceptable level of proliferation resistance if it is accompanied with strong safeguards and security measures, along with implementation of long-term geological isolation. The fuel cycle produces separates plutonium and, given the absence of compelling reasons for its pursuit, should be strongly discouraged in the expansion scenario on non-proliferation grounds. Advanced fuel cycles may improve proliferation resistance, but risks should be minimized.

Europe's contribution to proliferation risks is limited

Europe's role will be very modest on the world nuclear power scene; furthermore, its contribution to discussions on how to manage proliferation risks can only be sustained in multilateral agreements. As argued above, the share of Europe's waste production in global numbers will decrease in the coming decades, and will not be changed in the nuclear expansion project. Still, extra proliferation risks are closely linked to the accumulation of waste by EU nuclear facilities. It is almost impossible to attach numbers to this issue. Hence, we decided to deal with proliferation in the same way as we proceed with monetizing the externality of waste production. We framed this issue in terms of the electricity price, and were still be able to generate an equal number of welfare gains (break-even point analysis) of other external impacts in the nuclear expansion scenario.

6.3 Waste disposal

Other studies describing the transition to a sustainable energy system highlight the necessity of taking into account not only the cost of nuclear power, but also public concerns and waste disposal (WBGU, 2003). The problem of nuclear waste management and the risk of proliferation are not fully integrated into the LCEP analysis. Today, the quantities of highly radioactive waste from nuclear power production continue to accumulate; a generally acceptable disposal route for this waste has yet to be identified. Scenarios with increasing shares of nuclear energy would thus have to consider the increasing quantities of nuclear waste. The cost of decommissioning is also becoming an increasingly important issue at Member State level, both for economic reasons and due to public concern. The cost of nuclear decommissioning is included in the analysis. However, the cost of returning nuclear power plant sites to their initial conditions has not yet been taken into account. The cost of nuclear waste management is taken into account (through the price of nuclear energy) but there is no consideration for the problem of increasing quantities of nuclear waste. As with proliferation, we recognize that the monetization is difficult and very uncertain. Hence, we choose to frame its importance (together with management costs of proliferations risks) in a calculated increase in the electricity price against an equal number of welfare gains (break-even point analysis) of other external impacts in the nuclear expansion scenario.

7 Overview of costs and benefits

Here we bring together all quantifiable results relevant for the CBA analysis. First, we show the impacts in 2030, and follow this with discounting monetized impacts. We disregard monetarization of externalities to waste and risks of proliferation. Table 7.1 shows the impacts in 2030, where it can be seen that the costs increase (see also Table 4.8). However, these costs exclude reducing permit imports against the prevailing permit price of 65 euro/t CO_2. These reduced imports are included as part of the business costs; hence these gains do not form an external impact, but instead, serve as a direct stimulus for the electricity producers, provided national governments create market opportunities to built a nuclear power plant. This table also shows the external benefit of air quality improvements to be even more substantial. Note that we disregard the impacts here of the externalities related to the production of waste and risks related to proliferation.

Table 7.1 Total Impacts in EU-25 in 2030 (NUC+ - LCEP)

	Bn euro
Investments	3
Variable Costs	2
Fuel costs	-6
Indirect Impacts (higher electricity price is passed on to non-energy sectors)	6
Total (see also Table 4.9)	**5**
Reduced Permit imports (CO_2 reduction = 3.35-3.23 Gt CO_2 * 65 euro/t CO_2)	-8
Total (minus indicates a benefit)	**-3**
Mortality benefits	-4
Morbidity benefits	-1
Total	**-8**

Below in Table 7.2 we show the discounted monetary valuations from either the changes in the energy system or the external effects of pollution. Note that we disregard here the impacts of the externalities related to the production of waste and risks related to proliferation. It can be seen that the net benefits of the EU's nuclear expansion project is equal to 171 billion euro (with business costs equal to 23 billion euro). Suppose now that we allocate this net-gain to increase management efforts on the externalities of waste and risks of proliferation, then 0.5

cent per KWh (=10% of the production price) can be allocated to these externalities, and the nuclear expansion project will still be a no-regret option from a CB perspective[7].

Table 7.2 Overview of discounted costs and benefits (bn euro)

Costs			Benefits		
Energy	Investments + O&M	23	Direct benefits	Avoided CO_2 rights	34
			Other Benefits		0
Business Costs		**23**	**Business Benefits**		**34**
Pollution costs	Waste	pm	$PM_{2.5}$ Benefits	Chronic Mortality	126
	Proliferation	pm		Infant Mortality	3
Supply security		0		Chronic Bronchitis	23
				Restricted Activity Days	13
External Costs		**0+pm**	**External Benefits**		**164**
Total		**23**	**Total**		**198**
Benefits - Costs		**171**			

[7] Nuclear expansion generates about 1300 TWh in 2030. Cumulating this number over the entire lifetime of the nuclear power plant leads to a total of 38000 TWh generated electricity generated. The total benefits divided by the total cumulated generated electricity results in 0.5 cent per KWh.

