Nuclear Development
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Risks and Benefits of Nuclear Energy

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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full member. NEA membership today consists of 28 OECD member countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

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FOREWORD

This report has been prepared by the OECD Nuclear Energy Agency (NEA) Secretariat, with the assistance of a consultant and under the guidance of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC). It results from a comprehensive literature survey covering national and international studies on economic, environmental and social aspects of energy chains for generating electricity. The data presented have been selected on the basis of the robustness of the studies which produced them and on the scientific and technical qualifications of their authors. They are by no means exhaustive, but address a broad range of issues and illustrate the types of information available to policy makers.

Emphasis is placed in the report on methodological approaches and illustrative results, aiming at providing policy makers with information and tools that they could use in support of decision making. Recognising that decision making requires not only reliable data but also priority setting based on the specific goals of national policies, the report does not provide an assessment of alternative options but rather an overview of the background materials on which assessments could be based.

The report benefited from inputs, comments and overall review provided by NDC members. However, its content reflects the views of the Secretariat and not necessarily those of all member country governments or their representatives in the Committee.

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The driving factors for decision making have changed over the last decades, evolving from criteria dominated by economics to a set of indicators encompassing society and the environment together with economics in a broader sustainable development perspective. Consequently, a comprehensive analysis of benefits and detriments of alternative options should be a cornerstone of policy making. In the energy sector, this analysis should be based on a large number of factors covering economic, social and environmental aspects.

While the overall approach to comparative assessment is generic and may be applied to all projects and in all countries, national or corporate choices mostly depend on priorities of the policy makers in the framework of the local or regional socio-economic context. In practice, however, the implementation of decision-making processes based on multi-criteria analyses is not widely spread.

The study on risks and benefits of nuclear energy was carried out under the umbrella of the Committee for Technical and Economic Studies on Nuclear Energy and the Fuel Cycle (NDC). It was conducted by the Secretariat, assisted by a consultant,[1] based on a comprehensive review of published literature on the subject matter. The report benefited from the outcomes of a seminar held in June 2006, during which the draft document was presented by the consultant and discussed by members of the Committee.

The present report is not intended as an assessment of nuclear energy and alternative options but as a source of information in support to decision making. The main objective is to present a methodology and illustrate its application. The examples given, in particular in Chapter 4, provide robust facts and figures drawn from authoritative studies that may be used as a basis for policy making according to national goals and specific criteria.

The overall objective of the report is to provide policy makers with authoritative information on qualitative and quantitative aspects of risks and benefits of nuclear energy covering economic, social and environmental aspects. The scope of the study covers key aspects of nuclear energy systems and illustrative comparisons of nuclear and other options for electricity generation.

The results presented were selected in the light of the robustness of the analyses which led to them and because of their illustrative value as relevant examples. They are by no means exhaustive and are not intended to cover the whole range of outcomes from national and international studies on comparative assessments of alternative energy sources for electricity generation.

The report includes an overview on the role of nuclear energy in total primary energy supply, its past evolution and projected future developments according to various scenarios. A framework for comparative assessment of alternative options for electricity generation is described and relevant

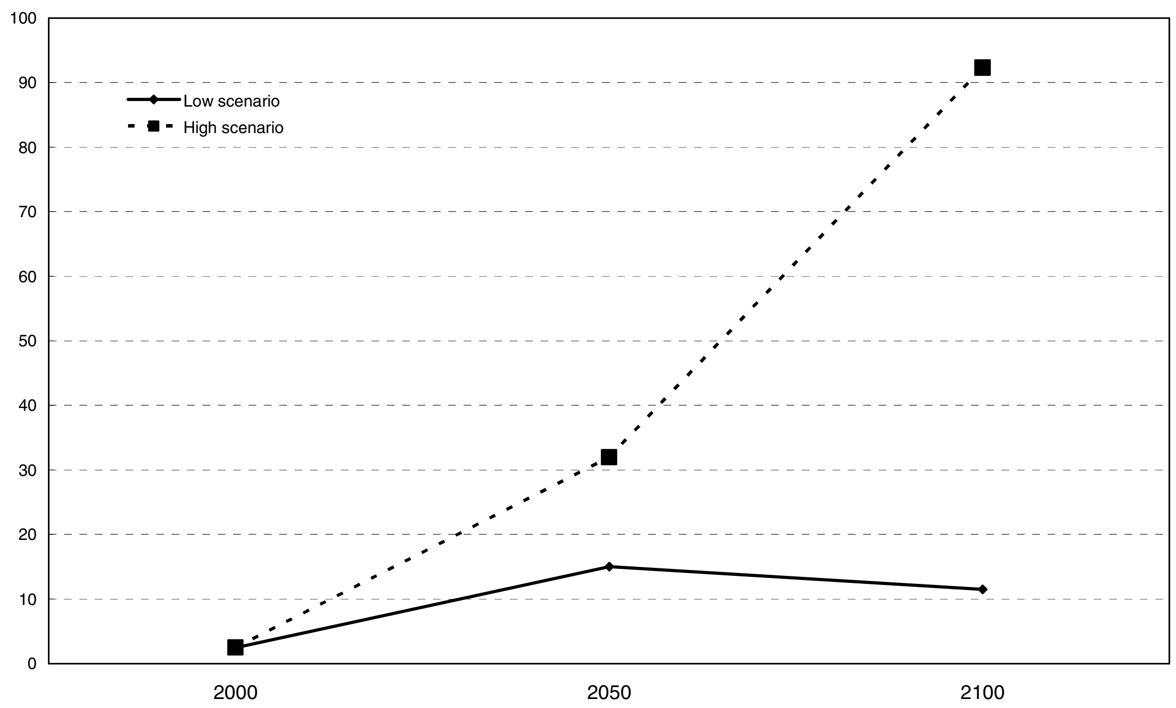
1. The background document which served as a basis for this report was prepared by Stephan Hirschberg from the Paul Scherrer Institute in Switzerland. The Secretariat wishes to acknowledge his essential contribution. All errors and omissions in the document remain the sole responsibility of the NEA Secretariat.

indicators are identified. Results from several studies on nuclear energy and other options are presented to illustrate the type of data available on selected indicators and criteria. Decision-aiding tools such as external cost evaluation and multi-criteria analysis are introduced. Nuclear energy systems of the next generation are described to highlight the expectations regarding technology progress.

Nuclear energy plays a significant role in total primary energy supply worldwide but its contribution is more important in industrialised countries of OECD and countries in transition than in developing countries. Nearly all scenarios for future energy demand and supply indicate a significant growth of nuclear electricity generation until the end of the century. Even in the low scenario shown in Figure ES.1 (IPCC, 2000), although nuclear electricity generation decreases after 2050 it remains higher in 2100 than it was in 2000.

However, in most scenarios, the share of nuclear energy in total supply will decrease during the 21st century to levels below 5%. The expected trends would limit drastically the role of nuclear energy in addressing concerns about security of energy supply and global climate change. Globally, with a contribution to total primary energy supply lower than 10%, nuclear energy would not make a significant difference in carbon dioxide emissions and would address security of supply only in some countries.

