NUCLEAR POWER:
MYTH AND REALITY

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Nuclear Energy and Climate Change

Nuclear Issues Paper No. 6

BY FELIX CHR. MATTHES

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1 Introduction

Global warming constitutes one of the major challenges of the 21st century. The wide range of research and modelling in this field demonstrates more and more clearly that ambitious emission reductions will be required if the impact of global warming shall be limited to a magnitude which is still tolerable.

The challenge of an ambitious climate policy will be of special relevance for the energy sector. Carbon dioxide emissions from the combustion of fossil fuels constitute the major share of global greenhouse gas emissions. If deep cuts in CO_2 emissions will be necessary during this century, the energy sector and especially the electricity generation sector must undergo a fundamental transition.

Among the technologies which could deliver a contribution to emission reduction, nuclear power generation plays a crucial role. The use of nuclear power has been subject to much controversy since it was introduced to the energy market. The risks related to this technology range from disastrous accidents to military or terrorist use of nuclear materials which are produced by the nuclear chain. Nuclear power generation fell into stagnation after the Chernobyl disaster and other accidents. Furthermore, after the liberalization of electricity markets in most of the OECD countries, many nuclear installations faced serious problems and new investments in nuclear power proved to be uneconomic for many investors. However, the growing debate on climate change put the debate on nuclear energy back on the agenda on a regular basis. Especially after the European Union introduced an emissions trading scheme and the emission of CO_2 no longer being free of charge, nuclear power has been more and more presented as a key technology in the portfolio of emission abatement options.

Climate change policy to combat the risks of global warming and the specific risks associated with nuclear power constitutes a complex area of conflicts. The debate faces the problem of different risk patterns and the question of alternatives. Risks for health, ecosystems as well as for social and economic structures must be assessed in comparison to availability and costs of potential alternatives. Against this background, the magnitude of future emission reduction needs to play a crucial role as well as the potential contribution to emission reduction. If only moderate emission reduction were required or a huge potential of attractive alternatives would be available, the debate on nuclear power would be of much less relevance than in the opposite case.

In this paper we try to structure the debate on climate change policies and nuclear power and draw some conclusions from the review of a range of literature and debates. In chapter 2 we give an overview of what the necessary magnitude of future emission reduction could be and define the basis for the discussion of nuclear power in the framework of an ambitious climate policy. In chapter 3 we describe an actual business as usual projection for both the CO_2 emissions and the development of nuclear power for the next decades. This projection is used as a reference case for the following discussion of emission abatement options. Against the background of the quite different risk patterns of global warming and nuclear power, we refer to an illustrative model for the systematic analysis and assessment of different types of risks in chapter 4. In chapter 5 we describe and assess the different options for emission reductions in a long-term perspective.

For the purpose of illustration we present a modelling experiment on what an 80% CO_2 emission reduction could look like in a highly industrialised country like Germany in chapter 6, after the very global analysis. We then elaborate what lessons could be drawn from such an exercise and the analysis carried out in the previous chapters. In chapter 7 we end with some key lessons learnt from the analysis presented in this paper.

Given the long-term nature of the global warming problem, the different options must assessed for a long period. We limited our analysis to the period up to 2050 because the assessment of technology and other options becomes more dominated by speculations, the longer the period under discussion is. So we limit the time horizon for analysis and discussion to five decades from the present time. Furthermore, all analysis presented in this paper is carried out on a global level. For many issues raised in the different chapters of this paper, a more regionalized discussion would be valuable and would allow for more insights into the developments and debates which are quite varied among the countries and regions of the world.

2 The challenge of climate change

Global climate change is probably the most significant challenge to energy and environmental policy for the next decades. The increasing scientific evidence on the fact and the consequences of global warming caused by anthropogenic emissions leads to the necessity of new approaches in energy policy. If greenhouse gas emissions continue to rise and the concentrations of these gases in the atmosphere will double or increase, even more significant interferences with the plant’s climate system will arise.

Carbon dioxide (CO_2) emissions from fuel combustions play a major role in climate change. CO_2 emissions from the burning of fossil fuels are responsible for about 80 percent of emissions worldwide. Carbon dioxide is one of the most significant of the greenhouse gases contributing to global warming. Although the concentration of some other greenhouse gases rose significantly during the last century, and although some gases have a very long atmospheric lifetime and some uncertainties remain, human-induced carbon dioxide emissions represent more than half of the increased radiative forcing causing anthropogenic global warming (Table 1).

Table 1 Current Greenhouse Gas Concentrations

	Pre-1750 concen-tration	**Current tropospheric concen-tration**	**GWP (100-yr time horizon)**	**Atmospheric lifetime**	**Increased radiative forcing**
				years	**W/m^2**
Concentrations in parts per million (ppm)					
Carbon dioxide (CO_2)	280	375	1	variable	1.46
Concentrations in parts per billion (ppb)					
Methane (CH_4)	730/688	1,852/1,730	23	124	0.48
Nitrous oxide (N_2O)	270	319	296	1,144	0.15
Tropospheric ozone (O_3)	25	344	n.a.	hours-days	0.35
Concentrations in parts per trillion (ppt)					
CFC-11 (trichlorofluoromethane) (CCl_3F)	zero	256/253	4,600	45	0.34 for all halocarbons collectively, including many not listed here.
(CCl_2F_2)	zero	546/542	10,600	100	
CFC-113 (trichlorotrifluoroethane) ($C_2Cl_3F_3$)	zero	80/80	6,000	85	
Carbon tetrachloride (CCl_4)	zero	94/92	1,800	35	
Methyl chloroform (CH_3CCl_3)	zero	28/28	140	4.8	
HCFC-22 (chlorodifluoromethane) ($CHClF_2$)	zero	15,811	1700	11.9	
HFC-23 (fluoroform) (CHF_3)	zero	1,412	12,000	260	
Perfluoroethane (C_2F_6)	zero	312	11,900	10,000	
Sulfur hexafluoride (SF_6)	zero	5.2111	22,200	3,200	0.0025
Trifluoromethyl sulfur pentafluoride (SF_5CF_3)	zero	0.1213	~ 18,000	~ 3,200 (?)	< 0.0001

Source: Blasing/Jon (2005)

The discussion aboutthe level at which greenhouse gas concentrations should be stabilized ‘that would prevent dangerous anthropogenic interference with the climate system’ (so Article 2 of the UNFCCC) is still under way. However, the limitation of the global mean temperature increase to 2 degrees Celsius above pre-industrial levels is increasingly seen as a threshold for a magnitude of global warming which will lead to unacceptable consequences and risks for nature and human societies.[1] Considering the fact that the global mean temperature has already risen by 0.6°C since the 19th century, only a further warming by 1.4°C is seen as tolerable. In addition, the mean long-term warming rate of 0.2°C per decade at most should not be exceeded.[2]

The translation of such targets into concentrations and emission trajectories is subject to remaining uncertainties (e.g. the climate sensitivity) and an extensive scientific debate. The following parameters are crucial for the identification of measures to be taken to limit global warming within acceptable 'climate windows'.

- the emission pathways over time for the different greenhouse gases but also for other gases which impact radiative forcing (e.g. sulphur emissions because SO_2 aerosols have a 'cooling effect'), where the growth rate, the time of peaking and the following rate of decrease are of special importance;
- the concentration or radiative forcing profiles for the different gases resulting from the emission pathways;
- the climate sensitivity used for recent modelling ranges from a temperature increase of 1.5 to 4.5 degrees Celsius for doubling of CO_2 concentrations with 2.5 degrees as a medium value; if the climate sensitivity would prove to be at the upper range, much more ambitious emissions reductions would be required to meet the 2 degrees target indicated above, if it would be at the lower range less restrictions would result for future emissions (however, much modelling is based on climate sensitivities of 2.5 to 2.8 degrees).

There is a wide range of results of modelling exercises to identify acceptable emission pathways under the 2 degrees restriction for global warming. In particular, alternative strategies for emission reductions for the different gases or alternative timings are of special importance for the debate.[3] Hare/Meinshausen (2004) indicate that

- with a stabilization of greenhouse gas concentrations at 550 ppm CO_2 equivalent (all gases, corresponding approximately to a 475 ppm CO_2 stabilization), the risk of overshooting 2 degrees is between 68% and 99% (mean 85%, 'very high' according to the definitions of IPCC);
- with a stabilization of greenhouse gas concentrations at 450 ppm CO_2 equivalent (all gases, corresponding approximately to a 400 ppm CO_2 stabilization), the risk of overshooting 2 degrees is between 26% and 78% (mean 47% - 'medium likelihood');
- with a stabilization of greenhouse gas concentrations at 400 ppm CO_2 equivalent (all gases, corresponding approximately to a 350 ppm CO_2 stabilization), the risk of overshooting 2 degrees is between 2% and 57% (mean 27% - 'unlikely').

[1] For example the European Council stated 'that to meet the ultimate objective of the UNFCCC to prevent dangerous anthropogenic interference with the climate system, overall global temperature increase should not exceed 2ºC above pre-industrial levels'.
[2] See WGBU (2003+2004).
[3] For more discussion of the exemplary concepts of 'early action' or 'delayed response' see Meinshausen et al. (2005).

Against this background, an ambitious climate policy should target a stabilization of greenhouse gas concentrations at 400 ppm to 450 ppm (that equals a stabilisation of CO_2 concentrations at 350 to 400 ppm).[4] For this range of stabilisation of concentrations, the greenhouse gas emissions should decrease by about 50% by 2050 (compared to 1990 levels).

Although there is a multitude of emission trajectories to meet these concentration levels, important interactions must be considered between the point at which the increasing emission trends peak and turn to a decrease on the one hand and the necessary rate of decrease of the turning point on the other hand. Meinshausen (2005) shows that a delay of global action by 10 years results in a doubling of the necessary emission reduction rate after peaking to half the global greenhouse gas emissions compared to 1990 levels. Against this background, 'early action' is not only necessary in terms of 'learning by doing' but also to avoid additional costs and burdens for the period beyond the peak of global greenhouse gas emissions.

Table 2 Exemplary emission reduction targets to stabilize CO_2 emissions at 400, 450 or 550 ppm, 2020 and 2050

Stabilization Level	Region	CO_2 Emissions	
		2020	2050
		compared to 1990 emission levels (if not indicated otherwise)	
400 ppmv CO_2	Global	+10%	-60%
	Annex I	-25% to -50%	-80% to -90%
	Non-Annex I	Substantial deviation from reference in Latin America, Middle East, East Asia and Centrally planned Asia	Substantial deviation from reference in all regions
450 ppmv CO_2	Global	+30%	-25%
	Annex I	-10% to -30%	-70% to -90%
	Non-Annex I	Deviation from reference in Latin America, Middle East, East Asia and Centrally planned Asia	Substantial deviation from reference in all regions
550 ppmv CO_2	Global	+50%	+45%
	Annex I	-5% to -25%	-40% to -80%
	Non-Annex I	Deviation from reference in Latin America, Middle East and East Asia	Deviation from reference in most regions, specially in Latin America and Middle East

Source: Ecofys (2004)

Table 2 indicates exemplary emission ceilings for the stabilization of CO_2 concentrations at different levels differentiated by country groups (Annex I and non-Annex I countries of the UNFCCC). If the stabilization of greenhouse gas concentrations at 400 to 450 ppm and of CO_2 concentrations between 350 and 400 ppm is necessary, the global CO_2 emissions would have to be decreased by about 60% by 2050 compared to 1990 levels.

For Annex I countries a reduction of CO_2 emissions by 80 to 90% would be required. Even for less ambitious stabilization targets the necessary emissions reductions for industrialized countries would amount to more than 70% compared to 1990 levels.

Furthermore, substantial emissions reductions would have to be achieved for developing countries in such emissions pathway. The CO_2 emissions could increase by 2020

[4] For the debate on temporary overshooting these levels and subsequent return ('peaking'), see Meinshausen (2005).

in this exemplary scenario but also must significantly decrease beyond the horizon of 2020.

However, the corridor of CO_2 emissions to limit global warming to 2°C compared to pre-industrial levels depends very much on climate sensitivity.[5] Table 3 illustrates this by data presented by WBGU (2003). If a high climate sensitivity is assumed, the cumulative CO_2 emissions for the period 2000-2100 are by factor 4 less compared to the case of a lower climate sensitivity.[6]

Table 3 Cumulative CO_2 emissions to limit global warming to 2°C compared to pre-industrial levels

Assumed climate sensitivity	Permissible cumulative CO_2 emissions 2000-2100	
°C	billion metric tons of Carbon	billion metric tons of CO_2
1.5	1,780 - 1,950	6,527 - 7,150
2.5	850 - 910	3,117 - 3,337
3.5	530 - 560	1,943 - 2,053
4.5	380	1,393

Source: WBGU (2004)

Against this background, the assessment of nuclear energy and other mitigation options must consider a framework of rapid and significant CO_2 emissions reduction where the peak of emissions should be reached for the industrialized countries within the next two decades, the global CO_2 emissions should be decreased by 30 to 60% by 2050 and the emissions of industrialized should be reduced by 60 to 90% by 2050. These ranges still represent large uncertainties as to whether the 2°C target can be met. Meeting the 2°C threshold should only be seen as 'likely' if the emission trajectories are close to the lower bounds of the ranges above.