8 Sensitivity analysis

We highlight the most important sensitivity assumptions, and relate this to the outcomes presented in Table 7.2. The sensitivity analyses include the following:

- No climate policies

It is still unclear how post-2012 climate policies will evolve. The price of carbon is one of the key determinants for energy producers to decide for or against nuclear energy. In this sense, the climate change externality will be included in energy prices as far as the EU and other non-EU countries are willing to agree upon a aggregate binding CO_2 emission target for all post-Kyoto countries. Emissions trading will then allocate emission reductions cost-effectively across countries, and the emission price is determined on the equilibrium price matching the supply and demand for emissions of all countries.

- Discount rates;

The applied discount rate is a crucial factor determining costs and benefits of the nuclear expansion strategy in the EU. We employ in the benchmark case a 2.5% discount rate for health impacts. Instead we also show the impacts of 4% and 0.1% discount rate of external health impacts.

- Increasing control costs as to compensate for health benefits

The health impacts are based on the assumption that the nuclear expansion strategy does not yield a response in terms of alternative end-of-pipe (EOP) abatement strategies for the pollutants of SO_2, NO_x, NH_3, and PM_{10}. The impacts on the emissions of these pollutants are translated to so-called end-points (concentration levels of different pollutants, and health impacts), which are in turn transformed to monetary values through valuation procedures as followed by the CAFE CBA methodology. Instead of this procedure, it can also be argued that the nuclear strategy enables the electricity sector to reduce their abatement efforts through implementing less EOP abatement measures. Alternatively, the avoided EOP costs can be argued to be monetary external health impact. We show the consequences of this line of reasoning.

- Higher oil prices

Recent fluctuations of the oil price boost it to higher levels than assumed in the LCEP base case calculations. In many EU countries, the price of gas is linked to oil, and hence the oil price may effect electric markets, and thus impact the nuclear expansion strategy. We will show the impacts of higher oil prices for energy markets and health damages.

8.1 No climate policies

In the Climate action (LCEP) and nuclear expansion (NUC+) scenarios, the permit price for CO_2 emissions in the Europe-30 wide emission trading regime has been set to 30 euro/t CO_2 in 2020, and 65 euro/t CO_2 in 2030. What happens if the climate policy will be less successful, or in other words, if the carbon price is lower than the assumptions we made in our LCEP scenario? Table 8.1 below (IEAE, 2006) shows the range of nuclear prices in relation to the competing alternatives of coal and gas-fired powerplants. Nuclear power, low costs estimate, is competitive with coal-fired powerplants, keeping in mind that the benchmark coal price increases up to 50 euro/t CO_2 by 2030, at the high cost estimate a carbon prices of 18 euro/t CO_2 and up is required to be competitive or a higher coal price (73 euro/t CO_2). Nuclear power seems also to be a competitive alternative to gas, because our scenarios assume gas prices to remain above 7 euro/MBtu (competitive with high nuclear cost estimate). The expansion of nuclear power is therefore not inconsistent with the views of IEA (2006).

Table 8.1. Some Nuclear Power Economics

	Low Nuclear power generation costs	**High Nuclear power generation costs**
Nuclear power generation costs	4.5 euro cents per kWh	7 euro cents/kWh
	Conditions for nuclear competitiveness	
Fuel costs in LCEP coal < 50 euro/t Gas >7 euro/MBtu	Gas price > 4.3 euro/MBtu Coal price > 52 euro/t	Gas price > 6.7 euro/MBtu Coal price > 73 euro/t*
CO_2 price that makes nuclear competitive	gas-fired combined cycle gas: 0 coal plant: 9 euro/tCO_2	gas-fired combined cycle gas: 0 euro/tCO_2 coal plant: 18 euro/tCO_2

* Note: FOB cash cost, not including capital charges, based on a standardised heat content of 6000 kcal/kg (comparable to a typical South African coal exported from Richard's Bay). The heat content of internationally traded coals ranges from 5 200 kcal per kg to 7 000 kcal/kg.
Source: IEAE (2006)

As long as the CO_2 emissions price remains above 42 euro/t CO_2, then the scenario outcome is a feasible result. But what happens if the climate policy fails completely, and there will be no emissions price? The direct impact is that the private sector climate benefits drop out of the equation. Hence there will be no incentives left for electricity producers to invest in nuclear energy, although it might remain competitive with gas. Moreover, if the costs of nuclear power generation remain low, then nuclear power may even remain competitive with coal. With substitution possibilities of nuclear for gas and less likely with coal, the likely impact on pollutants such SO_2, NO_x, and PM_{10}, and $PM_{2.5}$ will be very small. Hence, without climate policy there are little incentives for the private sector to invest in nuclear power, and as it may likely only substitute gas, there will also be very little health benefits.