Figure ES.1 Projected evolutions of nuclear electricity generation (10^3 TWh/year)



The sustainable development concept with its three pillars – society, economy and the environment – provides a framework for assessing and comparing alternative options. In the energy and electricity sectors, scientists and analysts have established robust approaches, selected relevant sets of indicators (see Table ES.1 and Chapter 3 for details) and tested them on a large number of case studies. However, the methodologies developed, which require extensive data collection and analysis, have not been broadly used for policy making so far.

Table ES.1 Illustrative set of technology specific indicators (Hirschberg *et al.*, 2004)

Dimension	Impact area	Indicator	Unit
Economy	Financial requirements	Production cost	*c/kWh*
		Fuel price increase sensitivity	
	Resources	Availability (load factor)	%
		Geopolitical factors	*Relative scale*
		Long-term sustainability: Energetic resource lifetime	*Years*
		Long-term sustainability: Non-energetic resource consumption	*kg/GWh*
		Peak load response	*Relative scale*
Environment	Global warming	CO_2-equivalents	*tons/GWh*
	Regional environmental Impact	Change in unprotected ecosystem area	*km^2/GWh*
	Non pollutant effects	Land use	*m^2/GWh*
	Severe accidents	Fatalities	*Fatalities/GWh*
	Total waste	Weight	*tonnes/GWh*
Social	Employment	Technology-specific job opportunities	*Person-years/ GWh*
	Proliferation	Potential	*Relative scale*
	Human health impacts (normal operation)	Mortality (reduced life expectancy)	*Years of life lost/GWh*
	Local disturbance	Noise, visual amenity	*Relative scale*
	Critical waste confinement	"Necessary" confinement time	*Thousands of years*
	Risk aversion	Maximum credible number of fatalities per accident	*Max fatalities/ accident*

The literature on risks and benefits of nuclear energy is very large, including many national and international studies. It provides a comprehensive set of results on various relevant indicators covering most economic and environmental aspects. As for many other sectors of activity, the social aspects, which are more difficult to quantify, have been studied less thoroughly. Although additional research could strengthen the robustness of the outcomes, the existing published studies constitute a sound basis for evaluating the nuclear option.

Authoritative studies show that nuclear energy systems in operation today have excellent technical and economic performance and are environmentally sound. Like other advanced technologies, nuclear energy contributes to social and economic progress and in particular to increase in human capital assets. However, some aspects of its use, e.g., highly radioactive waste accumulation and risks of weapon proliferation, raise civil society concerns. As a consequence of these concerns, nuclear energy is diversely supported by policy makers and the public in different countries.

Results from scientific studies and analyses provide a wealth of data which could be used by policy makers. However, the outcomes from analytical studies on risks and benefits of alternative energy sources generally are complex to interpret and case specific. The ongoing development of user-friendly decision-aiding tools, which could assist in the implementation of a sustainable framework for comparative assessment within policy making, should promote a more holistic approach to energy mix choices in the future.

Technology progress is essential in the energy sector to address the challenges of the 21st century. In the nuclear energy field, ambitious RD&D programmes, building on industrial experience and scientific knowledge, aim at the design of advanced systems responding better to sustainable development goals. The evolution from the current generation of reactors to generation III+ systems and eventually to Generation IV systems is expected to strengthen the potential contribution of nuclear energy to sustainable supply in the medium- and long-term.

The main findings from the study, summarised in the concluding chapter, cover many aspects of nuclear energy assessment, including its role in total energy supply and illustrative indicator evaluations. Those findings provide insights on the efforts required to enhance the recognition of all indicators of sustainable development in policy making.

While decisions may, in each case, continue to be based upon the specific objectives and priorities of policy makers, a better knowledge of new methodologies and approaches to comparative assessment of alternative options could improve the robustness of decisions and lead to better choices from a global viewpoint.

References

Hirschberg, S., R. Dones, T. Heck, P. Burgherr, W. Schenler and C. Bauer (2004), *Sustainability of Electricity Supply Technologies under German Conditions: A Comparative Evaluation*, PSI report No. 04-15. Paul Scherrer Institut, Villigen, Switzerland.

IPCC (2000), *Special Report on Emissions Scenarios*, A special report of Working Group III of the IPCC, Cambridge University Press, Cambridge, United Kingdom.

Chapter 1

INTRODUCTION

1.1 Preamble

The socio-economic landscape of decision making has evolved over the last decades from an economic-growth-driven context to a broader drive towards sustainable development goals. In this context, policy makers in the energy and electricity sectors need to rely on a comprehensive assessment of alternative options covering their risks and benefits from economic, environmental and social viewpoints.

The role of the analyst in this regard is to provide robust information and data – covering, in so far as feasible, all dimensions and aspects for each option considered – intended to serve as a background for decision making. Methods and decision-aiding tools, such as multi-criteria techniques, may be offered also by analysts to decision makers in order to assist them in comparative assessment of alternative options.

The bottom line, however, is that decision makers will take decisions based on trade-offs reflecting their preferences and the relative importance of various indicators from their specific viewpoint. In this connection, it is important to stress that the present report is not aiming at assessing alternatives but rather at providing facts and figures together with insights on methodological approaches that policy makers may use in carrying out comparative assessments.

This report is based on a broad but not exhaustive review of published literature. A large number of studies have been carried out by international organisations and national institutes on the economic, environmental and social aspects of energy systems. Published studies include extensive investigations of external costs of a wide spectrum of energy supply options as well as detailed analyses of specific features of energy systems such as accident risks or broad economic impacts. At the national level, the Environmental Impact Assessments of nuclear and other energy projects provide a relevant framework and interesting country specific results.

The lessons learnt from past studies are multiple, but a few key findings are especially relevant as an introduction to the present report:

- Analyses covering the entire energy chains from resource extraction to delivery of final services: require extensive research; are data intensive; need thorough data-consistency checking; and their findings and conclusions are fully valid only in the specific context considered.
- There are generic methodologies and approaches which can be adopted to analyse different energy chains and they provide a robust framework for comparative assessment.
- However, although approaches may be generic, results are case specific. Indicators in the field of environmental and social impacts in particular are very sensitive to local conditions, and drawing generic conclusions from results related to a specific case would be misleading.

1.2 Overall objective

The overall objective of the project is to provide policy makers with authoritative information on qualitative and, whenever feasible, quantitative aspects of risks and benefits of nuclear energy covering economic, environmental and social aspects. The term "risk" is used here in a broad sense and refers not only to potential accidents but also to burdens and impacts from normal operation.

The specific goal of the study is to provide an inventory and a description of the risks and benefits of nuclear energy, including:

- Economic risks (e.g., financial) and benefits (e.g., cost stability).
- Environmental risks (e.g., severe accident) and benefits (e.g., nearly carbon-free electricity generation).
- Social risks (e.g., long-term liabilities) and benefits (e.g., broad access to reasonably low cost electricity).

1.3 Basic approach and scope

The risks and benefits of nuclear energy can be comprehended and judged in a balanced manner only in a comparative perspective that addresses nuclear energy along with other major technological options for generating electricity. Detailed, systematic and structured approaches to such comparisons have been developed and implemented in the last decade.

Published studies and results from work on risks and benefits of alternative energy sources and other industrial activities are integrated in the present survey as a mean to put nuclear energy in a broad perspective. The literature on which the report is based was selected according to criteria related to consistency of the results and prioritising the most recent studies. The intention was not to be exhaustive, to assure completeness or to reflect all sources of information on the risks and benefits of nuclear energy and alternatives.