[5] The climate sensitivity is expressed as the increase of the global mean temperature in the case of doubled greenhouse gas concentration.

[6] Other authors (e.g. Meinshausen 2005) conclude from modelling results that meeting the 2°C target is only 'likely' if cumulative CO_2 emissions from fossil fuels can be limited to 400 billion metric tons of carbon (Gt C) for the period beyond 1990. If the cumulative emissions between 1990 and 2000 are considered, this would result in a remaining emission budget of 333 Gt C (or about 1,221 Gt CO_2) for emissions from fossil fuel combustion.

3 Business as usual

CO_2 emission trends

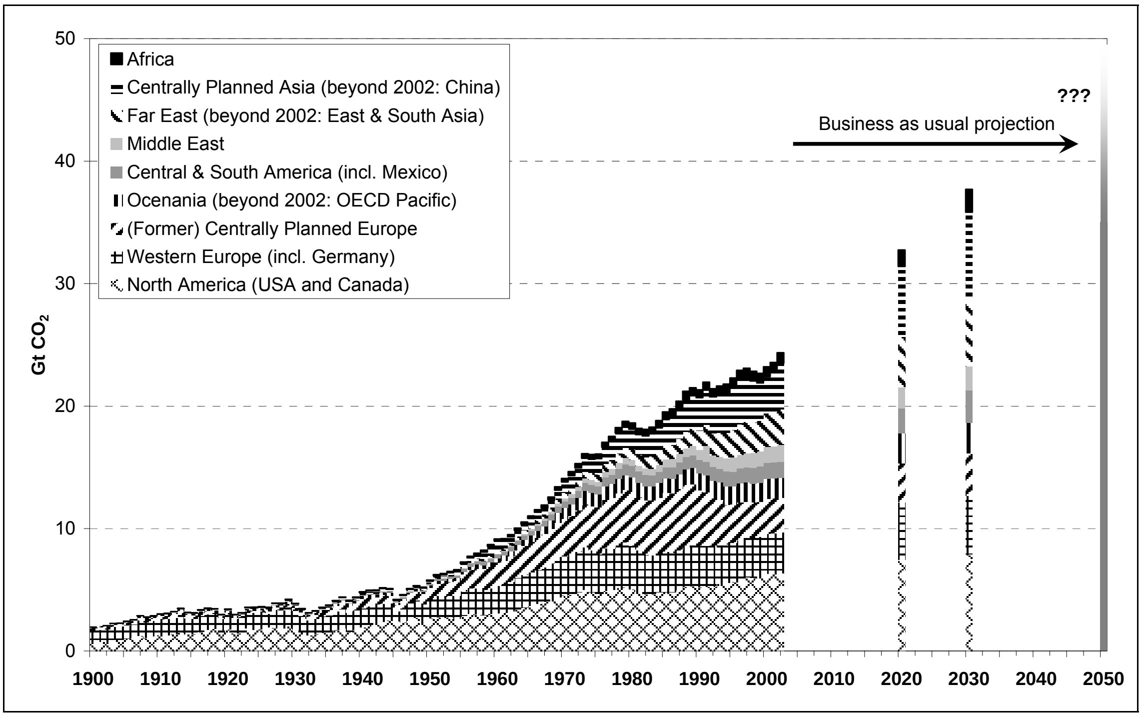
Since the beginning of the twentieth century, the global CO_2 emissions have grown by factor 12. Whereas the emissions of the most important greenhouse gas from North American and Western Europe dominated the global trend by 1950, the emissions from the socialist countries increased very quickly in the post-World War II period. Before the oil crisis of the 1970s the centrally planned countries in Europe represented 22% of the global CO_2 emissions from fuel combustion, Western Europe 23% and Northern America 32%.

The most significant trends for the global CO_2 emissions from the 1980s onwards are

- the steady emissions growth in Northern America;
- the more or less stagnating emission trends in Western Europe;
- the sharp decrease of CO_2 emissions after the collapse of the centrally planned countries in Europe;
- the rising emissions in centrally planned Asia (especially China) and in the other emerging economies in the Far East.

In 2002 the share of Northern America in the global CO_2 emissions was only 26%. The share of Western Europe (14%) was comparable with centrally planned countries in Asia (15%) and exceeded the share of the economies in transition (12%).

Figure 1 Global CO_2 emissions from fuel combustion, 1900-2050



Source: Marland et al. (2005), IEA (2004), own calculations

However, in terms of cumulative emissions Northern America and Western Europe caused the lion's share of CO_2 emissions in the period from 1900 to 2002. The total CO_2 emissions in this period amount to 1,012 billion metric tons of CO_2 (t CO_2). In terms of cumulative emissions the contributions of the different regions are roughly comparable to the situation in actual emissions in 1970. The countries in Northern America are responsible for about 32% of the total cumulative CO_2 emissions, Western Europe represents a fraction of 22% and the former socialist countries in Europe constitute 18%. The share of centrally planned Asia and other countries of the Far East are still low with 8% and 5% respectively.

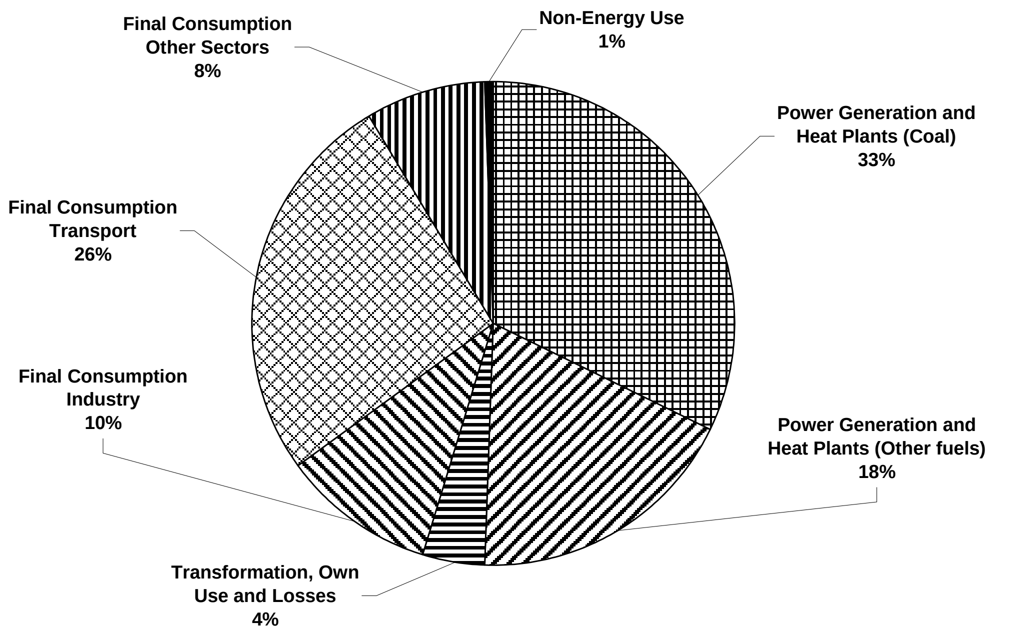
The reference case projection of the International Energy Agency (IEA 2004) foresees a continuation of the most recent trends:

- the global CO_2 emissions from fuel combustion could grow by 62% in the period from 2002-2030;
- the increase of CO_2 emissions for the OECD countries in North America emission would amount to 33%;
- the emissions in Western Europe and the European Union could grow by about 20%;
- the emissions in the OECD countries in Asia and the Pacific region would also increase by about 20%;
- the CO_2 emissions from the economies in transition (especially Russia) would rise again by 40%;
- the CO_2 emissions in many developing countries (China, India, Indonesia, Brazil, etc.) would multiply by a factor of 1.2 to 1.6.

Figure 2 indicates the key sectors for emissions growth in the projection of IEA. Half of the projected emissions growth in the period of 2002 to 2030 originates from the power sector, and about one third from coal-based power generation. The second key sector is transport which causes about 26% of the emissions growth. Although all sectors must be subject to emission reduction measures, the power generation and the transport sector must play an exceptional role in any emission abatement strategy.

Even in a projection with quite different dynamics of emissions growth in the world regions, the 'historic responsibilities' in terms of cumulated CO_2 emissions would only change slightly. The countries of Northern America are responsible for 28% of the total cumulative CO_2 emissions in the period from 1900 to 2030, the Western European countries constitute 18% and the former socialist countries in Europe 14%. The fast-growing countries in Asia and the Far East would still represent 12% and 9% of the global cumulative CO_2 emissions in the period 1900 to 2030.

Figure 2 Sectoral contributions to growth of global CO_2 emissions from fuel combustion, 2002-2030



Source: IEA (2004), own calculations

In comparison to the emission budgets referred to in Chapter 2, the emission trend in the reference case projection of the IEA could hardly be matched to any emission trajectory to comply with the 2°C target if climate sensitivity is higher than 2.5°C. If climate sensitivity were to be about 2.5°C, the emissions trends would have to take on a rapidly decreasing trend immediately after 2030 in order to maintain a certain chance in limiting global warming to 2°C compared to pre-industrial levels (Table 4).

Table 4 Cumulative CO_2 emissions to limit global warming to 2°C compared to pre-industrial levels and the reference case for CO_2 emissions trends by 2030

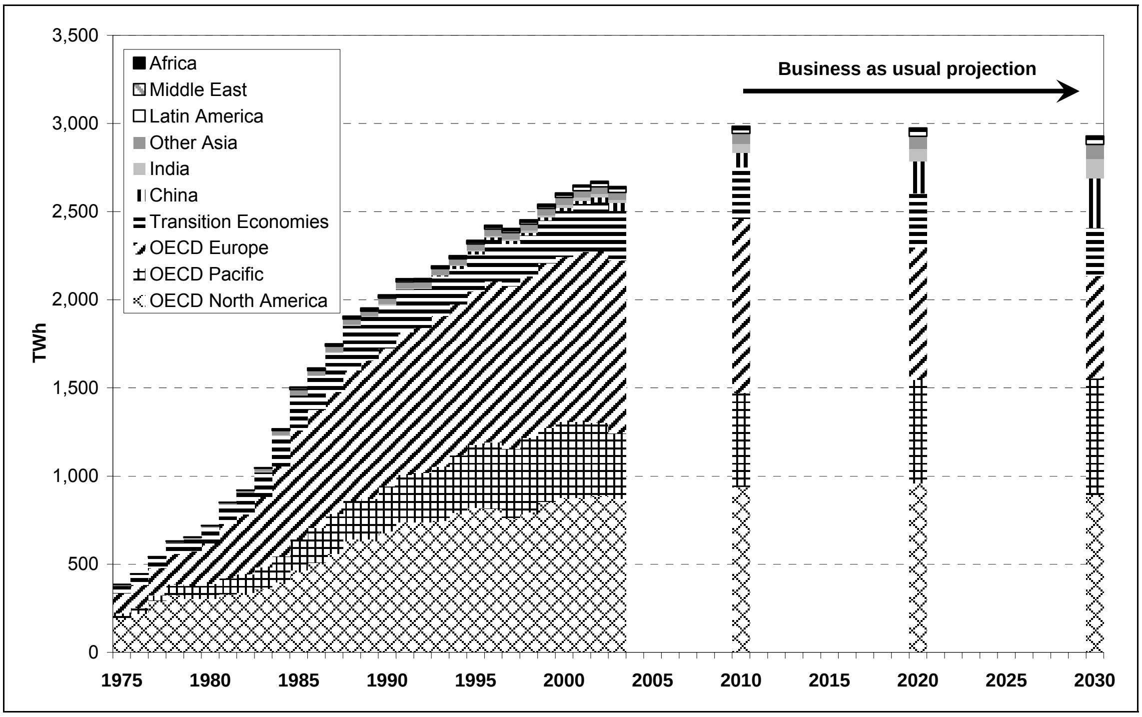
Assumed climate sensitivity	Permissible cumulative CO_2 emissions 2000-2100	Cumulative CO_2 emissions 2000-2030	Emission budget left
°C	billion metric tons of CO_2		
1.5	6,527 - 7,150	~ 900	86% - 87%
2.5	3,117 - 3,337	~ 900	71% - 73%
3.5	1,943 - 2,053	~ 900	54% - 56%
4.5	1,393	~ 900	35%

Source: WBGU (2004), IEA (2004), own calculations.

Nuclear power generation

In contrast to the global energy demand and the global CO_2 emissions, the development of nuclear energy was mainly a development within the OECD countries and the European socialist countries or transition economies. The strong growth of nuclear power generation from the 1970s to the 1980s flattened significantly after the Chernobyl disaster. Only a little growth can be observed for the years after 2000. The share of nuclear power generation was 22% in 2003 for the OECD countries and 6% for the non-OECD countries. Only some countries in the world produce more than one third of their electricity from nuclear energy, among those are OECD countries (France, Sweden, Belgium, Hungary, Korea, Slovakia, Sweden, Switzerland) but also some countries with economies in transition (Bulgaria, Slovenia, Armenia, Lithuania and Ukraine).