8.2 Discount rates

The discount rate applied to external impacts is assumed to be 2.5% for external health impacts. We could alternatively assume a higher discount rate of 4% for long-term aspect such as air pollution, or lower discount rates as applied by Stern (2006). With higher discount rates, the avoided health damages decrease from 164 bn euro to 92 bn euro (see Table 8.2), and hence 0.3 cent per KWh (6% of the production price of nuclear electricity) can be allocated to long-term aspects of nuclear waste, and the nuclear expansion strategy will still be a no-regret option from a CBA perspective.

Table 8.2. Overview of discounted costs and benefits (bn euro) against 4%

Costs			Benefits		
Business Costs		**23**	**Business Benefits**		**34**
Pollution costs	Waste	pm	$PM_{2.5}$ Benefits	Chronic Mortality	69
	Proliferation	pm		Infant Mortality	2
Supply security		0		Chronic Bronchitis	14
				Restricted Activity Days	8
External Costs		**0+pm**	**External Benefits**		92
Total		**23**	**Total**		**126**
Benefits - Costs		**103**			

Table 8.3. Overview of discounted costs and benefits (bn euro) against 0.1%

Costs			Benefits		
Business Costs		**23**	**Business Benefits**		**34**
Pollution costs	Waste	pm	$PM_{2.5}$ Benefits	Chronic Mortality	402
	Proliferation	pm		Infant Mortality	6
Supply security		0		Chronic Bronchitis	56
				Restricted Activity Days	31
External Costs		**0+pm**	**External Benefits**		496
Total		**23**	**Total**		**533**
Benefits - Costs		**510**			

On the other hand, if governments perceive it to be more reasonable to apply lower discount rate of 0.1%, then the monetized benefits related to air pollution, increase u to 496 bn euro (see Table 8.3). Moreover, if governments then consider externalities related to nuclear waste production to be lower than 1.5 cent per KWh (30% of the production price of nuclear electricity), then the nuclear expansion strategy still remains profitable from a welfare point of view.

8.3 Increasing control costs as to compensate for health benefits

Air benefits can also be measured as avoided compliance costs, although the policy response with respect to air pollutants is less likely to occur, because we defined lower concentrations from nuclear expansion as an external effect. But if EOP abatement efforts go down because of the nuclear expansion then the monetized benefits will also go down. Table 8.1 estimates this to be almost 2 bn euro per year by 2030, which is almost 40% of the calculated health benefits. However, the European commission proposed to tighten national air emission ceilings by 2020. A cost-benefit assessment that will includes the effect of these new proposals would find less health benefits (lower average emission factors) but higher benefits in avoided emission control techniques (remaining option costs more).

Table 8.4. Avoided Air pollution control costs saved in EU-25

Air pollutant	saved control costs/kg	saved emissions	saved emissions	total saved control costs
2030		**Kton**	**%**	**(million Euro)**
SO2	12,3	65	2,7%	800
NOx	9,7	94	1,7%	912
PM2.5	31,5	8	0,9%	252
Total				1963

Source: Own calculations based on cost curves of RAINS-database

Table 8.5 presents again the overview of discounted benefits and costs with benefits based on avoided costs of abatement efforts instead of a reduction monetized health damages. The avoided health damages decrease from 164 bn euro to 55 bn euro (see Table 8.2), and hence 0.15 cent per KWh (3.5% of the production price of nuclear electricity) can be allocated to long-term aspects of nuclear waste, and the nuclear expansion strategy will still be a no-regret option from a CBA perspective.

Table 8.5. Overview of discounted costs and benefits (bn euro) if benefits are not measured through monetized but based on avoided abatement measures

Costs		**Benefits**	
Business Costs	**23**	**Business Benefits**	**34**
External Costs	**0+pm**	**External Benefits**	**55**
Total	**23**	**Total**	**89**
Benefits – Costs	**66**		

8.4 Higher oil prices

It is not straightforward to predict what the impacts will be of higher oil prices. Based on model simulations with a modified version of energy-economy model MERGE that also includes the issue of local air pollution (see Bollen et al., 2007), we conclude that nuclear expansion strategy will only result in lower benefits with respect to the climate change and air pollution. Below, it can be seen that there will be a decline in both CO_2 emissions and the demand for oil, thus also lowering the energy related PM_{10} emissions.