The scope of the study covers key aspects of nuclear energy, related to economic, environmental and social dimensions of sustainability, that are considered relevant for policy making. The study focuses on qualitative and quantitative information available from publications that emerged from past and ongoing research work on nuclear and non-nuclear electricity generation, primarily in OECD countries. Emphasis is placed on experience-based data with results from modelling exercises.

1.4 Structure and content of the report

Chapter 2 sets the scene for the detailed evaluation of the risks and benefits of nuclear energy. It describes the current role of nuclear energy on the basis of available statistics and illustrates various trends by some national programmes. Scenarios on future nuclear energy development elaborated and published by different international and national organisations are presented to provide a range of possible developments and highlight the large uncertainties on energy mixes in the long term.

Chapter 3 describes the methodology and assessment frameworks that apply to comparative assessment of nuclear energy and other electricity supply options. It offers a set of indicators proposed in previous studies for the energy sector. The chapter is completed by an extended but not exhaustive list of references providing the reader with a wealth of information on previous work in the field.

Chapter 4 provides illustrative results of the studies reviewed, including values of many indicators related to the economic, environmental and social dimensions of sustainable development for different energy chains. The sources of the data presented are given in the list of references at the end of the chapter.

Chapter 5 introduces decision-aiding tools such as external cost valuation and multi-criteria decision analysis (MCDA) and provides illustrative results of those methodologies.

Chapter 6 provides an overview on advanced nuclear systems under development, highlighting the goals pursued by designers and ongoing RD&D programmes that should lead to the deployment of those systems by mid-century or earlier.

Chapter 7 summarises the main findings from the study in each area considered and provides some insights on the way forward.

Chapter 2

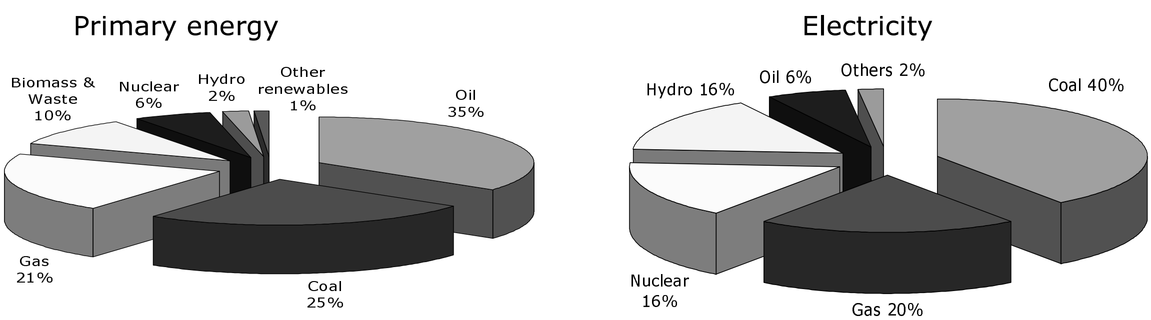
NUCLEAR ENERGY OUTLOOK

2.1 Status and trends

At the beginning of 2007, 435 nuclear power plants with a total installed capacity of nearly 370 GWe were in operation in some 30 countries and 30 nuclear units were under construction in 13 countries, representing a capacity of around 24 GWe. During 2006, two new units with a total capacity of 1.5 GWe were connected to the grid, one in India and one in China, and the construction of seven new units was initiated in China, the Republic of Korea and Russia. During the same year, eight units were shutdown definitively, two in Bulgaria, one in Slovakia, one in Spain and four in the United Kingdom, reducing by 2.25 GWe the capacity in service. The outcome was a decrease by some 0.75 GWe of the nuclear capacity in operation in the world.

Nuclear energy produces close to a quarter of the electricity consumed in OECD countries and its share in the world electricity supply is about 16%. The contributions of nuclear and other energy sources to the world primary energy and electricity supply in 2004 are provided in Figure 2.1, drawn from the International Energy Agency statistical data (IEA, 2006).

Figure 2.1 World primary energy and electricity supply in 2004 (IEA, 2006)



Nuclear power is a mature technology which provides a significant contribution to electricity generation worldwide. Its development, however, has been more important in industrialised countries of OECD and in countries in transition than in developing countries. The total operating experience of nuclear power plants worldwide exceeds 12 000 reactor-years, almost 90% of which is in OECD countries. One indicator of the technology maturity is the availability of nuclear power plants, which has been monitored by several international organisations over decades. The average worldwide unit capability factor[1] for all operational reactors has been very near to or above 80% over the last decade, reaching 84% in 2004 and 2005 (IAEA, 2007).

1. **Unit capability factor** is defined as the ratio of the actual electricity generation over a given time period to the electricity that would have been generated if the unit had operated at 100% of its design capacity over the same time period, expressed as a percentage. These energy generation terms are in both cases determined relative to reference ambient conditions.

From a global viewpoint, the history of commercial nuclear energy includes two contrasted periods: two decades of rapid development with an exponential increase of installed nuclear capacity; and subsequently one and a half decade of slow growth with a decreasing number of new plants starting construction yearly and some definitive shut downs leading to a stagnation of the total number of units in operation.

Figure 2.2 Net nuclear capacity (GWe) in operation in the world (IAEA, 2007)

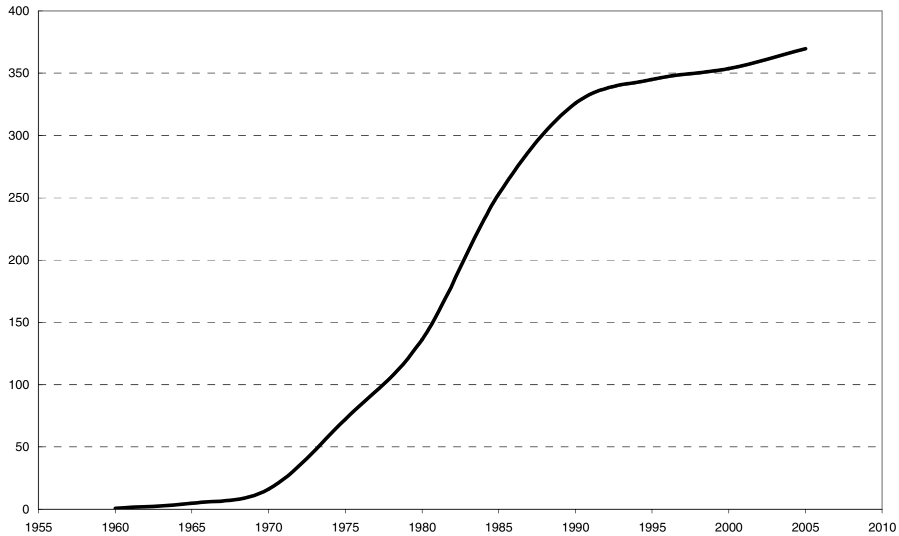


Figure 2.3 Number of operating reactors according to their age (IAEA, 2007)