Figure 3 Nuclear power production, 1975-2030



Source: IEA (2004+2005)

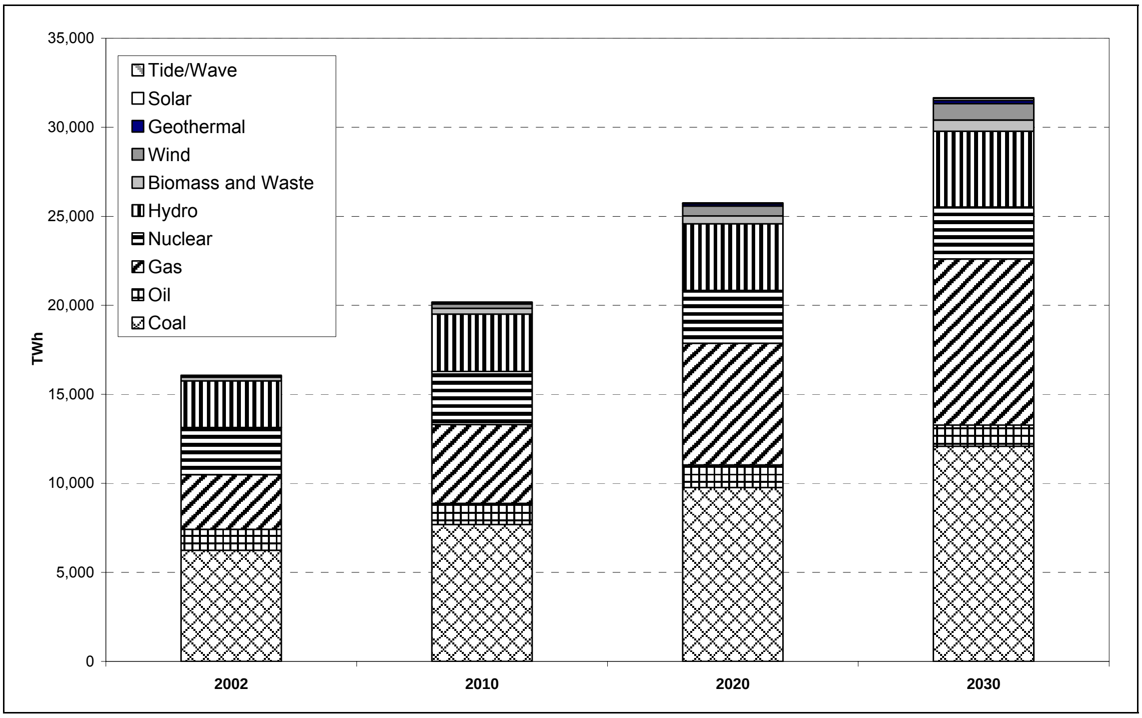
The main reasons for the declining dynamics of nuclear power in many regions of the world can be found in the following factors:

- the increasing public resistance to nuclear power in many countries, especially regarding major nuclear accidents, the disposal of radioactive waste, the transport of nuclear materials and the problems of proliferation and terrorism;
- the economic problems nuclear plants faced after the liberalization of electricity markets in some OECD countries, including the problem of financing decommission and the disposal of nuclear waste;
- the increasing safety requirements and standards for new and existing nuclear plants;

- the comparatively low prices for fossil fuels and strong improvements in competing power production technologies.

The reference case projection for nuclear power generation indicates a small growth by 2010 and a slight decrease for the two decades beyond 2010. This trend results from three different trends. Especially in the European OECD countries a strong decrease in nuclear power production is assumed. In these countries as well as the European Union the electricity production is to decrease by 40% in the next three decades. In Northern America as well as in the transition economies the nuclear power production is assumed to be more or less stagnating. However, in the Asian OECD countries and in some developing countries a massive increase in nuclear power production is foreseen by IEA (2004). In the Asian OECD countries this projected increase amounts to 60%. Starting from very low levels, nuclear power production in China is assumed to rise by factor 10 and in India by factor 4.8. For other developing countries a much smaller but nevertheless significant growth in nuclear energy is seen (Latin America +38% for 2002 to 2030, in Africa +18%).

Figure 4 Electricity production in the business as usual case, 2002-2020



Source: IEA (2004)

Although a slight increase in nuclear power production is foreseen in the World Energy Outlook, the share of nuclear in total power generation should decrease significantly. In 2002 the share of nuclear was 17%, by 2030 it will decrease to only 9%. And even in the China, the country with the strongest increase nuclear power, would only contribute 5% to the total power generation. The major growth in electricity generation in the World Energy Outlook 2004 comes from coal- and natural gas-based power production. Although a strong growth is also projected for the electricity production from renewable energy sources, these sources (apart from hydropower) will play a less important role in the reference case projection outlined by the IEA.

4 Dealing with complex structures of risks

The risks of global warming and the risks related to nuclear energy constitute an area of conflict where a more systematic approach for the assessment of different types of risk is necessary in order to develop guidelines and strategies.

The German Advisory Council on Global Change (WBGU) has proposed a model which enables the comparison and the assessment of different risks. In the WBGU model, risks should be categorized by the following criteria (WBGU 2000):

- the probability of occurrence
- the extent of damage
- the certainty of assessment of probability and of the extent of damage
- the ubiquity (global effect)
- the persistency (very long removal periods)
- the irreversibility (damages are not reversible)
- the delay effect (very long time lags)
- the mobilization potential (high psychological and political relevance)

Based on these criteria, risks can by clustered by different 'areas'. Risks in the 'normal area' are characterized by the following attributes (WBGU 2000):

- low uncertainties regarding the probability distribution of damage;
- a small catastrophic potential overall;
- a low to medium uncertainty about both the probability of occurrence and the associated magnitude of damage;
- low statistical confidence intervals with respect to probability and magnitude of damage,
- low levels of persistency and ubiquity (scope in time and space);
- a high reversibility of potential damage;
- a low potential for social conflict and mobilization

A more problematic situation arises for the critical area, which consists of a 'transitional area' and a 'prohibited area'. Risks in the 'critical area' have at least one of the following characteristics (WBGU 2000):

- a high uncertainty for all risk parameters;
- a high damage potential;
- the probability of occurrence is high (close to 1)
- a high uncertainty of assessment, but reasonable grounds to assume that major damage is possible;

- high persistency, ubiquity and irreversibility, reasonable grounds must exist to assume that damage is possible;
- a major potential for mobilization is to be expected (refusal, protest, resistance) for reasons of perceived distributional injustice or other social and psychological factors.

The differentiation between the ‘transitional area’ and the ‘prohibited area’ is based on the possibility of reducing the risk or of building a consensus whereby the opportunities exceed the damages (WBGU 2000):

- If risk-reducing measures are possible whose implementation promises a transition into a ‘normal area’ risk, the risk should be seen in the ‘transitional area’.
- If the extent of damages is so severe and no measures can be taken for a significant limitation of damages or no consensus can be built in the society so that these risks are accepted due to the associated opportunities, the risk should be considered to be part of the ‘prohibited area’.

Against this background, the key questions regarding all risks to be allocated in the critical areas are:

- Are there existing measures or ones under development which could reduce the extent of damage with a high certainty and in a foreseeable future to a dimension which could refer to the ‘normal area’? If this is not the case, all efforts should be taken to substitute the regarding technology, etc.
- Is there an existing consensus in the society or could such a consensus be built where the risks of severe damages could be accepted due to the associated opportunities for the society. If this is not the case, all efforts should be taken to substitute the regarding technology, etc. This dimension is of special complexity if the problem is to have a strong international and inter-generational dimension and no institutional arrangements exist to reflect a consensus in the society in this respect.

In addition to the criteria to categorize risks, the WBGU introduced several risk classes, indicating the dimensions for a couple of environmental and other risks. Table 5 gives an overview on the risk classes ‘Damocles’, ‘Cyclops’, ‘Pythia’, ‘Pandora’, ‘Cassandra’ and ‘Medusa’.

Table 5 Overview of risk classes: characterization and substantive examples

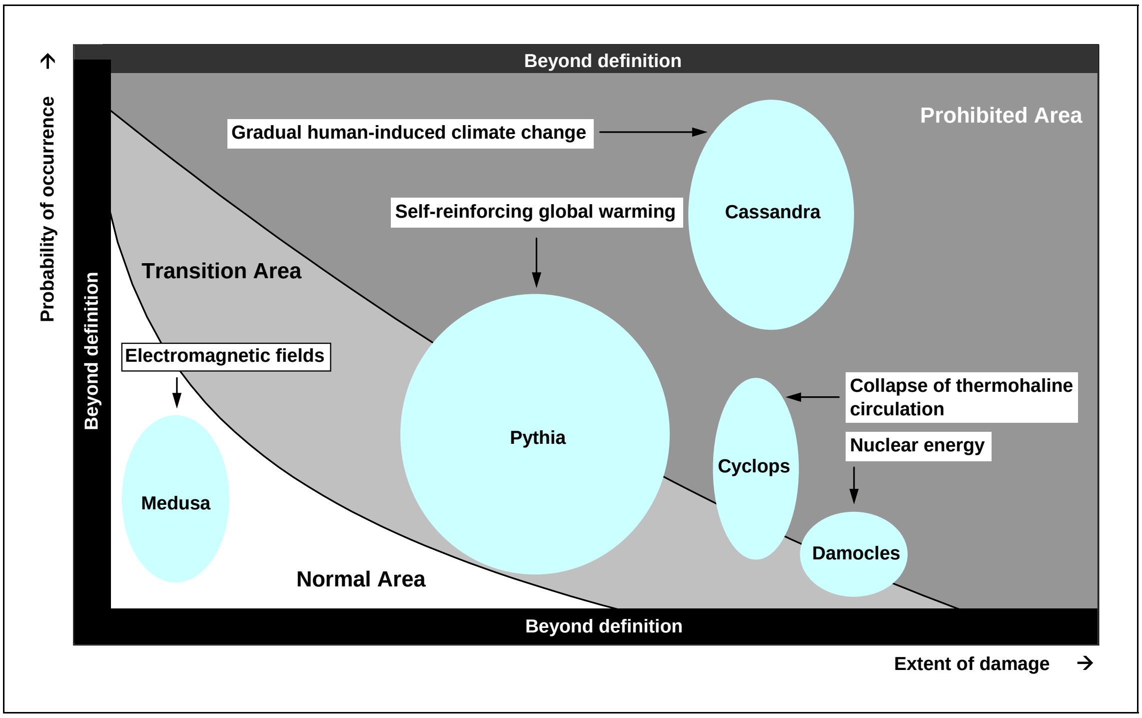
Risk class	Characterization	Examples
Damocles	▪ Probability of occurrence is low ▪ Certainty of assessment of probability is high ▪ Extent of damage is high ▪ Certainty of assessment of extent of damage is high	▪ Nuclear energy ▪ Large-scale chemical facilities ▪ Dams ▪ Meteorite impacts
Cyclops	▪ Probability of occurrence is unknown ▪ Reliability of estimation of probability is unknown ▪ Extent of damages is high ▪ Certainty of assessment of extent of damages tends to be high	▪ Floods ▪ Earthquakes ▪ Volcanic eruptions ▪ AIDS infection ▪ Mass development of anthropogenically influenced species ▪ Nuclear early warning systems and NBC-weapons systems Collapse of thermohaline circulation
Pythia	▪ Probability of occurrence is unknown ▪ Certainty of assessment of probability is unknown ▪ Extent of damage is unknown (potentially high) ▪ Certainty of assessment of extend of damages is unknown	▪ Self-reinforcing global warming ▪ Release and putting into circulation of ▪ BSE/nv-CJD infection ▪ Certain genetic engineering applications ▪ Instability of the West Antarctic ice sheets
Pandora	▪ Probability of occurrence is unknown ▪ Certainty of assessment of probability is unknown ▪ Extent of damage is unknown (only assumptions) ▪ Certainty of assessment of extend of damages is unknown ▪ Persistence is high (several generations)	▪ Persistent organic pollutants (POPs) ▪ Endocrine disruptors
Cassandra	▪ Probability of occurrence tends to be high ▪ Certainty of assessment of probability tends to be low ▪ Extent of damage to be high ▪ Certainty of assessment of extent of damages tends to be high ▪ Long delay of consequences	▪ Gradual human-induced climate change ▪ Destabilization of terrestrial ecosystems
Medusa	▪ Probability of occurrence tends to be low ▪ Certainty of assessment of probability tends to be low ▪ Extent of damage to be low (exposure high) ▪ Certainty of assessment of extent of damages tends to be high ▪ Mobilization potential is high	▪ Electromagnetic fields

Source: WBGU (2000)

For the debate on nuclear energy and climate the risk classes of ‘Cassandra’ and ‘Damocles’ are of special relevance. From the dynamic perspective, the WBGU calls for precautionary measures of climate policy and for major efforts to limit the ‘Cassandra’ type risk of global warming (see Figure 5) within the concept of tolerable windows:

- The increase of global mean temperature should be limited to 2°C compared to the pre-industrial levels.
- The rate of temperature change should be lower than 0.2°C per decade.