Table 8.6. Impact of higher oil prices in Europe in a climate action scenario

		Base case	high oil price scen.	%
CO_2	emissions in Gt C	0.54	0.52	-5 (≈-50% compared to 1990 emission level)
	price in euro/t CO_2	49	42	-16
Oil	demand in EJ	16	11	-33
	supply price in $ / barrel*	18	30	70
PM_{10}	emissions in Mt PM_{10}	0.28	0.22	-22
	Premature deaths in thousands	12	9.8	-22

Source: MNP calculations with modified MERGE model (Bollen et al., 2007)

* Be aware that oil price in the above baseline without climate policies is equal to 54 $ / barrel and drops to 30$ / barrel from lower demand in the climate policy scenario

Up to 2030, higher oil prices in combination with climate and local air pollution policies will in Europe entail more gas and somewhat larger decline of oil in non-electric markets, and generate little impacts on electricity markets up to 2030[8]. The environment will improve as emissions of several pollutants will decline. Consequently, as oil will be phased out of energy systems, the CO_2 emissions price will decline with 16% (see model results of MERGE as summarized in Table 8.6) and the premature deaths from energy related PM_{10} emissions with 22%. These reduction percentages are employed to derive the impacts of the overview table.

With higher oil prices, the avoided health damages decrease from 164 bn euro to 127 bn euro (see Table 8.7), and hence 0.4 cent per KWh (7.5% of the production price of nuclear electricity) can be allocated to long-term aspects of nuclear waste, and the nuclear expansion strategy will still be a no-regret option from a CBA perspective.

Table 8.7. Overview of discounted costs and benefits (bn euro): higher oil price

Costs			**Benefits**		
Energy	Investments + O&M	23	Direct benefits	Avoided CO_2 rights	30
			Other Benefits		0
Business Costs		**23**	**Business Benefits**		**30**
External Costs		**0+pm**	**External Benefits**		**127**
Total		**23**	**Total**		**157**
Benefits - Costs		**134**			

8.5 Alternative rules for monetizing health impacts

Finally, if other rules apply to the monetization of the health impacts, then this will change the net-benefits of the nuclear expansion strategy. We consider assumptions that may result both in higher and lower health benefits from the nuclear expansion strategy. The maximum estimate stems from the assumption of higher VSL (2 mn euro instead of 1 mn euro for premature deaths of PM exposure), and the minimum estimate is based on the assumption that there is no mortality impact from PM exposure.

With higher VSL (lower VOLY), the avoided health damages increase (decrease) from 164 bn euro to 497 bn euro (39 bn euro), and hence 1.5 respectively 0.15 cent per KWh (30% respectively 3% of the production price of nuclear electricity) can be allocated to long-term aspects of nuclear waste, and the nuclear expansion strategy will still be a no-regret option from a CBA perspective.

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[8] If there were no climate policy, and if also the gas price is linked to oil, then there will be an expansion of coal on electricity markets. But the climate policy is stringent, and hence does not allow any expansion of coal-fired power plants without CO_2 capture

Table 8.8. Overview of discounted costs and benefits (bn euro): morbidity only / high death

Costs			Benefits		
Energy	Investments + O&M	23	Direct benefits	avoided CO_2 rights	34
			Other Benefits		0
Business Costs		**23**	**Business Benefits**		**34**
Pollution costs	Waste	Pm	PM $_{2.5}$ Benefits	Chronic Mortality	0/459
	Proliferation	Pm		Infant Mortality	3
Supply security		0		Chronic Bronchitis	23
				Restricted Activity Days	13
External Costs		**0+pm**	**External Benefits**		39/497
Total		**23**	**Total**		**73/531**
Benefits - Costs		**50/508**			

and storage facilities.

9 Concluding observations

Nuclear energy is back again on the European political agenda. The arguments pro nuclear are its potential economic attractiveness serving to mitigate climate change and reducing the strategic dependence on gas. The arguments contra nuclear energy are the risks of accidents, proliferation, the long term waste-disposal issue, and limited resource availability. We add a new element to the debate. If the EU decides to expand on its nuclear capacity, then this will likely reduce the demand for fossil energy - and besides a reduction of CO_2 emissions - and depress the emissions of Europe’s air pollutants. Thus the background level of concentration of Particulate Matter will decline, and may yield significant improvements in human health.