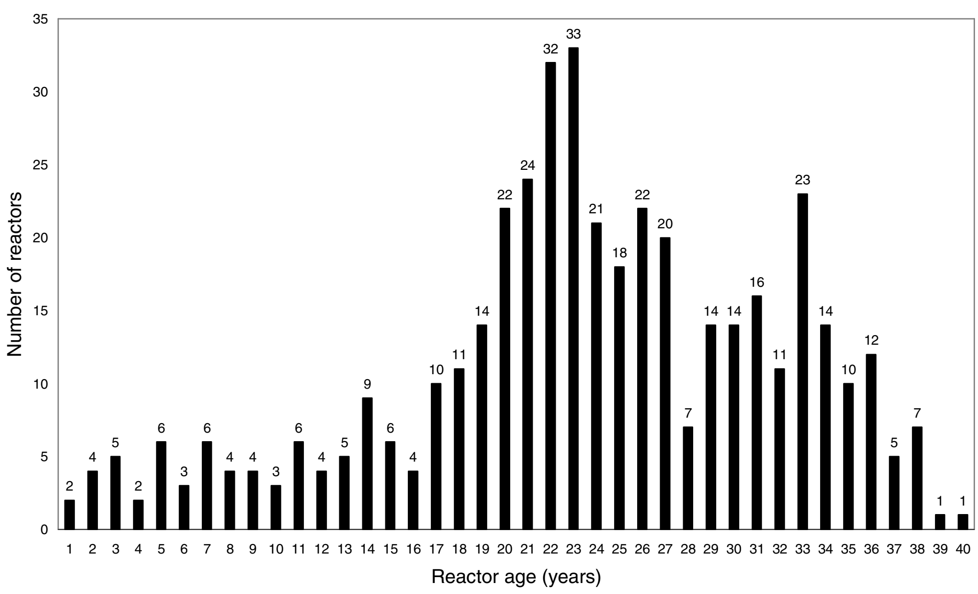


Figure 2.2, which provides the evolution of nuclear capacity in service worldwide indicates clearly this trend. Figure 2.3 shows how this development pattern is reflected in the age of the current fleet of reactors in operation.

Although nuclear capacity became significant only in the 70s, the period of exponential growth in installed nuclear capacity started in the early 1960s with the grid connection of the first commercial reactors and ended in the early 90s. The year 1985 was a turning point with the highest number (33) of grid connections and after 1990 the yearly number of grid connections remained lower than 10. Nuclear power programmes slowed down owing to various factors. The Three Mile Island accident in 1979 and the Chernobyl accident in 1986 had a strongly negative influence on the penetration of nuclear energy, although the latter concerned a reactor type in operation only in the former Soviet Union. Other drivers for the reduced interest in the nuclear energy option include low fossil fuel prices and relative security of supply when the fears raised by the first oil crisis did not materialise. As a result, the average annual increase of installed nuclear capacity in the world, during the last decade was some 2.5 GWe, i.e., around 3 new reactors per year.

The recent renewed interest in the nuclear energy option is driven by several factors including the excellent performance of nuclear units in operation, the competitiveness of existing nuclear power plants, including in deregulated markets, and the policy maker and civil society concerns regarding security of energy supply and global climate change. However, while there is a growing realisation that nuclear energy offers opportunities to respond to a rapidly growing electricity demand, to contribute to security of supply and to reduce the risk of global climate change, the views on the benefits and drawbacks of the nuclear option continue to vary widely. Therefore, nuclear energy policies differ in various OECD and non member countries.

In the OECD Pacific region, Japan and the Republic of Korea continue a steady expansion of their nuclear programmes. Australia, after a long period of opposition to nuclear energy, is re-considering this option (Commonwealth of Australia, 2006). Several non-OECD countries of the region have high interest in nuclear energy, notably China which, in order to satisfy its electricity hunger driven by rapid economic growth, has plans to build more than 30 reactors in the next 15 years.

In North America, the interest for nuclear energy remains high in Canada and the change of governmental attitude in the United States is of major importance. For the latter, the first important step was the major modification of the licensing process, aiming at removing the obstacles and creating a level playing field for nuclear energy. The new Energy Bill approved in summer of 2005 confirms the support by the Government and Congress for nuclear energy. It extends the coverage of the Price-Anderson Act, which limits the liability for current nuclear-power-plant accidents to $9 billion each, to new plants. Its “standby support insurance” will ensure that the first six new plants to go through federal and state licensing processes can recover up to $500 million for delays caused by regulatory logjams or lengthy legal challenges during construction. It also provides production tax credits for the first six plants, giving them the same incentives as power produced by wind turbines, and it provides $1.2 billion in tax write-offs to help offset the costs of funds needed to ensure that the plants can be safely decommissioned.

Although public acceptance remains an issue for nuclear power, in parallel with demonstrated good technical, safety and economic performance of the existing plants, there are indications of public opinion in the United States becoming more favourable towards this technology. Based on an opinion poll conducted in August 2005 (Bisconti Research Inc., 2005), 83% of Americans living in close proximity to nuclear power plants favour nuclear energy; 76% are willing to see a new reactor built near them; 89% consider nuclear to be important for covering the electricity demand in the USA. The survey demonstrates that “NIMBY” – or “Not In My Back Yard” – does not apply at most existing nuclear power plant sites in the United States.

In Europe, the picture is mixed. The European Union (EU) countries are divided on the nuclear issue. Five out of 13 EU-members having nuclear power plants, including Belgium, Germany and

Sweden with large nuclear contributions to the national electricity generation, have decided a progressive phase-out of the nuclear option while other countries continue their efforts towards further development of nuclear energy. In some countries having an official policy aiming at nuclear phase-out, such as Spain, life extension of the existing plants is actively pursued. In Switzerland, a moratorium on construction of new nuclear plants expired and the public rejected with large majority the proposal to phase out the operating plants.

The recent orders of two new reactors, one in Finland and one in France, shows some concrete renewed interest for the nuclear option in the European region. In Finland, the project proposed by the industry and approved by the Government and the Parliament to build a new reactor resulted from a thorough participatory process in consultation with civil society. Simultaneously, progress regarding the construction and entry into service of a high level waste repository constitutes a major step in the expansion process of the nuclear programme with support from local community. Finland and France have opted for an evolutionary advanced technology, the European Pressurised Reactor (EPR) which is an evolutionary system based on thoroughly tested French and German designs.

Regarding public opinion in Europe, the results of a poll carried out through interviews of some 25 000 citizens of the 25 EU countries provide a snapshot of the present situation (EC, 2007). The opinions of interviewed citizens on the use of nuclear energy in their respective countries vary widely from 6% in favour in Austria to 41% in favour in Sweden, in spite of the moratorium. Germany, where a nuclear phase-out has been legally adopted, and France, where the present government supports nuclear energy, have similar proportions – 20 and 21% respectively – of citizens in favour of using this energy source. In general, the opinion is more favourable to nuclear energy use in countries where nuclear power plants are in operation than in countries where there is no nuclear power programme in place. On average, for the entire EU-25, the proportion of citizens favouring the use of nuclear energy is 20% and the proportion opposed is 37% while 36% have “balanced views” and 6% no view at all.