Figure 5 Classes of risk and their location in the normal, transition and prohibited areas



Source: WBGU (2000).

On the ‘Damocles’ risk of nuclear energy, the WBGU states: “If even best efforts cannot reduce the catastrophic potential expediently or can only do so at exorbitant cost, then … such a source of risk should only be approved under two conditions: firstly, if the utility of this source of risk is of existential importance and, secondly, if it can be ensured that all technological, institutional and organizational options are exploited to ensure that the catastrophic event does not occur in the first place and, should it occur after all, damage is mitigated as far as possible. This second precondition gains particular relevance if such sources of risk are exported by technology transfer to other countries”.

With regard to this assessment the situation regarding nuclear energy is a complex one:

- A first key issue is whether the full set of technological, institutional and organizational options for transferring the ‘Damocles’ risk into a ‘Medusa’ type one exists, i.e. the limit the extent of damages and maintain the low probability of occurrence. These options should be assessed with respect to the current use of nuclear power as well as the use of nuclear energy to a much larger extent in any regions of the world.

- The second question is whether nuclear power could be an existential part of the risk substation regarding global warming, i.e. the substitution of a ‘Cassandra’ type risk which definitely is part of the ‘prohibited area’.

With current reactor technologies the extent of damage (regarding major accidents, terrorist attacks, management and disposal of radioactive materials, etc.) definitely cannot be limited to a range required by the ‘normal’ area’. Furthermore high uncertainties remain regarding the ability of future rector generations to comply with the requirements given above and the strong relation between the risks of nuclear power and social, political and institutional stability.

Against this background, the first decisive question on the future of nuclear power in the global energy system is whether alternative options exist to ensure an appropriate quantity of energy services on the global level within the framework of strong constraints on greenhouse gas emissions. Second, the question of whether and how the risk of climate change could be limited to acceptable levels without relying on nuclear energy must be dealt with, as well as whether this could be done within the framework of acceptable consequences (costs, social acceptance, other risks).

5 Mitigation options

Preliminary remarks

The wide range of scientific analysis on emission reduction strategies to stabilize greenhouse gas concentrations in the atmosphere shows that there is no single option which is able to deliver all emission reduction needed. However, the contribution of different options will strongly depend on the level of concentration stabilization. If less ambitious reduction targets are focussed upon, a lot of flexibility would obviously exist regarding the extent to which the different technological options would be exhausted. In such a scenario it could be much easier to abandon the use of nuclear power for the reasons discussed in the previous chapter.

The technology mix for greenhouse gas reduction strategies was analyzed with many different methodological approaches, e.g. in the Third Assessment Report of the IPCC (2001) but also in many other studies (e.g. Schrattenholzer et al. 2004, WBGU 2004).

In the analysis presented here, we refer to these studies with a simple approach. If we assume that in the business as usual case (BAU), the global CO_2 emissions from fuel combustion will increase to between 40 and 50 billion tons by the year 2050, and the necessary reduction to stabilize the CO_2 emissions at a level at which the 2°C target can be achieved is between 30 and 60% below the 1990 levels, the gap to be closed by mitigation options will be between 25 and 40 billion tons of CO_2 in the year 2050. In a simplified model we assume a linear trend and do not take into account different options of emission peaking and reduction pathways after peaking which could be characterized by different gradients of emission decrease. We use this simplified model to show potential contributions and potential interactions between different clusters of abatement strategies.

Nuclear power

442 reactors with a total capacity of 368.6 GW were operated worldwide for power production in 2004. The vast majority of these reactors are light water reactors in different designs. In 2003 a share of 15.7% of global power production was generated in nuclear power plants. The share of nuclear power differs significantly between the OECD and the non-OECD countries. In the OECD countries about 2,223 TWh electricity were generated in nuclear power plants in 2003 which corresponds to a share of 22.3% in 2003. The nuclear power production in non-OECD countries amounted to 412 TWh in 2003 which is equal to a share of only 6%.

The BAU projection of the OECD indicates only a slow growth in nuclear power by 2030. The increase of the total capacity from 359 GW in 2002 to 376 GW in 2030 corresponds to a net growth of 600 MW annually on average for the period from 2002 to 2030. In other words, every two years a new nuclear power plant with a capacity of 1,200 MW must be commissioned to follow this route. However, if the age structure of the existing nuclear power plants is considered, on average between 4 and 5 GW new nuclear capacity must be put into operation every year (between 3 and 4 large power plants).

The potential contribution of nuclear power to ambitious emissions reduction targets was assessed in a number of studies.

- A tenfold expansion of nuclear power production in the period from 2000 to 2075 (van der Zwaan 2002) would indicate a worldwide nuclear power capacity of 2,050 MW with a production of 17,283 TWh in 2050. This is approximately the sixfold power generation of the BAU case. On average 35 GW of nuclear capacity would have to be added every year by the year 2050. Such an increase in nuclear power production would not only substitute coal but also a significant share of gas-based electricity generation. Following this extreme und obviously unrealistic scenario, a CO_2 reduction of 9,700 Mt CO_2 in the year 2050 would result.
- Pacala/Socolow (2004) suggest an extension of 700 GW by the middle of this century, which is equivalent to a threefold capacity compared to the current level. Considering the necessary replacement of existing plants, on average 25 GW capacity must be put into operation annually to reach a capacity of 1,060 GW for nuclear power plants in 2050. The total power production would amount to 8,260 TWh in this case and would reduce 7,000 Mt CO_2 in the year 2050, if only coal power plants were to be substituted. In the case of a mix of coal and gas-fired power plants being replaced by the additional nuclear plants, the contribution to emissions reduction would amount to 5,000 Mt CO_2 in the year 2050.

Based on the historic experience regarding the development of nuclear power, both scenarios seem very unrealistic. However, the major risks and concerns regarding nuclear power should be mirrored in these two scenarios. In addition it must be highlighted that such scenarios imply that nuclear power must reach significant shares in total power production in countries and regions where nuclear energy today plays no or only a minor role. A three- or sixfold extension of nuclear power generation in North America, Europe or Japan will not be feasible, given the significant share of nuclear energy in their power mix.

The main risk from nuclear reactors is a major accident with massive radioactive releases. Such radioactive releases would substantially harm health, ecosystems and social and economic systems (UNDP/UNICEF 2002). The vast majority of the existing plants and, in the next three decades, also the vast majority of new nuclear plants would be light-water reactors which will be evolutionarily developed on the basis of current reactor concepts. For all of these reactors, very serious inherent safety flaws must be acknowledged (Froggatt 2005).

Even if the probability of a disastrous accident seems to be very low on a specific basis,[7] the extension of nuclear power by three or six times over the next 50 years would lead to an enormous risk of one or more disastrous accidents. Modelling exercises on the economic consequences of a major accident in a German nuclear power plant showed that the total costs of such a disaster could amount to about 2,000 to 5,000 billion $ (Ewers/Rennings 1991+1994).

[7] Sailor et al. (2000) refer to a risk of an accident with large external release of radioactivity of about 10^{-5} to 10^{-6} per reactor year. However, the possibility of concerted terrorist attacks was not taken into account for these assessments at that time.

Apart from light-water reactors several reactor concepts are in various stages of development and implementation. For all of these 'evolutionary concepts' (so called 'Generation III reactors') major and inherent risks exist for different accident scenarios, leading to a massive release of radioactive materials. In some countries, research has started to develop 'revolutionary reactor concepts' (so called 'Generation IV reactors') which shall be much more safe, reliable and economical than the Generation III reactors and should at the same time be resistant in terms of proliferation, etc. (NERAC 2002). A closer look at the technical concepts shows that many safety problems are still completely unsolved and some empirical evidence exists which shows that safety improvements in some respects could create new safety problems (Froggatt 2005). Last but not least, the question as to how these reactor concepts might balance safety improvements against the goal of low investment and operational costs remains entirely open. It is also worth mentioning that the development of the new reactor generation requires enormous investment and the outcome is still very uncertain. Generation IV reactors would be available – if they will be available at all – 20 to 30 years from now at the earliest. Whether and in which way the design of new reactors could adequately respond to the threat of concerted terrorist attacks (including airplane crashes) is still very uncertain. Comparable problems could arise from a stronger penetration of nuclear power plants in countries or regions where the risk of military conflicts is much higher than in those countries and regions where the majority of reactors is operated today.

The availability of nuclear fuel will be a main precondition for a massive contribution of nuclear power to ambitious emission reduction targets in 2050. Currently the annual demand for nuclear fuel is about 70,000 tons of uranium. For a three- to sixfold expansion in a comparatively short timescale, the demand for nuclear fuel would be increased several times, even in the case of the efficiency of fuel use being increased significantly. The supply of nuclear fuel would have to rely on speculative (undiscovered) resources (see Kreusch et al 2005) in a few decades. The uranium mining capacities would have to be extended substantially, which will take many years in the light of past experiences.[8] Furthermore, significant new enrichment capacities would be required. Lovins (2005) reports that 15 new enrichment plants must be built for 700 GW additional nuclear power plants.

Against this background, Rothwell/van der Zwaan (2003) rank light-water reactors systems as non-sustainable against the criterion of non-renewable resource depletion. Moreover, the roadmaps for Generation IV reactor systems clearly highlight the problem of finite fuel resources for light-water reactor systems (NERAC 2002). If the availability (and the costs) of nuclear fuel for light-water reactor systems is seen as a problem, once-through fuel cycles will be of limited importance in future. At present once-through fuel cycles are the preferred option because of the lower costs and the exclusion of risks from the reprocessing of spent fuel. Although the Generation IV reactor concepts are still speculative in many aspects, with their focus on 'closed fuel cycles', the wide-range introduction of fast breeder reactors and the reprocessing of spent fuel is back on the agenda (NERAC 2002). If the nuclear technology chain is extended to breeder reactors and reprocessing facilities (and additional transport re-

[8] Price et al. (2004) give an overview of mining projects where the time between the beginning of exploration and the start of production was 20 to 30 years and the time between the discovery of the deposit and the start of production was 10 to 20 years.

quirements) the risks of accidents as well as the vulnerability with regard to terrorist attacks or military conflicts will be increased significantly. Lovins (2005) illustrates the dimension of reprocessing for the case of additional 700 GW nuclear power plants which would require about 50 new reprocessing plants worldwide.

The challenges of proliferation are of growing importance following the end of the Cold War. The actual non-proliferation problems (Iran, North Korea) indicate that with an expansion of nuclear power – even in regional terms – additional risks will arise (Nassauer 2005). An electricity system with 1,000 GW nuclear capacity with light-water reactors would produce about 290 t plutonium (Pu) annually. In the case of the nuclear capacity amounting to 2,000 GW in 2050, the annual plutonium production would reach 560 t Pu annually. Such quantities of fissile material would pose serious problems in terms of non-proliferation and would require a completely new quality of international safeguarding regimes. If the once-through fuel cycle were to be substituted by closed fuel cycles with reprocessing and separation of plutonium, serious threats to international security could arise in both cases, the amount of plutonium to be handled and the regions where significant amounts of plutonium would occur. Furthermore, it would be erroneous to assume that the risk of proliferation would became zero or negligible, which also cannot be assumed for the Generation IV reactor concepts.

Although numerous studies were carried out to identify and to demonstrate the long-term reliability of final depositories, no country found a permanent solution for final nuclear waste disposal. The research on developing final depositories as well as public participation procedures or efforts to win public acceptance for nuclear disposal sites are very much continuous (Kreusch et al. 2005). If the amount of nuclear waste were to grow significantly, the gap between the generation of high-level radioactive waste and the availability of disposal sites would deepen more and more. Van der Zwaan (2002) uses the example that a twofold growth of US nuclear power production would require a repository capacity with an equivalent of the Yucca Mountain project every 25 years. According to Lovins (2005) the extension of the global nuclear capacity by 700 GW would require depository sites with a capacity of 14 Yucca Mountain projects.

Last but not least, the economics of nuclear power generation are decisive for the future role of nuclear power in the framework of an ambitious climate strategy. Without a price on CO_2 (either with a carbon tax or within the framework of an emissions trading scheme), it is unlikely that nuclear power could compete in competitive markets (Thomas 2005). However, the gradual phase-in of market-based instruments of climate policy (e.g. the European Union emissions trading scheme) could change this situation on the one hand. The level of CO_2 prices which could significantly improve the economic performance of new nuclear power plants is still controversial. Sailor et al (2000) refer to a carbon price of approximately 100 US$/tC (27 US$/t CO_2) which would be necessary for new nuclear power plants to compete in the market. Other assessments show significantly higher thresholds for the economic competitiveness of nuclear power generation. On the other hand, it should be considered that many other factors distort the economic appraisal of nuclear power generation. The lack of sufficient decommissioning funds, very generous liability regulations, tax breaks and other discounts in many countries hide the real costs of electricity from nuclear power. If nuclear power should play a more significant role in future, these hidden costs will increasingly come to the surface because the burden to those entities which must carry the burden in the end will be more and more obvious.