This report aims to quantify the (dis-) advantages of an expansion of 45 % in the next 25 years in the EU. As physical and monetary impacts are diverse and involve small risks with large uncertain consequences, it is not our aim to sketch a single or robust conclusion. Rather, we bring together the elements that we do understand, and hopefully add to the debate on nuclear energy. However, we neglect transaction costs involved of governmental authorities providing appropriate information and communication means to raise public confidence in safety, efficiency, and advantages of nuclear power.

The expansion of nuclear energy involves a net benefit in terms of business costs, which is mainly driven by the gain of reduced permit imports (of the climate policy). There are mid-term health benefits that offset the monetized value of expected number of deaths from reactor accidents. And the longer term health benefits increase the net benefits. The current waste management efforts exceed no more than 0.1 cent per KWh. Suppose now that waste management and proliferation will increase costs up to 0.5 cent per KWh (range 0.05-1.5 cent per KWh) , then this can be shown, on average generates more welfare gains than losses. This break-even price can be higher (lower) if lower (higher) discount rates are employed or the maximum (minimum) discounted monetary estimate for avoided premature deaths applies. Nevertheless, it is in the end up to the decision makers to conclude whether these air related benefits are sufficient to cover long-term prevailing problems such as the disposal of radioactive waste and proliferation risks.

Finally, there are the findings of a recent survey, conducted among 18,000 citizens of 18 countries representing the major regions in the world, showing that 62% believe that existing nuclear reactors should continue to be used, and 59% not favoring new nuclear plants. If the EU pursues the nuclear expansion, then both industry and the governments have to raise public confidence to overcome the public resistance against nuclear power. But if there are in the meantime any severe incidents, or accidents, or use by terrorists of a simple atomic bomb or radiological device, then the positive arguments mentioned above will diminish and lead to an overall setback to the acceptance of nuclear energy.

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Appendix I: Detailed tables of all cases

Emissions of pollutants in 2030 for CLE (Baseline) and NUC (variant)

Country	SO2 NUC kton	NOx NUC kton	NH3 NUC kton	PMfine NUC kton	SO2 CLE kton	NOx CLE kton	NH3 CLE kton	PMfine CLE kton	SO2 NUC-SEP % dif	NOx NUC-SEP % dif	NH3 NUC-SEP % dif	PMfine NUC-SEP % dif
AUST	23	109	52	25	23	109	52	25	-0.4	-0.2	0.0	-0.1
BELG	58	158	74	20	70	172	74	21	-16.8	-7.9	0.0	-5.6
BULG	119	82	124	33	117	81	124	33	2.0	0.9	0.0	1.1
CYPR	7	18	6	2	7	18	6	2	0.0	0.0	0.0	0.0
CZRE	29	85	65	11	32	89	65	11	-11.2	-4.9	0.0	-6.3
DENM	12	95	76	12	12	95	76	12	-0.1	0.0	0.0	0.0
ESTO	7	12	15	4	7	12	15	4	1.0	0.4	0.0	0.5
FINL	52	101	31	22	53	103	31	22	-2.3	-1.1	0.0	-0.8
FRAN	303	763	671	151	306	767	671	151	-1.2	-0.6	0.0	-0.4
GERM	251	743	584	99	295	799	584	105	-15.0	-7.0	0.0	-5.0
GREE	103	202	49	36	103	202	49	36	0.0	0.0	0.0	0.0
HUNG	82	85	88	24	67	77	88	21	23.7	10.4	0.0	13.3
IREL	15	55	112	9	15	55	112	9	0.0	0.0	0.0	0.0
ITAL	240	615	383	84	241	616	383	84	-0.2	-0.1	0.0	-0.1
LATV	6	14	18	3	6	14	18	3	-0.4	-0.2	0.0	-0.2
LITH	18	22	60	8	21	24	60	9	-13.3	-5.8	0.0	-7.5
LUXE	2	17	5	2	2	17	5	2	-0.6	-0.3	0.0	-0.2
MALT	2	4	1	0	2	4	1	0	0.0	0.0	0.0	0.0
NETH	60	228	135	25	65	235	135	25	-7.1	-3.3	0.0	-2.4
NORW	14	148	23	14	16	155	23	14	-10.3	-4.8	0.0	-3.4
POLA	327	331	336	81	328	332	336	81	-0.2	-0.1	0.0	-0.1
PORT	85	158	65	39	85	159	65	39	-0.1	0.0	0.0	0.0
ROMA	114	190	285	59	115	191	285	59	-1.2	-0.5	0.0	-0.7
SKRE	26	52	33	12	23	48	33	11	17.0	7.4	0.0	9.5
SLOV	15	17	19	4	14	16	19	4	13.5	5.9	0.0	7.6
SPAI	341	632	357	80	344	634	357	80	-0.8	-0.4	0.0	-0.3
SWED	39	137	47	35	50	151	47	37	-20.9	-9.8	0.0	-7.0
SWIT	13	55	59	6	13	55	59	6	-0.6	-0.3	0.0	-0.2
TURK	674	771	508	254	674	771	508	254	0.0	0.0	0.0	0.0
UNKI	202	774	299	63	202	774	299	63	0.0	0.0	0.0	0.0
Sum	3239	6674	4582	1218	3305	6776	4582	1226	-2.0	-1.5	0.0	-0.7