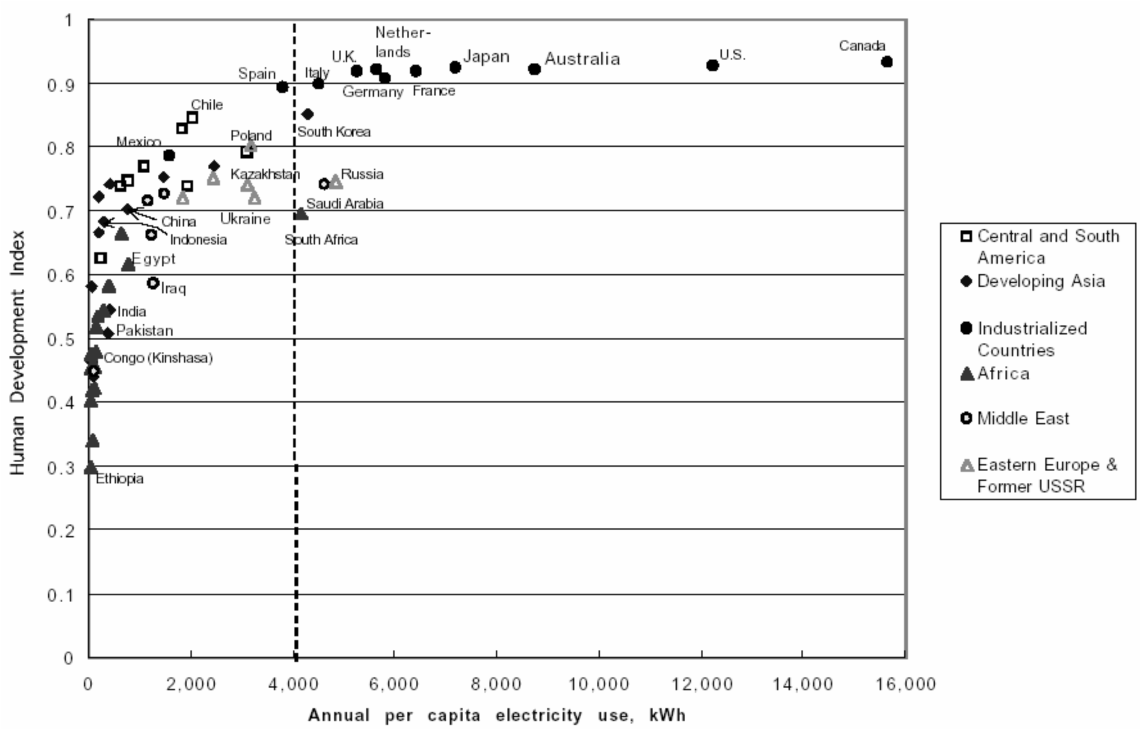
2.2 Nuclear development scenarios

Nuclear energy is one component of global energy and electricity supply and its future development can be investigated only in the framework of global energy demand and supply analyses. In this context, the main drivers for nuclear energy development are the need for energy and electricity and the relative advantages of the nuclear option versus alternatives.

Most energy analysts consider primary energy demand growth as inevitable owing to expected increasing population and economic development. In spite of the drastic energy efficiency improvements foreseen by analysts, economic and social drivers likely will lead to dramatic energy consumption growth rates. The Intergovernmental Panel on Climate Change (IPCC) scenarios (IPCC, 2000) which cover a wide range of possible futures project at least a doubling of world primary energy consumption by 2100 and increases up to a factor of 6 or more, in the absence of policy measures aiming at reducing consumption.

The correlation between energy or electricity consumption and well being has been demonstrated in many studies. Figure 2.4, extracted from a report on energy future and human development (Pasternak, 2000), illustrates this point, showing the strong correlation between the annual per capita electricity use and Human Development Index (HDI),[2] defined and monitored by the United Nations, for a large number of countries from different geopolitical areas.

Figure 2.4 Correlation between electricity use and HDI (Pasternak, 2000)



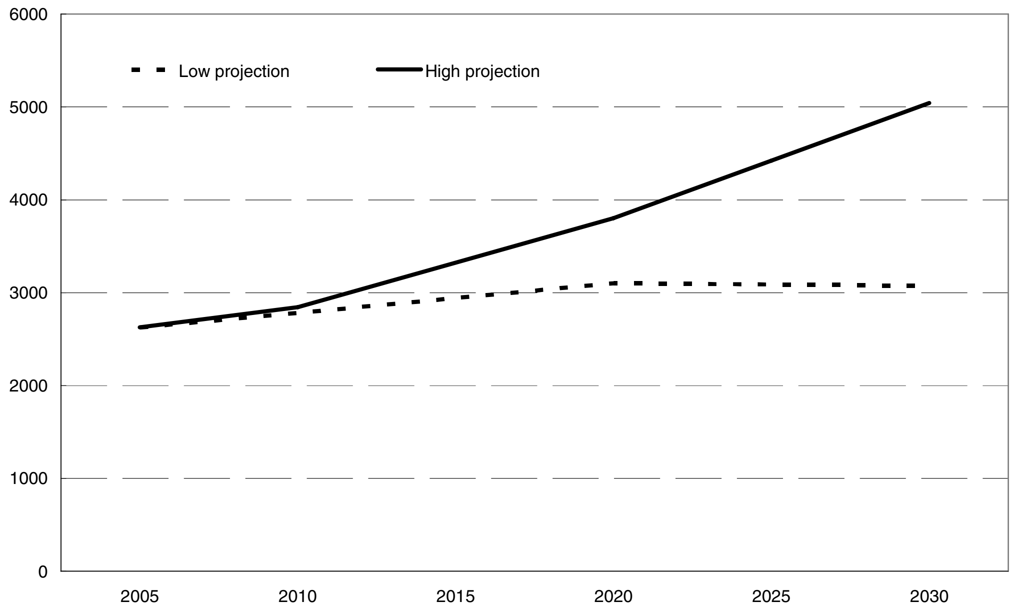
Scenarios on the development of nuclear energy in the 21st century, which have been published by many institutes and organisations over time, demonstrate the large uncertainties on future energy demand and the role that nuclear energy may play in global supply. While short- and medium-term projections of nuclear installed capacity and/or nuclear electricity generation are based mainly on extrapolation of current trends, long-term scenarios generally result from economic modelling. Three sets of nuclear development scenarios are presented below to illustrate possible futures. They are not intended to include all possibilities, although the set of scenarios developed and analysed in the framework of the IPCC is fairly comprehensive.

2.2.1 IAEA projections

The IAEA publishes yearly a booklet providing projections of nuclear electricity generation in the world, by region, based on nuclear power programmes of its Member States and expert judgment. The low and high projections considered by the IAEA correspond respectively to extrapolation of recent trends and moderate revival owing to increasing electricity demand, concerns on security of supply and greenhouse gas emissions. The latest edition (IAEA, 2006) gives projections up to 2030 (see Figure 2.5); it indicates a very small progression of nuclear electricity generation between 2005 and 2030 in the low projection while in the high projection the nuclear electricity generation would double in 25 years.

2. The UN Human Development Index (UNDP, 2000) combines measures of infant mortality, life expectancy, food supply, literacy rate, educational opportunities and political freedom.

Figure 2.5 IAEA projections of nuclear electricity generation up to 2030 in the world (TWh/year)



It should be noted that in both projections, the share of nuclear energy in total electricity supply would decrease by 2030 to 12% of a total consumption reaching 25 10^3 TWh in the low projection, and to 13% of a total of some 38 10^3 TWh in the high projection.