In summary, nuclear power could contribute to a certain extent to ambitious emissions reduction targets at the global level. This contribution would not substitute any other option on the one hand but could be significant on the other hand. For such significant contribution, the use of nuclear power must be expanded in a dimension which has strong implications. These implications must be assessed to enable a well-founded comparison with other emission abatement options. The massive expansion of nuclear power

- would significantly increase the risks for health, ecosystems, social and economic systems because of major accidents (including terrorist attacks);
- would create the problem of nuclear waste and proliferation in a new dimension in terms of amount of material and regions and countries where the problems would emerge;
- would require the substitution of the once-through fuel cycle by more or less closed fuel cycles and the re-entry in reprocessing and the fast breeder technology that would lead to additional risks and additional vulnerabilities of the technology chain;
- would require heavy investments in the full technological chain, including mining, enrichment and reprocessing which would necessitate long-lasting preparatory activities;
- would require strong grid and other infrastructures for stabil operations;
- will be more attractive if a price is put on CO_2 emissions on the one hand, but would bring other distortions to the surface which strengthen the economic performance of nuclear power generation.

These risks and problems are subject to political and scientific debates in manifold dimensions. For some risks technological or institutional proposals do exist on how the problems or their consequences could be limited or excluded (see Sailor et al. 2000, van der Zwaan 2002). However, it is extremely speculative whether such proposals ever will work or could be implemented sufficiently in the real world and within an appropriate timeframe.

Against this background, the following sections will analyse what other options could contribute to ambitious emission reduction strategies, what is their potential, what are the related restrictions, requirements, time-scales and policy tools, what are other implications and what are the costs compared to those of nuclear power.

If the risks and problems of nuclear power mentioned above are assessed seriously, the key question is whether the potential alternatives to the use of nuclear power (including their implications) would allow ambitious emission reduction targets to be achieved. In other words,

- would it be possible to reach ambitious emissions reduction targets without nuclear power in terms of potentials or costs or

- would the implications of single alternatives or the alternatives at all obstruct emission reduction strategies in the end or
- could a strategy with a significant contribution of nuclear power prove to be counterproductive for ambitious emission reduction strategies because other options would not be able to evolve.

The key issue on the assessment of nuclear power is targeting ambitious emissions reductions in a climate change strategy, to what extent there is explicitly (in terms of potentials) or implicitly (in terms of consequences and implications for other abatement options) a strong necessity to include nuclear power in the portfolio to meet ambitious challenges and targets of climate change strategies and policies.

End use energy efficiency

The World Energy Outlook (IEA 2004) assumes an annual improvement of energy intensity between 1.3 and 1.6% at the global level for the next three decades. In other words, the same economic value (in terms of purchasing power parities) will be created in the year 2030 with one third less primary energy compared to 2002. However, the strong economic growth at the global level will more than compensate the gains from energy efficiency. In the period of 2002 to 2030 the IEA estimates a global economic growth by a factor of 2.4 (the projected population growth for this period is about 30%). Consequently, the primary energy consumption will increase by almost 60%. If these trends were to continue, a primary energy consumption of about 21 million tons of oil equivalent and annual CO_2 emissions from fuel combustion of 48 billion tons of CO_2 could result by 2050.

However, large efficiency potentials will not be implemented in the BAU case although many of these options will be cost-effective from a general point of view. Jochem et al (2000) show significant energy efficiency potentials (5 to 80%) in all sectors and for all regions in the world. The IPCC (2001) highlights key areas of energy consumption where considerable possibilities exist for a more efficient use of energy.

In the end use sectors the following key areas for energy efficiency improvements are seen as the most significant ones:

- energy consumption of buildings (including appliances), IPCC (2001) refers here to an emission reduction potential of 1,000 to 1,100 Mt C (3,667 to 4,033 Mt CO_2) for the time horizon of 2020; Pacala/Socolov (2004) assume the same amount for the time horizon of 2050 which could be seen as a conservative estimate;
- the main efficiency potentials in industry are seen in energy efficiency and improved material efficiency, according to IPCC (2001) the total reduction potential amounts to 1,300 to 1,500 Mt C (4,767 to 5,500 Mt CO_2) annually in 2020;
- energy consumption from transport is significant because of the fast-growing emissions in this sector; IPCC (2001) estimates a saving potential of 300 to 700 Mt C (1,100 to 2,567 Mt CO_2) in 2020; Pacala/Socolov (2004) refer to 2,000 Mt C (7,333 Mt CO_2) for the time horizon of 2050.

In total, a reduction potential of up to 16,000 Mt CO_2 could be estimated for 2050 if comprehensive measures for the improvement of energy efficiency in the end use sector were to be implemented. This is a share of 40 to 60% of the gap between BAU and ambitious emissions reductions to enable a stabilization of CO_2 concentrations in the range of between 400 and 450 ppm.

One of the main advantages of strategies focussed on energy efficiency is that many options are cost-effective from an aggregated point of view and emission reductions could be implemented at low or even at no additional cost. However, the main problems regarding the implementation of energy efficiency measures are of a non-economic nature. The major problem of energy efficiency strategies is that manifold obstacles and structural barriers on the one hand (ranging from a lack of information and motivation to the user-investor dilemma) and very heterogeneous structures regarding actors, motivations and capabilities on the other hand.

Significant improvements in energy efficiency can be brought about by current technologies. Furthermore, technological and organisational innovations will play an additional role over time. The key problem of energy efficiency policies is the necessity of a steady phase-in and permanent efforts. Especially in the field of energy efficiency improvements the step-by-step approach and an early start will be of much higher importance than certain technological breakthroughs. The long-living capital stock, e.g. in the building sector, will require early action to use the existing windows of opportunity.

Energy efficiency improvements in the energy sector

Technological developments especially in the power sector have shown significant improvements during recent years. For the coming years and decades, additional efficiency gains can be assumed if the dynamics of research and development are to be enforced. Compared to today’s global average of 30 to 35%, the efficiency of coal-fired power plants could increase to 50% and natural gas-fired power plants to 65% in the near future (EK 2002). In the longer perspective, combined cycle gas turbines could reach efficiencies close to 70% and new super critical steam turbines could show a net efficiency of 55% within the next two decades.

A much stronger improvement in high efficient power production could be delivered by combined heat and power (CHP or the combined heat, power and cooling (CHPC) production. The use of waste heat from electricity production for heating, industrial processes or even for cooling could raise the total efficiency of CHP and CHPC plants to 90%. CHP and CHPC can be applied at the level of large scale installations with several hundreds of megawatts for process heat supply in industrial enterprises and district heating systems. However, with micro CHP installations of several kilowatts (Pehnt et al. 2005) a huge potential of heat supply could be made available for high efficient CHP technologies.

Whereas the steady improvement of power plants is included in many BAU projections and the additional potential for emissions reduction is limited, the potential of CHP is still far from being exhausted in the recent projections. A simplified calculation underlines the important potential for CHP and CHPC in an integrated CO_2 reduction strategy.

If we assume an additional power production from non-biomass CHP of 20% of a global electricity generation of 30,000 TWh in 2050 (considering a significant reduction by improved energy efficiency), this would lead to an annual CO_2 reduction of 2,000 Mt CO_2 only by virtue of an efficiency increase in power production and not taking into account additional effects from fuel switching.

Fuel switch in the power sector

In the business as usual scenario of the IEA (2004), power production from fossil fuels will dominate the supply of electricity by the year 2030. For the period from 2002 to 2030, coal-fired power plants are projected to extend capacities from 1,135 GW to 2,156 GW and gas-fired power plants are projected to increase the total capacity from 893 to 2,564 GW. For the whole period this equals on average an annual growth of 36 GW for hard coal and 60 GW for natural gas. If we consider also that during the next three decades about half of the existing capacities must be replaced by new plants in the period 2002-2030, 57 GW of new coal plants and 76 GW of new gas plants must be commissioned on average every year. If we extend this trend to the year 2050, new investment in coal plants would amount to about 2,700 GW for coal plants and about 3,600 GW for gas plants. A decision for new coal plants with a capacity of 1 GW equals a decision on annual emission of about 4.7 Mt CO_2 (average efficiency for new plants of 40% and a load factor 0.63) for the lifetime of the plants which is about 40 years or more. A similar estimate for new investments in natural gas plants leads to an annual emission of 1.3 Mt CO_2 per GW (assuming an average efficiency of 55% and a load factor 0.40).

Due to the less carbon-intensive fuel and the significantly higher efficiency of gas-fired power plants, electricity generation from new gas plants creates 57% less CO_2 compared to a new coal plant. Against this background, additional fuel switch in the power sector from coal to gas could open significant potentials for emission reduction.

Pacala/Socolow (2004) assume a replacement of 28 GW baseload power generation from coal by gas to achieve further emission reductions. This is about half of the annual investment in new coal power plant as shown above. If 50% of the new investment in coal would be shifted to natural gas by the year 2000, coal plants with a total CO_2 emission of 6,300 Mt CO_2 in 2050 would be replaced by gas-fired power plants with total emissions of 2,700 Mt CO_2. If all new investments in coal plants would be replaced by investments in natural gas, the emission levels would double: 12,700 Mt CO_2 for coal and 5,500 Mt CO_2 for natural gas. If we assume the substitution of 50% of the new investments in coal plants, an annual emission reduction potential of 3,600 Mt CO_2 would occur for the year 2050.

Of course the additional investments in gas-fired power plants will require additional supplies of natural gas. For the rough estimate referred to above, the additional gas demand for power production is 29 EJ for the year 2030 and 49 EJ for the year 2050. The gas demand in the business as usual scenario of the IEA (2004) amounts to 176 EJ in 2030. In other words, the demand of natural gas would increase by about 16% compared to the BAU case. The additional gas demand for the time horizon of 2050 should be in the same sort of magnitude. In the framework of a sustainable energy strategy, this amount of natural gas should be compensated by energy efficiency measures either in other sectors (e.g. the building sector) or in the power sector itself.

The key technology to decrease the additional demand for natural gas is combined heat and power (CHP) or combined heat, power and cooling (CHPC) production. If one quarter of the new gas-fired power plants would be based on CHP or CHPC, the additional gas demand would decrease by about 7%.

Renewable energy

The global flows of renewable energies are three orders of magnitude larger than the current and projected global primary energy demand (Rogner 2000). A variety of technologies already exists for the use of renewable energies and a wide range of technologies is under development. The main challenges for the massive extension of renewable energy use are as follows (Rogner 2000, WBGU 2004):

- only few options for using renewable energies are currently competitive compared to energy supply from fossil or nuclear energies within the current economic framework (no internalization of external costs);
- the use and the economics of renewable energies are affected by several constraints, such as land-use conflicts (e.g. biomass), latitude (e.g. solar energy), location (e.g. wind power and geothermal energy) or nature protection and social constraints (e.g. hydro power);
- the global distribution of current and future energy supplies from renewable energies shows different patterns; the potential of renewable energies is much smaller in Europe (not including the former Soviet Union) and Asia than in the Americas or in the solar-rich continents and regions.

Renewable energy already covers a significant share of the global primary energy supply today. However, many uncertainties exist on the exact share at the moment because the major part of renewable energies used today is traditional biomass which is not a commercial energy in many regions of the world. Furthermore, the use of 'traditional biomass' (e.g. firewood) cannot be assumed as sustainable energy use in many regions of the world because of its contribution to deforestation and desertification. The International Energy Agency (IEA 2004) estimates a share of about 10% of total primary energy demand which is currently covered by biomass in 2002. IEA (2004) assumes that about 70% of the global energy use of biomass is 'traditional biomass' which could cause serious sustainability problems. All in all the use of 'modern biomass' for sustainable energy production could be increased by factor six and more in terms of technological potentials which meet the requirements of sustainability (Rogner 2000, WGBU 2004).

Hydro power is the second source of renewable energy which represents a non-marginal share of global primary energy supply at the moment. Hydro power represents 16% of the current worldwide power production and about 6% of global primary energy supply. Although a significant technical potential exists for the extension of hydro power use Rogner (2000) indicates a technical potential which is factor five greater than the current use), it is the option among all renewable energies with the smallest potential for further increase.

In addition to these sources of renewable energy a few other sources can play an increasing role for the primary supply of the next decades.

First of all, power generation from wind showed significant growth rates duringrecent years. In the period from 1990 to 2002 power generation from wind increased with an average growth rate of about 30% annually in both the OECD and the non-OECD countries (Turkenburg 2000, IEA 2005). For the technological potential for the future use of wind energy, Rogner (2000) indicates 640 EJ which is about one hundred times more than the current levels.

Electricity generation from solar energy is still in a very early stage of development. Although the growth of power generation from photovoltaics grew by about 30% annually during recent years (Turkenburg 2000, IEA 2005) and solar thermal electricity production is assumed to show significant growth again in the next years, the contribution of solar energy to the global power production is still very small. However, the huge potential for power production from solar energy and the rapid technological development could lead to a significant share of solar energy in total primary energy supply within the next five decades (van der Zwaan/Rabl 2004).