Health impacts in 2030 for CLE (Baseline) and NUC (variant)

	cle	cle	cle	cle	cle	cle	nuc	nuc	nuc	nuc	nuc
	PM2.5 Chronic Mortality			Infant mortality	Chronic bronchitis	Restricted Activity days	PM2.5 Chronic Mortality			Infant mortality	Chronic bronchitis
	concentration ug/m3	Life-years lost months	deaths thousands	deaths	number per 1000 adults	cases>27 year per mn adults	concentration ug/m3	Life-years lost months	deaths thousands	deaths	number per 1000 adults
Austria	8.2	6.4	4.8	12	3	4	8.2	6.4	4.8	12	3
Belgium	19.8	15.2	14.5	34	10	12	18.2	14.0	13.4	31	9
Denmark	8.4	5.7	3.3	13	2	3	8.4	5.7	3.3	12	2
Finland	2.6	2.1	1.0	2	1	1	2.6	2.0	1.0	2	1
France	10.0	8.3	43.1	133	33	37	10.0	8.2	42.9	132	33
Germany	14.1	10.2	89.7	190	64	73	13.2	9.6	84.2	175	60
Greece	6.6	4.7	4.9	15	4	4	6.6	4.7	4.9	15	4
Ireland	5.9	5.3	1.5	11	1	2	5.9	5.3	1.5	10	1
Italy	8.0	5.6	34.4	68	24	28	8.0	5.6	34.4	69	24
Luxembourg	15.9	14.6	0.5	2	0	0	15.8	14.6	0.5	2	0
Netherlands	19.5	16.6	22.8	59	17	20	18.9	16.2	22.1	57	17
Portugal	4.1	2.8	2.6	11	2	2	4.1	2.8	2.6	11	2
Spain	4.6	3.6	13.0	40	10	11	4.6	3.6	13.0	40	10
Sweden	2.4	1.7	1.6	3	1	1	2.2	1.6	1.4	3	1
UK	7.5	5.6	30.8	114	22	25	7.5	5.6	30.8	108	22
EU-10											
Czech Rep.	11.5	8.3	9.5	19	6	7	11.0	7.9	9.0	18	5
Estonia	4.3	2.7	0.5	1	0	0	4.4	2.7	0.5	1	0
Hungary	13.2	7.7	10.3	22	6	6	14.7	8.5	11.4	24	6
Latvia	5.7	5.1	1.2	4	1	1	5.7	5.1	1.2	4	1
Lithuania	7.9	3.8	2.2	10	1	2	7.5	3.6	2.1	9	1
Malta	5.9	5.8	0.1	1	0	0	5.9	5.8	0.1	1	0
Poland	11.7	9.1	33.2	66	22	25	11.7	9.1	33.2	68	22
Slovakia	11.3	9.0	4.6	16	3	3	12.1	9.7	5.0	17	3
Slovenia	10.7	8.5	1.6	3	1	1	11.4	9.0	1.7	3	1
Cyprus	5.9	6.2	0.4	2	0	0	5.9	6.2	0.4	2	0
Norway	1.5	1.1	0.5	2	0	0	1.4	1.0	0.4	2	0
Switzerland	6.3	4.9	3.3	7	2	3	6.3	4.9	3.3	7	2
Bulgaria	10.0	5.8	6.6	19	3	3	10.1	5.9	6.6	20	3
Romania	10.7	6.2	18.6	76	11	12	10.6	6.2	18.5	79	11
Turkey	5.3	5.6	20.2	1064	19	21	5.3	5.6	20.2	1021	19
EEA	7.2		381.3	2020	271	307	7.2	0.00	374.5	1957	266
EU-15	7.3		268.6	708	196	222	7.3	0.00	260.8	679	190
EU-10	10.5		63.7	144	40	45	10.5	0.00	64.7	149	41
non-eu25	10.4		49.1	1168	35	40	10.4	0.00	49.0	1129	35
EU25	7.3		331.9	850	235	267	7.3	0.00	325.1	826	230