2.2.2 IEA scenarios

In the *World Energy Outlook 2006* (IEA, 2006), two scenarios of energy and electricity demand and supply by 2030 are considered. The reference scenario is based on present government policies and provides a business-as-usual case and the alternative scenario assumes that governments would implement the policies currently under consideration to address security of supply threat and global climate change risks.

In both scenarios population growth – 1% per year on average from 2004 to 2030 – and economic development – 3.4% per year GDP growth for the world – are driving energy and electricity demands. In the reference scenario, energy demand increases by more than 50% and electricity generation nearly doubles between 2004 and 2030. The total primary energy supply and electricity generation by source in 2030 for the two scenarios are summarised in Table 2.1.

Although the policy measures assumed to be implemented in the alternative scenario would reduce total energy demand by nearly 10% in 2030 as compared to the reference scenario, it would not succeed in stabilising fossil fuel consumption and, therefore, would not be sufficient to reduce greenhouse gas emissions from energy consumption.

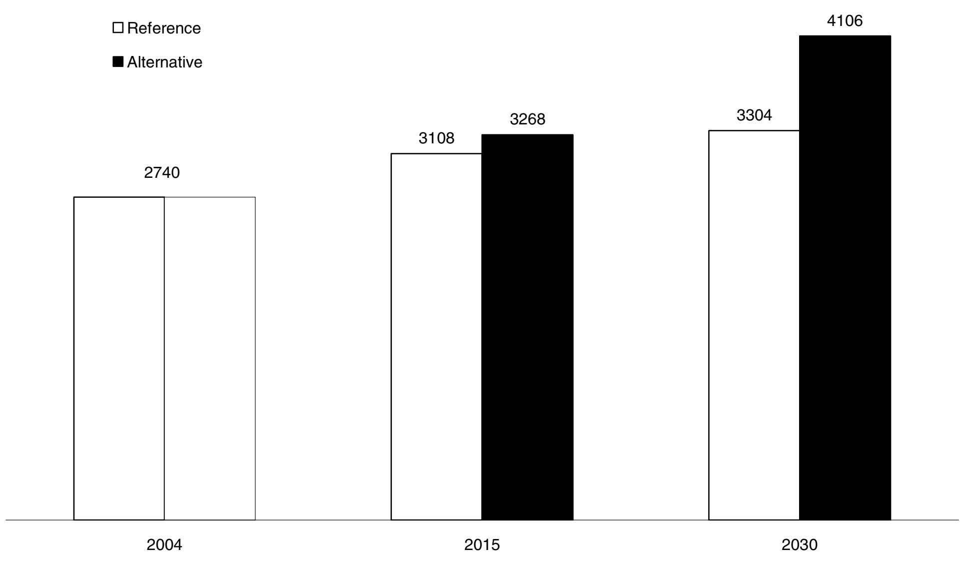
The dependence of the world on hydrocarbons, according to the IEA scenarios, would not change significantly by 2030 and would remain higher than 50% while renewable energy sources and nuclear energy together would contribute some 20% to total primary energy supply in the world. Consequently, the carbon dioxide emissions from energy production and consumption would double in 2030 as compared to the 1990 level in the reference scenario and would increase by more than 65% in the alternative scenario.

Table 2.1 Energy supply and electricity generation in 2030 in the world (IEA, 2006)

	Reference scenario				Alternative scenario			
	Energy		Electricity		Energy		Electricity	
	Mtoe	%	TWh	%	Mtoe	%	TWh	%
Coal	4 441	26	14 703	44	3 512	23	10 914	37
Oil	5 575	33	940	3	4 955	32	869	3
Gas	3 869	23	7 790	23	3 370	22	6 170	21
Nuclear	861	5	3 304	10	1 070	7	4 106	14
Hydro	408	2	4 749	14	422	3	4 903	16
Biomass & waste	1 645	10	805	2	1 703	11	983	3
Others renew.	296	2	1 459	4	373	2	1 890	6
Total	17 095	100	33 750	100	15 405	100	29 682	100

The evolution of nuclear electricity generation in the two scenarios is shown in Figure 2.6. According to the IEA, in the reference scenario the installed nuclear capacity in the world would increase by less than 15% between 2004 and 2030 and in the alternative scenario it would progress more significantly but only by some 43%. The share of nuclear in total electricity generation would decrease from around 16% at present to 10% and 13% respectively in the reference and alternative scenarios by 2030. It means that the contribution of nuclear energy to addressing either security of supply or global climate change concerns would remain modest even in the alternative scenario.

Figure 2.6 IEA scenarios of nuclear electricity generation in the world (TWh/year)



2.2.3 IPCC scenarios

The IPCC carried out a very comprehensive assessment of state-of-the-art energy and greenhouse gas emission scenarios up to 2100 (IPCC, 2000). The objective of the endeavour was to provide alternative images of future evolutions and to analyse the relative influence of various driving forces on energy demand and greenhouse gas emissions. It is stressed in the report that reality is very unlikely to match any single scenario included in the assessment.

The three scenarios presented below were selected to illustrate contrasted futures. They do not provide the extremes of the range included in the IPCC assessment in terms of energy demand but cover the whole range of greenhouse gas emissions corresponding to all scenarios.

The scenarios A1G and A1T are characterised by rapid economic growth with substantial reduction of regional differences in per capita income, with global population peaking in mid-century but declining thereafter, and by rapid introduction of new and more efficient technologies. The main difference between the two A scenarios is the reliance on fossil fuels, with A1T characterised by the assumption that policies aiming at implementing sustainable/non-fossil energy mixes are adopted broadly while A1G assumes that voluntary policies are not implemented or are not effective and that hydrocarbons, oil and gas, remain dominant in the supply mix.

The B1 scenario is characterised by significantly lower economic growth than in the A scenarios but practically the same population pattern, rapid changes in economic structures towards a service and information economy with reductions in material intensity, and by forceful introduction of clean and resource-efficient technologies.

Figure 2.7 illustrates the evolution of total primary energy demand and supply mixes in the world for the three selected scenarios. Besides a high degree of uncertainty, the wide range of total demand by 2100 indicates the drastic influence of economic growth, industrial structure evolution, policy measures and technology progress on energy consumption patterns.

The differences in primary energy demand result in even larger differences in CO_2 emissions in the light of the shift to low-carbon sources in scenarios A1T and B1. Among all IPCC scenarios, A1G has the highest cumulative CO_2 emissions in the period 1990-2100 (2 169 GtC), while B1 has the lowest (837 GtC), closely followed by A1T (1 063 GtC). It needs to be emphasized that even the fossil-intensive scenario A1G by no means represents a worst case, since substantial credit is taken for expansion of clean and efficient fossil technologies.

With regard to the role of nuclear energy, the selected IPCC scenarios give rather contrasted pictures in 2050 and 2100, as illustrated in Figure 2.8. However, in all scenarios the contribution of nuclear energy to total supply increases between 2010 and 2100. In absolute value, taking into account the total demand growth, B1 corresponds to multiplying by 4 the production of nuclear energy between 2010 and 2100 while it would be multiplied by 10 in scenario A1T and by 30 in scenario A1G.