The biggest technological potential among the renewable energies lies in geothermal energy which is already used for power production in several regions of the world. Rogner (2000) indicates a potential of 500 EJ which can be assumed to become economical within 10 to 20 years and a potential of 5,000 EJ which could become economical within 40 to 50 years.

Last but not least, ocean energy (tidal, wave, thermal, salt gradients) could deliver an enormous contribution to the global primary energy supply in the medium and long term. Rogner (2000) estimates a technical potential of 7,400 for the different options of ocean energy use.

Table 6 Actual and future costs of power production from renewable energy sources

	UNDP (2000)		ICCEPT (2002)		Enquete-Kommission (2002)			
	actual	future	actual	beyond 2020	actual	2010	2020	2050
	¢/kWh				ct/kWh			
Hydro	2…10	2…10	2...10	2...10	5.5...15	-	-	-
Wind power onshore	5…13	3…10	3...5	2...3	4.5...9	3...6	3...6	3...5
Wind power offshore			6...10	2...5	6.3...10	4...6	3...5.5	3...4.5
Photovoltaics	25…125	5…25	50...80[a] 30...50[b] 20...40[c]	~ 8[a] ~ 5[b] ~ 4[c]	50...100	29...58	12.5...25	9...18
Solar thermal power plants[d]	12…18	4…10	12...18	4...10	8...16		5...6	~ 4
Biomass	5…15	4…10	5...15	4...10	3.5...30	-	-	-
Geothermal	2…10	1…8	2...10	1...8	-	-	-	-
Marine	8…20	5…15						

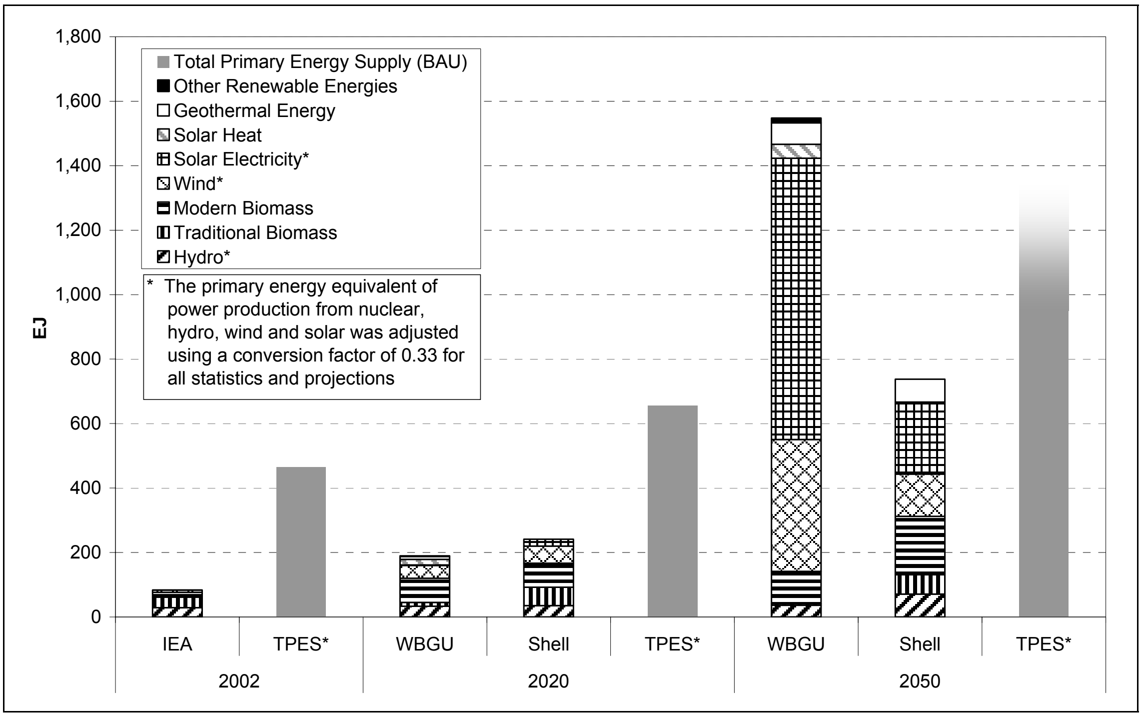
Notes: [a] at 1,000 kWh/m^2 (Central Europe). - [b] at 1,500 kWh/m^2 (Southern Europe). - [c] at 2,500 kWh/m^2 (Southern Regions). - [d] at locations with 2,500 kWh/m^2

Source: Turkenburg (2000), ICCEPT (2002), EK (2002).

However, although the technical potentials for the use of renewable energies for power production are enormous, the key barrier for a broader use of renewables is their economic competitiveness. Besides hydro power and some options of biomass use, most technologies for power generation from renewable energies are in an early stage of development. If research and development is intensified and early market introduction is continued, a significant cut in costs is assumed in many studies. Significant 'learning effects' from early and widespread market introduction were shown for many options of power production from renewable energies (IEA 2000).

Table 6 indicates different cost projections for key technologies for power production from renewable energies. This overview underlines that significant cost cuts can be assumed for the next two decades, especially for wind power, power production from biomass and geothermal energy. In the medium and long term (more than two decades) solar power and electricity generation from ocean energies could especially show significant cost reductions.

Figure 6 Projections for the contribution of renewable energies to total primary energy supply, 2002-2050



Source: WBGU (2004), Shell (2002), IEA (2004), own estimates and calculations.

Figure 6 gives an overview of two different projections for the future growth of renewable energies.[9] Both scenarios are intervention scenarios, they assume strong political interventions to achieve a sustainable energy system on a global scale. Depending on the assumption on the future total primary energy supply, between 50 and 100% of the total primary energy supply could be covered by renewable energies. However, the comparison also indicates the differing assessments of the future contribution of renewable energies. Whereas Shell (2002) sees a comparable growth for

[9] For the purpose of this paper the data from different sources were adjusted for a common methodology. The widely-used energy statistics of the IEA take into account the energy content of electricity (3.6 MJ/kWh) from hydro, wind and solar for the conversion into primary energy. For nuclear power production a conversion efficiency of 33% is assumed by the IEA. In contrast to this definition, the projections of IPCC (2000) do not use this conversion for nuclear energy. Instead they use the energy content of electricity. For the purpose of this paper electricity produced by nuclear, hydro, wind and solar energy was converted into primary energy with a conversion factor of 33% to enable an appropriate comparison for the contribution of fossil, nuclear and renewable power production to primary energy supply.

biomass, wind and solar energy in its ‘Spirit of the coming age’ scenario, the WBGU (2004) assumes a potential for a much more aggressive growth and technological breakthroughs for wind and solar energy and a much less significant increase in biomass use in the energy sector. In both projections geothermal energy will play a significant role.

In summary, renewable energies could fully, or to a large extent, cover the future primary energy demand from the technical point of view. However, some technologies for a broader use of renewable energies are in an early stage of development. ICCEPT (2002) indicates the following clusters of renewable energies for power generation:

- matured technologies: biomass (co-firing), large and small hydro-electricity, tidal barrages, off-grid photovoltaics;
- emerging technologies on the brink of becoming matured technologies: onshore wind power plants, photovoltaics for buildings, biomass (combustion);
- emerging technologies: offshore wind, biomass (gasification);
- conceptual technologies on the brink of becoming emerging technologies: advanced photovoltaics, wave and tidal stream, biomass (hydrolysis), geothermal (hot dry rock);
- conceptual technologies: photosynthetic hydrogen.

This long list of technology options offers sufficient flexibility for different scenarios of technological developments and progress in terms of cost reduction for power generation from renewable energies. The major contribution could come from biomass, wind and hydro power by 2020. For the time horizon beyond 2020 the key challenge will be how much power generation from solar technologies could be achieved and how far wind, geothermal and ocean power generation options could be deployed.

Nevertheless, major efforts will be necessary to improve the economics of different technologies, to achieve further technological breakthroughs and to build the necessary infrastructure. A key issue in terms of infrastructure is the intermittent generation from photovoltaic and wind power plants. An electricity supply system with high shares of intermittent power generation will create completely new requirements for grids and the flexibility of other power sources. The progress achieved in recent years (matured prognosis models, development of high efficient and flexible power generation technologies based on gas, etc.) underlines that the integration of intermitting power sources should be seen more as a challenge than as a barrier for the wide range deployment of renewable energies in the power sector. However, also for renewable energies other ecological or social constraints must be taken into account. In some regions of the world siting constraints exist for wind power generation and for some ocean technologies (tidal barrages) or hydro power options, negative local environmental and social impacts could arise.

Against this background, it should be highlighted that major improvements in terms of technology or economics of power generation from renewable energies will raise an enormous power generation potential in a comparatively short timescale. If major costs reductions for solar energy or even wind and biomass technologies will be achieved and the necessary infrastructure is available, this will change the energy system rapidly. In other words, the contribution of renewable energies to the global primary energy supply will either continue to remain at a comparatively low level in future or will very much dominate the primary energy structure beginning from the middle of this century. A ‘middle way’ for the contribution of renewable energies is difficult to imagine.

Carbon capture and storage

One of the emerging technologies to lower the release of greenhouse gas emissions into the atmosphere is the option of carbon capture and sequestration (CCS). CCS covers technologies to collect and concentrate CO_2 from different sources, transport it to suitable storage locations, and store for a long period of time. CSS could be applied for CO_2 from combustion of fossil fuels or from industrial processes on the one hand and for CO_2 emissions from carbon neutral biomass combustions on the other hand. The latter option would constitute a net sink for CO_2 emissions and should be considered as playing a role in long-term climate policy.

Although some technologies of the CSS chain already exist, are matured or economically feasible, further technologies must be developed or improved and major efforts will be needed to achieve an integrated system of CCS which is reliable in terms of technology, economics and public acceptance. Carbon capture and storage is subject to intensive research and development activities and is undergoing in-depth analysis and assessments (see IPCC 2005, IEA 2004b+2005b).

From the economic point of view, the capture of CO_2 is the key for the CCS option. The main challenge is that the capture of CO_2 requires a significant amount of energy which decreases the electric efficiency of power plants significantly. The capture of CO_2 emissions could lower the electric efficiency by about 10 percentage points and would compensate a lot of the technological progress which was achieved during the last two decades. In addition, the effective capture rates do not lead to an emission-free plant because the percentage of net CO_2 reduction ranges only between 80 and 90% for the preferred technologies (IPCC 2005). Carbon capture could be based on different technologies:

- post-combustion capture,
- pre-combustion capture,
- capture with oxyfuel technology (combustion with pure oxygen),
- capture from industrial processes (e.g. steel or ammonia production),
- post-combustion capture,
- pre-combustion capture,
- capture with oxyfuel technology (combustion with pure oxygen),
- capture from industrial processes (e.g. steel or ammonia production).

For the options of pre-combustion and oxyfuel capture the technology of power generation must undergo a fundamental transition. Although these technologies exist already as demonstration plants (IGCC – integrated gasification combined cycle) or as demonstration projects currently planned, there is not yet enough evidence that these technologies could prove sufficient for commercial operation. Especially the IGCC technology lost the competition with steam turbines with critical and supercritical parameters during the last two decades. Pulverized coal-fired power plants with conventional steam turbines proved to correlate much better with the requirements of day-to-day commercial operations than the more innovative and more efficient IGCC technology.

The transport of CO_2 could rely on existing technologies (pipelines, shipping) and will be less cost-intensive if the distances are in the range of 200 to 300 km. If much longer distances have to be bridged between the sources of CO_2 and the storage locations, the transport costs could also prove to be significant cost drivers.

For the storage of CO_2 three major options exist. The captured CO_2 could be injected into geological formations, or into the deep ocean (at depths greater than 1,000 m) or could be mineralized and the minerals could be stored in suitable sites. Among these three options only the storage in geological formations could be seen as acceptable in the light of current knowledge. Some evidence exists that the injection of significant amounts of CO_2 into the deep ocean could harm marine ecosystems. The effects of CO_2 injections for marine ecosystems over large ocean areas and long time scales are widely unknown. The mineral carbonation of CO_2 would induce huge material flows, the need for large-scale product disposal and other environmental problems. For example, the mineral carbonation process would require 1.6 to 3.7 tonnes of silicates per tonne of CO_2 stored and produce 2.6 to 4.7 tonnes of material for disposal. These material flows and the related processes (mining, crushing, milling, transport and disposal) would also create comparatively high costs.

As a result the storage in geological formations (exhausted oil and gas fields, unminable coal seams, deep saline formations) should be seen as the key option for CCS in the next decades. IPCC (2005) indicates a range of 200 to 2,000 billion tonnes of CO_2 for the economic potential for CCS over the next century. The lower bound is characterised by the IPCC as ‘virtually certain’ (probability of 99% or more), the higher figure is seen as ‘likely’ (probability of 66 to 90%). Against this background CCS could deliver a significant contribution to long-term emissions reductions. However, CCS will constitute a temporary mitigation option and storage capacities should be seen as a finite resource.