Health Damage in 2030 for CLE (Baseline) and NUC (variant)

	cle Low Chronic Mortality VOLY	cle High VSL	cle Infant mortality deaths	cle Chronic bronchitis	cle Restricted Activity days	cle Low Total	cle High Total	nuc Low Chronic Mortality VOLY	nuc High VSL	nuc Infant mortality deaths	nuc Chronic bronchitis	nuc Restricted Activity days	nuc Low Total	nuc High Total
	bn	bn	bn	bn	bn	bn	bn	bn	bn	bn	bn	bn	bn	bn
Austria	2.7	9.6	0.0	0.7	0.3	3.7	10.6	2.7	9.6	0.0	0.7	0.3	3.7	10.6
Belgium	8.0	29.0	0.1	1.9	0.9	11.0	32.0	7.4	26.7	0.1	1.8	0.9	10.2	29.4
Denmark	1.6	6.5	0.0	0.4	0.2	2.3	7.2	1.6	6.5	0.0	0.4	0.2	2.3	7.2
Finland	0.6	2.0	0.0	0.1	0.1	0.8	2.2	0.6	2.0	0.0	0.1	0.1	0.8	2.2
France	25.7	86.3	0.4	6.2	3.1	35.4	96.0	25.6	85.9	0.4	6.2	3.0	35.2	95.5
Germany	47.0	179.4	0.6	12.2	6.0	65.7	198.1	44.1	168.3	0.5	11.4	5.6	61.7	185.9
Greece	2.5	9.9	0.0	0.7	0.4	3.7	11.0	2.5	9.9	0.0	0.7	0.4	3.7	11.0
Ireland	1.0	3.0	0.0	0.3	0.1	1.4	3.5	1.0	3.0	0.0	0.3	0.1	1.4	3.5
Italy	17.6	68.9	0.2	4.6	2.3	24.7	76.0	17.6	68.8	0.2	4.6	2.3	24.7	75.9
Luxembourg	0.3	1.0	0.0	0.1	0.0	0.4	1.1	0.3	1.0	0.0	0.1	0.0	0.4	1.1
Netherlands	14.1	45.6	0.2	3.3	1.6	19.1	50.7	13.6	44.3	0.2	3.2	1.6	18.6	49.2
Portugal	1.3	5.2	0.0	0.4	0.2	1.9	5.8	1.3	5.2	0.0	0.4	0.2	1.9	5.8
Spain	7.4	26.0	0.1	1.8	0.9	10.2	28.9	7.3	25.9	0.1	1.8	0.9	10.2	28.7
Sweden	0.8	3.2	0.0	0.2	0.1	1.2	3.5	0.8	2.9	0.0	0.2	0.1	1.0	3.2
UK	16.6	61.6	0.3	4.2	2.1	23.2	68.2	16.6	61.6	0.3	4.2	2.1	23.2	68.2
EU-10														
Czech Rep.	4.9	18.9	0.1	1.1	0.5	6.6	20.6	4.7	18.1	0.1	1.0	0.5	6.3	19.7
Estonia	0.2	1.1	0.0	0.0	0.0	0.3	1.1	0.2	1.1	0.0	0.0	0.0	0.3	1.1
Hungary	4.3	20.6	0.1	1.1	0.5	6.0	22.3	4.8	22.8	0.1	1.2	0.6	6.7	24.7
Latvia	0.8	2.4	0.0	0.1	0.1	0.9	2.5	0.8	2.4	0.0	0.1	0.1	0.9	2.5
Lithuania	0.8	4.4	0.0	0.3	0.1	1.2	4.8	0.7	4.2	0.0	0.3	0.1	1.1	4.6
Malta	0.1	0.3	0.0	0.0	0.0	0.1	0.3	0.1	0.3	0.0	0.0	0.0	0.1	0.3
Poland	18.8	66.5	0.2	4.2	2.0	25.1	72.9	18.7	66.4	0.2	4.2	2.0	25.1	72.8
Slovakia	2.7	9.3	0.0	0.6	0.3	3.6	10.2	2.9	10.0	0.1	0.6	0.3	3.8	11.0
Slovenia	0.9	3.3	0.0	0.2	0.1	1.3	3.6	1.0	3.5	0.0	0.2	0.1	1.3	3.8
Cyprus	0.3	0.7	0.0	0.0	0.0	0.3	0.8	0.3	0.7	0.0	0.0	0.0	0.3	0.8
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Norway	0.2	0.9	0.0	0.1	0.0	0.3	1.0	0.2	0.9	0.0	0.1	0.0	0.3	1.0
Switzerland	1.9	6.6	0.0	0.5	0.2	2.5	7.3	1.8	6.6	0.0	0.5	0.2	2.5	7.3
Bulgaria	2.8	13.1	0.1	0.5	0.3	3.6	13.9	2.8	13.2	0.1	0.5	0.3	3.6	14.1
Romania	7.8	37.1	0.2	2.0	1.0	11.1	40.4	7.8	37.0	0.2	2.0	1.0	11.0	40.2
Turkey	15.4	40.4	3.2	3.6	1.8	24.0	48.9	15.4	40.4	3.1	3.6	1.8	23.8	48.8
EEA	209	763	6	51	25	292	845	205	749	6	51	25	286	830
EU-15	147	537	2	37	18	205	595	143	522	2	36	18	199	577
EU-10	34	127	0	8	4	46	139	34	129	0	8	4	46	141
non-eu25	28	98	4	7	3	42	112	28	98	3	7	3	41	111
EU25	181	664	3	45	22	250	733	177	650	2	44	21	245	718