Figure 2.7 Primary energy supply by source (EJ) for selected IPCC scenarios

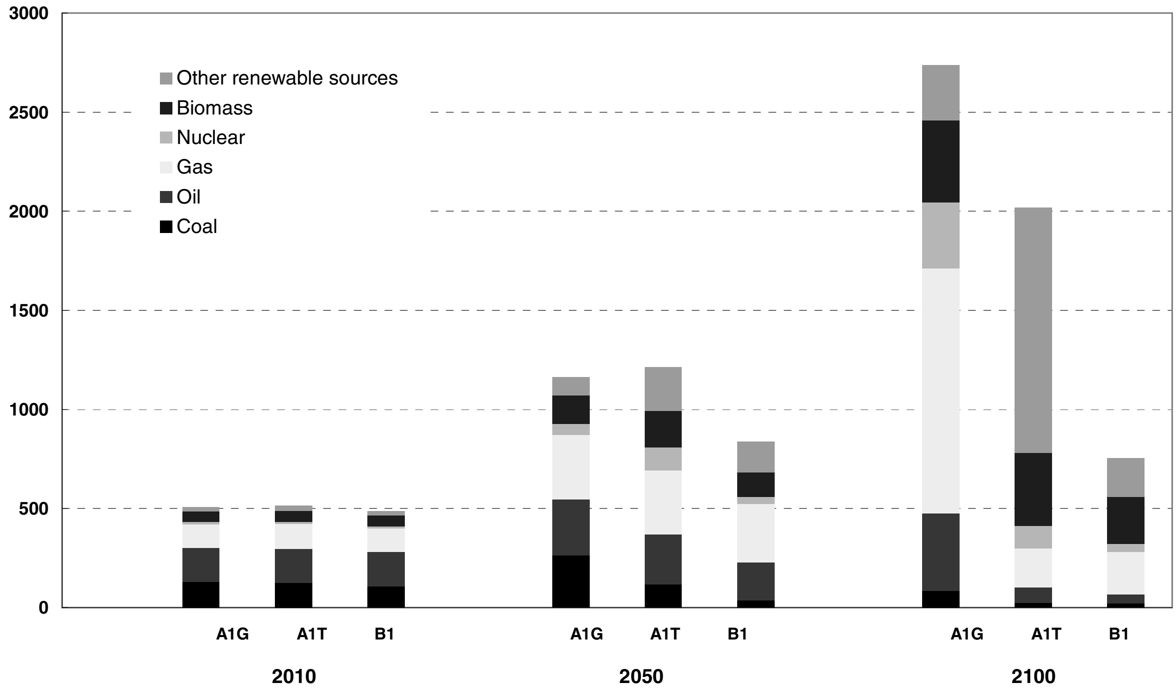


Figure 2.8 Share of primary sources in total supply in IPCC scenarios

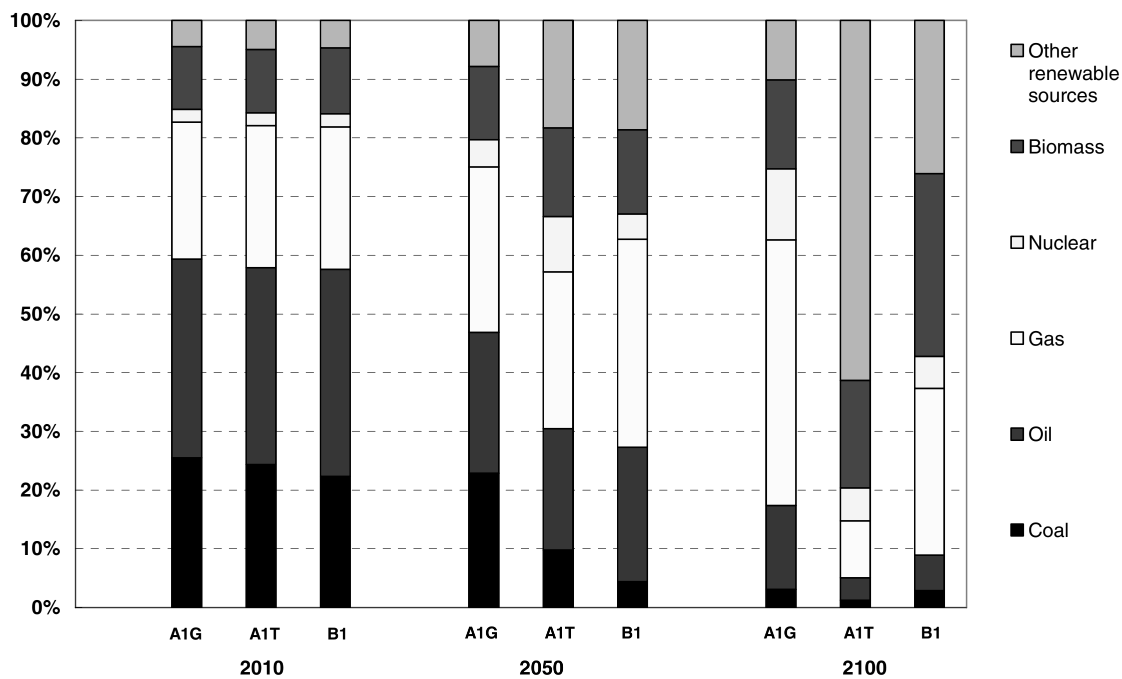
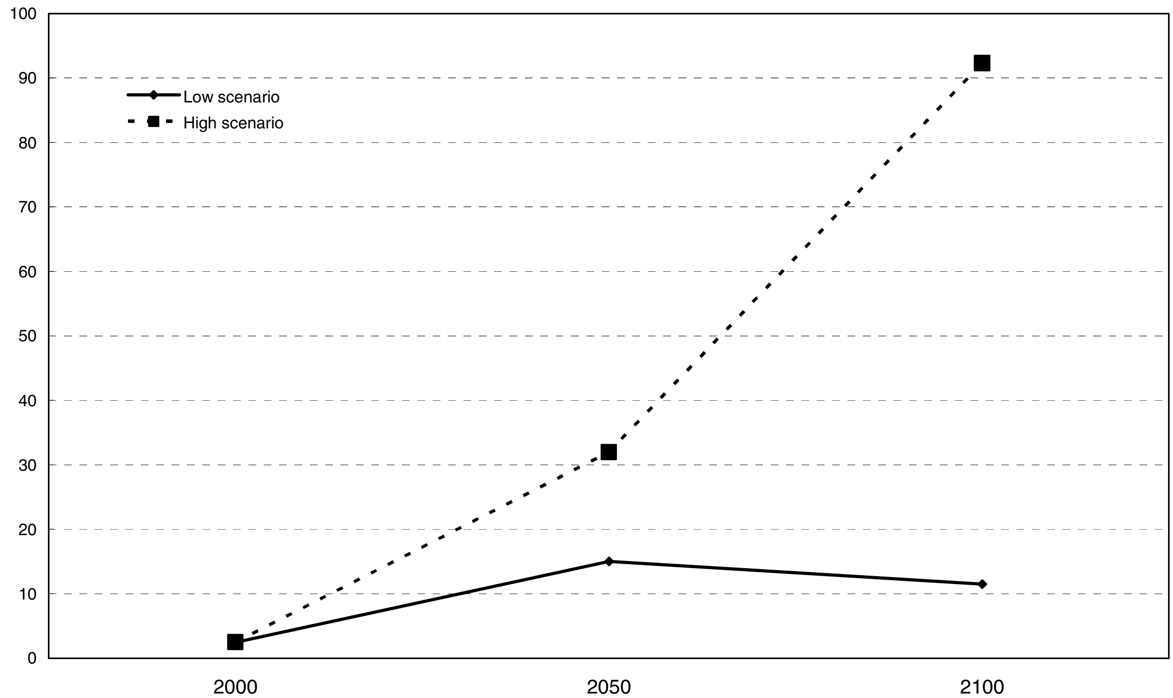


Figure 2.9 shows the projected evolutions of nuclear electricity generation to 2100 according to the IPCC scenarios B1 and A1G.