Table 7 indicates the cost ranges for the different components of a CCS system. For the case of storage in geological formations the capture of CO_2 will constitute the most significant part of costs. Long distances for CO_2 transport could increase the costs of a CCS system on the one hand. On the other hand the use of captured CO_2 for enhanced oil recovery (EOR) or enhanced coalbed methane recovery (ECBM) raise economic benefits which would lead to lower costs of the CCS system. However, the opportunities to raise such benefits would decrease significantly in the framework of very ambitious emission reduction targets. In total the abatement costs for CCS show with 15 to 90 \$/t CO_2 a range comparable to many renewable energy sources.

Table 7 Cost ranges for the components of a CCS system of large-scale, new installations

CCS system components		Cost range	Remarks
Capture	Capture from a coal- or gas-fired power plant	15...75 US$/t$CO_2$ net captured	Net costs of captured CO_2 compared to the same plant without capture.
	Capture from hydrogen and ammonia production or gas processing	5...55 US$/t$CO_2$ net captured	Applies to high-purity sources requiring simple drying and compression.
	Capture from other industrial sources	25...115 US$/t$CO_2$ net captured	Range reflects use of a number of different technologies and fuels.
Transport		1...8 US$/t$CO_2$ transported	Per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) Mt CO_2/yr.
Storage	Geological storage[a]	0.5...8 US$/t$CO_2$ net injected	Excluding potential revenues from EOR or ECBM.
	Geological storage: monitoring and verification	0.1...0.3 US$/t$CO_2$ injected	This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements
	Ocean storage	5...30 US$/t$CO_2$ net injected	Including offshore transportation of 100-500 km, excluding monitoring and verification
	Mineral carbonation	50...100 US$/t$CO_2$ net mineralized	Range for the best case studied. Includes additional energy use for carbonation

Note: [a] Over the long term, there may be additional costs for remediation and liabilities.

Source: IPCC (2005).

Some risks could arise from CCS systems especially regarding the storage of CO_2. Global risks result from a potential leakage of a fraction of the stored CO_2 to the atmosphere. Such leakage could contribute again to global warming. The selection of sites for CO_2 storage must reflect the necessity that the stored CO_2 should remain in the reservoirs for a time horizon of 100 to 1,000 years. With regard to local risks a sudden and rapid release of CO_2 (resulting from well failures, etc.) could endanger human life and health. Gradual and diffuse leakages could affect groundwater and ecosystems or cause acidification of soils. Many such risks could be reflected by appropriate selection and design of storage sites and comprehensive monitoring and remediation strategies. Although the risks mentioned above should not be underestimated, a few options for reducing the related hazards are at hand and should be implemented.

Nevertheless, a wide range of problems must be resolved in order to establish CCS as an effective option for ambitious emission reduction strategies. Besides technological, economic and safety problems, major problems on liabilities, ownership, the legal framework and also on monitoring and verification must be solved until CCS can be seen as an effective abatement option.

The assessments of the contribution of CCS to global emission reductions differ widely for the time horizon of the next five decades. IPPC (2005) points out that the majority of CCS deployment will occur in the second half of this century. In contrast, WBGU (2004) assumes a significant annual contribution of CCS to emission reductions (> 15 Gt CO_2) already in 2050. Pacala/Socolow (2004) assume an emission reduction of 3.7 Gt CO_2 from coal-fired baseload power plants with a capacity of 800 MW and natural gas-fired baseload power plants with a capacity of 1,600 MW equipped with CCS for the middle of this century.

If the technological development is driven massively forward and the outstanding problems (reliability of reservoirs, infrastructures, legal issues, etc.) can be solved and public acceptance for CCS could be established, CSS could contribute to emission reduction in 2050 with several billion tonnes of CO_2. In an early phase the deployment of CCS will take place in the industrialised countries; the worldwide spreading will depend on many factors (infrastructure, institutional capacities, etc.). However, it should be considered that CCS still belongs to the emerging emission reduction options, although it is based partly on matured components.

Preliminary conclusions

The perception that no single abatement option will be sufficient to achieve the necessary emission reduction to stabilize greenhouse gas concentrations in the atmosphere at levels which limit global warming to a tolerable dimension belongs to the common knowledge of the climate debate. The question of whether single abatement options can be eliminated from the portfolio of abatement measures is much more difficult and controversial.

If we assume a gap to be closed between the business as usual trend for CO_2 emissions and the necessary emission reduction (induced, for example, by the ‘2°C target’) is in the range of 25 to 40 Gt CO_2 in 2050, rough estimates on the different abatement options show the following results:

- about 5 Gt CO_2 from an expansion of nuclear power generation to the threefold of current capacities;
- about 4 Gt CO_2 from enhanced energy efficiency for buildings;
- about 5 Gt CO_2 from enhanced energy and material efficiency in industry sectors;
- about 7 Gt CO_2 from enhanced energy efficiency in the transport sector;
- about 2 Gt CO_2 from enhanced energy efficiency in the energy sector (apart from fuel switching);
- about 3.6 Gt CO_2 from fuel switch (coal to gas) in the electricity sector;
- about 15 Gt CO_2 (or more) from renewable energies (in both the electricity and the heat sector);
- between 4 and 10 Gt CO_2 from carbon capture and sequestration.

In total, emission abatement options between 45 and 55 Gt CO_2 (compared to business as usual) could be available in 2050. In this framework, the contribution of nuclear energy should not be seen as indispensable even for a very ambitious emission reduction pathway. However, uncertainties, risks and interactions exist in different dimensions for all options.

- Although global warming and nuclear power have risks with different patterns, the main tension exists between these two challenges. Although some risks for health and ecosystems must be stated for single options (from renewable energies to CCS), no other abatement option shows comparable dimensions of risks for health, ecosystems and social and economic systems as it must assumed for nuclear energy.

- In contrast to renewable energies and CCS, the nuclear option has strong ties to the electricity supply system as it is today for at least the near future. Renewable energies and CCS require a fundamental transition of the electricity system (new base technologies, significantly changed geographical structure, grid integration, etc.). However, if nuclear power should contribute significantly to emission reduction, significant changes in the technology chain (reprocessing, breeder technology) would be required after two or three decades. Many uncertainties still exist on whether this is feasible or not.
- The changes in the technological chain of nuclear power require long-lasting preparations (from mining to waste disposal) and many uncertainties must be stated if all parts of the chain are to be prepared in time.
- The requirements resulting from a significant share of renewable energies and CCS in power supply for the electricity system (increased flexibility, integration of decentralisation and centralisation, handling of intermitting power production, enhancement of infrastructure for electricity and CO_2) could come into conflict with the requirements from enhanced nuclear power (large units, centralised grid structures, low flexibility).
- The only abatement option which has similar ties to the existing electricity supply system is fuel switch and the enhanced efficiency in the power sector (including CHP). Although their contribution is limited over time, these two options could play a key role in the start of the transition of the electricity system.
- The most efficient abatement potentials from the economic point of view (various ways to enhance energy efficiency) require comprehensive political interventions because of the manifold obstacles for the implementation of energy efficiency measures. This is different for the short-term implementation of measures in the power sector. A sufficient level of CO_2 prices (and an appropriate design of the emissions trading scheme, etc.) could initiate the necessary measures.
- Key abatement options in the medium term (some renewable energies, CCS) are not competitive with nuclear power in the short term if the externalities of nuclear power are not reflected appropriately (liability and insurance, decommissioning funds, etc.) or other distortions exist (direct or indirect subsidies). If nuclear power should more than stagnate during the next decades (otherwise the contribution to emission reduction would be negligible), nuclear power will face significant economic challenges from the necessary changes in the technological chain. From this perspective the nuclear track could prove to be the wrong track.
- No other technology in the emission abatement portfolio shows a comparable mobilization potential. If one or more disastrous accidents in nuclear facilities (including enrichment, reprocessing and disposal facilities) were to occur, the acceptance for the nuclear track would be lost within a very short space of time. This could be disastrous for climate policy if it was intended that nuclear power deliver a significant contribution to emission reduction.

If these complex interactions are reflected, a careful design of strategies for the short, medium and long term is needed and is possible. If nuclear power is not considered as indispensable (as could be drawn from the analysis above) in the short term, fuel switch from coal to gas in the electricity sector should be focussed upon for the next two to three decades, combined with strong efforts to enhance energy efficiency in the power and the end-use sectors. This could be seen as a bridge to the time when learning effects for renewable energies have decreased their costs significantly on the one hand and R&D efforts related to CCS show results on the other hand.

6 Key strategies: a case study on Germany

In order to assess the variety of emission reduction options and strategies for a highly industrialised country, the Study Commission (Enquete-Kommission) on ‘Sustainable Energy in the framework of globalization and liberalization’ of the German Bundestag commissioned a modelling exercise to analyse different strategies to reach an 80% reduction of CO_2 emissions (compared to 1990 levels) by the year 2050 (EK 2002).

The main purpose of the modelling exercise was to identify the pattern of energy supply and their implications within an ambitious climate policy. In the analysis, four different scenarios were developed (which were also subject to a comprehensive sensitivity analysis):

- In a ‘Reference Scenario’ the existing policies and measures were extended and no ambitious climate policy was assumed for the time horizon beyond 2012.
- In a ‘Renewables and Efficiency’ scenario, the goal of an 80% CO_2 emission reduction should be met without relying on carbon capture and sequestration or nuclear energy (assuming the current phase-out strategy of Germany).
- In an ‘Energy Sector Focus’ scenario, the option of carbon capture and sequestration was additionally enabled.
- In a ‘Fossil-nuclear Energy Mix’ scenario, the nuclear option was enabled in addition to all other abatement options.

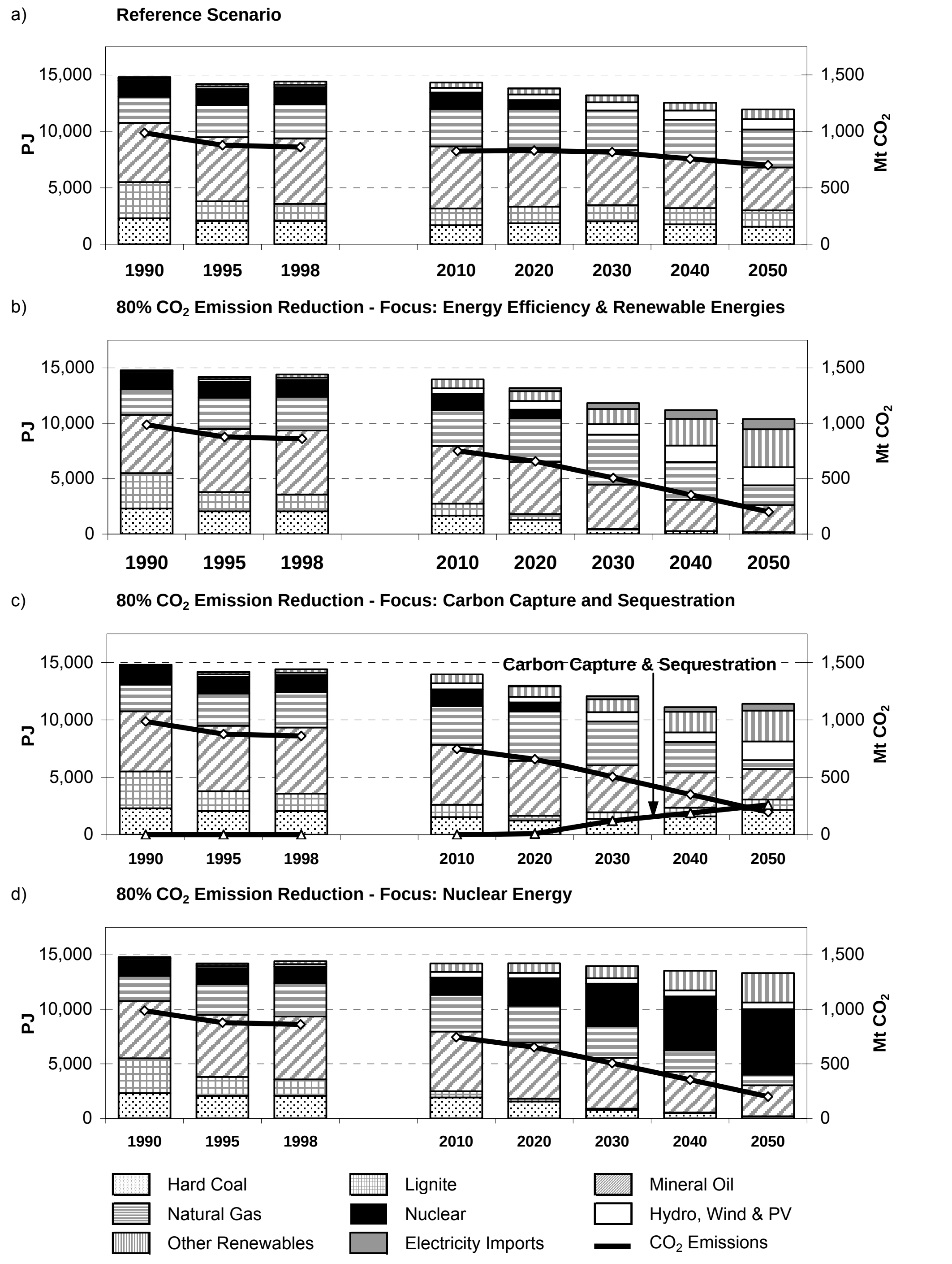
The modelling exercise was carried out with different simulation and optimization models to ensure robust results.