Health Damage in 2020 and 2030 in CLE (Baseline) and NUC (variant)

country	CLE Low 2020	CLE Low 2030	CLE High 2020	CLE High 2030	NUC Low 2020	NUC Low 2030	NUC High 2020	NUC High 2030	CLE-NUC Low 2020	CLE-NUC Low 2030	CLE-NUC High 2020	CLE-NUC High 2030
EU-15	191	205	548	595	187	199	536	577	4.3	5.9	12.4	17.3
Austria	3	4	10	11	3	4	10	11	0.0	0.0	0.0	0.0
Belgium	10	11	30	32	10	10	29	29	0.2	0.9	0.7	2.5
Denmark	2	2	6	7	2	2	6	7	0.0	0.0	0.0	0.0
Finland	1	1	2	2	1	1	2	2	0.0	0.0	0.0	0.0
France	32	35	87	96	32	35	86	96	0.3	0.2	0.7	0.5
Germany	62	66	183	198	59	62	174	186	3.1	4.1	9.3	12.2
Greece	3	4	10	11	3	4	10	11	0.0	0.0	0.0	0.0
Ireland	1	1	3	3	1	1	3	3	0.0	0.0	0.0	0.0
Italy	24	25	73	76	24	25	73	76	0.0	0.0	0.0	0.1
Luxembour	0	0	1	1	0	0	1	1	0.0	0.0	0.0	0.0
Netherland	17	19	44	51	16	19	43	49	0.5	0.6	1.2	1.5
Portugal	2	2	6	6	2	2	6	6	0.0	0.0	0.0	0.0
Spain	10	10	27	29	10	10	27	29	0.1	0.0	0.2	0.1
Sweden	1	1	3	4	1	1	3	3	0.1	0.1	0.3	0.3
UK	22	23	63	68	22	23	63	68	0.0	0.0	0.0	0.0
EU-10	43	46	130	139	43	46	129	141	0.3	-0.6	1.1	-2.2
Czech Rep.	6	7	20	21	6	6	19	20	0.1	0.3	0.3	1.0
Estonia	0	0	1	1	0	0	1	1	0.0	0.0	0.0	0.0
Hungary	6	6	22	22	6	7	22	25	0.0	-0.7	0.1	-2.4
Latvia	1	1	2	3	1	1	2	3	0.0	0.0	0.0	0.0
Lithuania	1	1	4	5	1	1	4	5	0.0	0.1	0.2	0.2
Malta	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0
Poland	24	25	68	73	24	25	68	73	0.0	0.0	0.0	0.1
Slovakia	3	4	9	10	3	4	9	11	0.1	-0.3	0.4	-0.8
Slovenia	1	1	3	4	1	1	3	4	0.0	-0.1	0.1	-0.2
Cyprus	0	0	1	1	0	0	1	1	0.0	0.0	0.0	0.0
Norway	0	0	1	1	0	0	1	1	0.0	0.0	0.0	0.0
Switzerlanc	2	3	7	7	2	3	7	7	0.0	0.0	0.0	0.0
Bulgaria	4	4	15	14	4	4	15	14	0.0	0.0	0.0	-0.1
Romania	11	11	40	40	11	11	40	40	0.1	0.0	0.5	0.2
Turkey	20	24	39	49	20	24	39	49	0.2	0.1	0.2	0.1
EEA	272	292	780	845	267	286	766	830	5.0	5.4	14.2	15.4
EU-15	191	205	548	595	187	199	536	577	4.3	5.9	12.4	17.3
EU-10	43	46	130	139	43	46	129	141	0.3	-0.6	1.1	-2.2
non-eu25	38	42	101	112	37	41	100	111	0.3	0.2	0.7	0.2
EU25	234	250	678	733	229	245	665	718	4.6	5.3	13.5	15.1