Figure 7 gives an overview of the modelling results.

In the business as usual case, a slight decrease of primary energy supply can be seen and the CO_2 emissions would decrease to a level 29% below the 1990 level, constituting an additional emission decrease of about 10 percentage points compared to the level achieved in 1998. The structure of primary energy is more or less maintained, with a decrease in mineral oil consumption and a slight increase in renewable energies. These development trends result from the demographic trends and the autonomous improvement of energy efficiency in the national economy.

If an emission reduction of 80% (compared to the 1990 level) should be achieved based on enhanced energy efficiency and an increase in the share of renewable energies, the primary energy supply would decrease significantly. Compared to the reference scenario, the gains from energy efficiency would amount to 13%. About 48% of the total primary energy supply would be covered by renewable energies. Especially biomass and wind energy would contribute significantly. The use of coal (hard coal and lignite) would be phased out by 2030, the use of natural gas and mineral oil would decrease significantly. However, natural gas and oil would still represent 40% of the total primary energy supply in 2050. It is worth mentioning that because of the geographical situation of Germany, electricity imports from regions with a more attractive potential for power generation from renewable energies would amount to 9% of the total primary energy supply.

Figure 7 Primary energy supply and carbon dioxide emission, scenarios from the case study on Germany



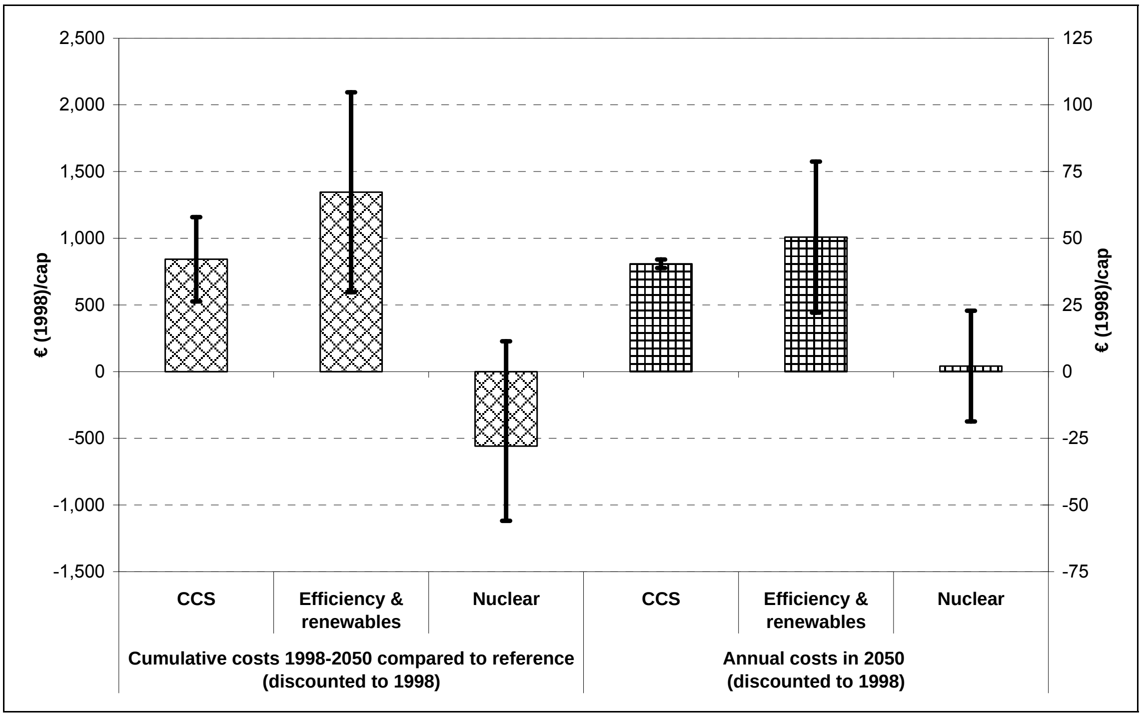
Source: EK (2002).

If the abatement option of CCS is taken into account, the structure of primary energy supply would be significantly different. Although strong efforts are assumed to enhance the energy efficiency in the end-use sectors, the level of total primary energy supply is only 4.5 below the level in the reference scenario. This is mainly due to the additional energy demand resulting from CCS which will start to be phased in in 2030 and could recover about 260 Mt CO_2 in 2050. However, the share of renewable energies will also grow significantly in this scenario and reach a share of 38% in 2050. The focus on CCS makes the use of coal for power generation attractive again after CCS becoming available. The share of natural gas in the total primary energy structure is to a large extent substituted by energy efficiency and renewable energy.

If the emission reduction strategy focuses mainly on nuclear power, this energy will dominate the primary energy structure in the year 2050. Nuclear power would fully substitute the use of coal and CCS would not compete with nuclear energy. In contrast to CCS, some renewable energies will be attractive (mainly biomass and some wind power) and cover a share of 23%. The level of primary energy supply is above the level from the reference scenario. This is mainly because of the conversion of electricity into primary energy with the low conversion factor of 33% (in other words, a statistical artefact) but also because no further (political) efforts for enhancement of energy efficiency in the energy and the end-use sectors were assumed. Mineral oil and natural gas play only a minor role in this scenario; the transportation sector was more or less completely shifted to hydrogen produced by nuclear power plants.

As was demonstrated by the scenario analysis, the strategy of emission reduction does not greatly depend on the potentials of the different clusters of abatement measures. Apart from the nuclear scenario (where serious questions could be raised regardless of whether such a development were seen as feasible or not) the variety of abatement options enables different strategies. In other words, the portfolio of emission abatement options covers more options than necessary for an 80% emission reduction by 2050.

Figure 8 Cumulative and annual costs per capita for the different scenarios



Source: EK (2002).

Regarding the costs related to the different scenarios (Figure 8), two main findings could be drawn. First, significant and different uncertainties exist for the scenarios.

Due to the variety of technologies used in the scenario focussed on energy efficiency and renewable energies, the range of costs is broader than for the scenarios in which single technologies play a more dominant role. Second, compared with the total system costs the abatement costs are not minor but are still at an acceptable level. Compared to the gross domestic product (GDP – in real terms), the abatement costs in 2050 reach a level of 2% at the maximum. The assessment of the nuclear scenario depends to a great extent on the assumptions on future costs of nuclear technologies. If the analysis is based on rather ‘optimistic’ assumptions, the use of nuclear is attractive. If more ‘pessimistic’ cost parameters are chosen, the costs could be comparable with the other scenarios. However, if in addition to the challenge of climate change, the external costs of nuclear energy are also considered (where a wide range of assumptions and no consensus exists) the cost differences between the nuclear and other scenarios greatly shrink or lead to cost advantages for the non-nuclear scenarios.

Although not all results from the modelling exercise on Germany can be extrapolated to other countries or regions and a lot of uncertainty and sensitivity exists for these kinds of long-term projections, some key lessons can be drawn:

- A multitude of abatement options exist to draft robust strategies for ambitious emission reduction pathways. Energy efficiency and renewable energies will play a role in every strategy but no reason can be found that makes options like nuclear energy indispensable.
- The abatement costs are not negligible for ambitious emission reduction targets but at less than 2% of GDP in 2050 are at a level which should be acceptable compared to the costs of global warming. The level of the emission reduction target will have a much more significant impact on the costs than the design of the abatement portfolio.
- Besides the risk of global warming and the costs of emission abatement, other risks must also be taken into account. There are enough degrees of freedom to implement an overall risk minimization strategy.

The ongoing debate on the magnitude of external costs of global warming as well as of nuclear energy indicates that the core of the problem is value decisions. This should not only apply to the challenge of global warming. A risk-minimizing strategy with ambitious emission reduction targets and the phase-out of nuclear power is feasible in terms of potentials and acceptable in terms of costs. The specific risk pattern of nuclear energy will make ambitious climate strategies much more vulnerable in terms of robustness and innovation if nuclear power shall contribute significantly to such strategy.

7 Conclusions

Global warming is probably one of the most significant challenges of the 21^{st} century. The magnitude of potential damages and the long time-scale of impacts and responses constitute a special pattern of (‘Cassandra’ type) risk. However, climate change is not the only major risk to health, ecosystems as well as social and economic structures. The potential consequences from nuclear power (disastrous accidents, waste disposal, proliferation, etc.) constitute a different (‘Damocles’ type) risk pattern but should also be considered seriously. The perception that no single abatement option will alone be sufficient to achieve the necessary emission reduction to stabilize greenhouse gas concentrations in the atmosphere at levels which limit global warming to a tolerable dimension belongs to the common knowledge of the climate debate. The question of whether single abatement options like nuclear power could or should be eliminated from the portfolio of abatement measures is much more difficult and controversial. An analysis of the interactions between the different abatement options shows that beside the fact the nuclear power is not indispensable for ambitious emission reduction strategies, the nuclear track could prove to be the wrong track and create an obstructive potential:

- Some requirements in terms of infrastructure and flexibility of the electricity system from renewable energies and CCS could come into conflict with the requirements of nuclear power generation which should be expanded significantly.
- Whereas learning effects and cost reductions can be assumed for renewable energies and CCS in the medium term, nuclear power will face additional cost burdens within this time-frame if the nuclear chain must undergo a fundamental adjustment because of resource availability and unsolved waste problems etc.
- The most important contributions to ambitious emission reductions from the cost-efficiency perspective will come from a strong enhancement of energy efficiency in both the energy sector and the end-use sectors. Due to manifold obstacles and barriers, long-term political efforts are needed to develop these potentials. The controversy on nuclear power often masks this necessity.

If these complex interactions are reflected, a careful design of strategies for the short, medium and long term is needed and is possible. If nuclear power is not considered to be indispensable in the short term, fuel switch from coal to gas in the electricity sector should be focussed on for the next two to three decades, combined with strong efforts to enhance energy efficiency in the power and the end-use sectors. This could be seen as a bridge to the time when learning effects for renewable energies have decreased their costs significantly on the one hand and R&D efforts related to CCS show results on the other hand. The analysis presented in this paper indicates that an overall risk minimization strategy could be designed and implemented. Ambitious emission reduction targets could be achieved with and without nuclear power for costs which do not exceed the capabilities of modern societies. In the framework of the necessary and fundamental transformation of the global energy system, a climate strategy without nuclear power makes for a probably more innovative and more robust strategy.

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Abbrevations

BAU	business as usual
cap	per capita
CCS	carbon capture and storage
CO_2	carbon dioxide
ECBM	enhanced coalbed methane recovery
EJ	exajoule
EOR	enhanced oil recovery
GDP	gross domestic product
Gt	gigatons (billion tons)
GWP	global warming potential
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
km	kilometer
m^2	square meter
Mt	megatons (million tons)
OECD	Organisation for Economic Co-operation and Development
ppm	parts per million
ppt	parts per trillion
R&D	research and development
SO_2	sulphur dioxide
t	metric tons
TWh	terawatthours (billion kilowatt-hours)
UNFCCC	United Nations Framework Convention on Climate Change
yr	year
W	watt

Heinrich Böll Foundation

The Heinrich Böll Foundation, affiliated with the Green Party and headquartered in the Hackesche Höfe in the heart of Berlin, is a legally independent political foundation working in the spirit of intellectual openness.

The Foundation's primary objective is to support political education both within Germany and abroad, thus promoting democratic involvement, sociopolitical activism, and crosscultural understanding.

The Foundation also provides support for art and culture, science and research, and developmental cooperation. Its activities are guided by the fundamental political values of ecology, democracy, solidarity, and non-violence.

By way of its international collaboration with a large number of project partners – currently numbering about 100 projects in almoust 60 countries – the Foundation aims to strengthen ecological and civil activism on a global level, to intensify the exchange of ideas and experiences, and to keep our sensibilities alert for change.

The Heinrich Böll Foundation's collaboration on sociopolitical education programs with its project partners abroad is on a long-term basis. Additional important instruments of international cooperation include visitor programs, which enhance the exchange of experiences and of political networking, as well as basic and advanced training programs for committed activists.

The Heinrich Böll Foundation has about 180 full-time employees as well as approximately 320 supporting members who provide both financial and non-material assistance.

Ralf Fücks and Barbara Unmüßig comprise the current Executive Board. Dr. Birgit Laubach is the CEO of the Foundation.

Two additional bodies of the Foundation's educational work are: the "Green Academy" and the "Feminist Institute".

The Foundation currently maintains foreign and project offices in the USA and the Arab Middle East, in Afghanistan, Bosnia-Herzegovina, Brazil, Cambodia, Croatia, the Czech Republic, El Salvador, Georgia, India, Israel, Kenya, Lebanon, Mexico, Nigeria, Pakistan, Poland, Russia, South Africa, Serbia, Thailand, Turkey, and an EU office in Brussels.

For 2005, the Foundation had almost 36 million € public funds at its disposal.

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