Figure 2.9 Projected evolutions of nuclear electricity generation (10^3 TWh/year)



2.3 Implications for climate policy, role of carbon-free technologies

Recently a goal has been proposed by the European Union to set a limit to the global warming at plus two degrees Celsius as compared to pre-industrial conditions. Such an increase, which is considered acceptable from a climate change viewpoint, would require a reduction of CO_2 emissions by 50 to 80% compared to the level of 2020. Such reductions should be implemented until 2050.

The Kaya equation provides a simple relation between CO_2 emissions, population (N), production per capita (GDP/N), energy intensity of the economy (E/GDP) and carbon content of energy (C/E):

$$CO_2 \text{ Emissions} = N \times (GDP/N) \times (E/GDP) \times (C/E)$$

Assuming that a reduction by 50% of CO_2 emissions would be adequate and considering the individual terms in the Kaya equation[3] the following findings may be highlighted.

- Population is projected to grow by a factor of 1.5 (IPCC, 2000). This means that, to reach the goal the product of the remaining three terms needs to be reduced by a factor of three.
- The world GDP per capita may be assumed to grow by 1% per year (this is an extremely modest growth having in mind the historical developments and in particular trends in countries with largest populations i.e. China and India). As a result of such growth, the

3. The reasoning adopted here follows Jancovici (2003) though some of the parameters have been changed.

product of the two remaining terms needs now to be reduced by a factor of five in order to reach the goal.

- Energy intensity may be assumed, rather optimistically to fall by 1.8% per year. This corresponds to the overall term reduction by a factor of 2.5. Thus, the remaining term needs now be reduced by a factor of two.
- Reducing carbon intensity of the world energy system by a factor of two in the next 40-50 years is a tremendously ambitious undertaking given that the past and current trends point in the opposite direction as shown in Table 2.2. Under less optimistic assumptions the reduction of carbon content would have to be even more drastic. Under all circumstances, moving towards the postulated goal would require an expansion of the nearly carbon-free technologies, i.e. renewable source and nuclear, much beyond any scenarios shown in this report. This is probably not realistic but illustrates the technological (and financial) challenges posed by the climate change issue.

Table 2.2 Change in Kaya Equation terms and carbon emissions disaggregated by region 1980-1999

Region	Average annual per cent change 1980-1999				
	Population	Standard of living	Energy intensity	Carbon intensity	Carbon emissions
Africa	2.54	-0.58	0.82	-0.01	2.77
Australia	1.36	1.98	-0.37	0.00	2.98
Brazil	1.61	0.76	1.83	-0.80	3.43
China	1.37	8.54	-5.22	-0.26	4.00
East Asia	1.78	5.00	0.92	-0.70	7.10
Eastern Europe	0.44	-1.91	-0.14	-0.61	-2.21
India	2.04	3.54	0.27	0.03	5.97
Japan	0.41	2.62	-0.57	-0.96	1.47
Middle East	2.98	0.04	2.45	-1.14	4.34
OECD	0.68	1.73	-0.88	-0.58	0.94
OECD Europe	0.53	1.74	-1.00	-1.06	0.18
United States	0.96	2.15	-1.64	-0.21	1.23
World	1.60	1.28	-1.12	-0.45	1.30

2.4 The way forward

As demonstrated in this chapter, the literature shows that given that policies aiming at reducing the risks of global warming and promoting sustainable development in the energy sector will be followed, the world will have to learn how to be more efficient when dealing with energy and how to promote carbon-free or low-carbon energy technologies. Satisfying demand will require a mix of all options satisfying these requirements, with no *a priori* discrimination. This implies increased need for nuclear energy as illustrated by realistic scenarios.

The review of the present situation and expected futures highlights that today nuclear energy is a significant component of energy mixes worldwide and that, irrespective of the scenario envisaged, nuclear power plants and fuel cycle facilities will remain in operation in various countries for several decades.

In this context, analysing the risks and benefits of the nuclear option is highly relevant for policy makers and may help operators and designers in enhancing the technical, economic and environmental performance of nuclear systems.

Climate change and security of supply issues will remain important for economic and social development and, in order to address those issues, technology progress will be needed as well as behavioural changes. A thorough assessment of all the energy options available, including nuclear energy, is a prerequisite to relevant choices for sustainable mixes.

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Chapter 3

METHODOLOGY AND ASSESSMENT FRAMEWORK

3.1 Sustainable development concept

The concept of sustainable development is well established and understood at the theoretical level and the principle of its relevance for policy making in the energy sector is broadly recognised. However, its practical application as a decision-making tool for implementing policy aiming at sustainable energy mixes remains very limited. This chapter presents the concept of sustainable development and an overview on attempts made to establish practical frameworks including indicator sets for the application of the concept to energy, with emphasis on nuclear power.

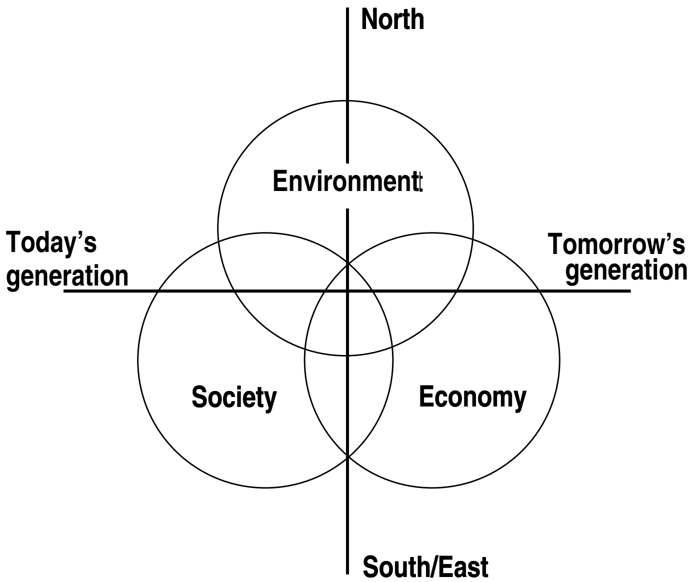
The sustainability definition, on which the Brundtland Commission (WCED, 1987) agreed, is now generally recognised as a standard. It states that sustainable development is "*a development that meets the needs of the present without compromising the ability of future generations to meet their own needs*." This definition served as a basis for the negotiations of the United Nations Conference on Environment and Development (UNCED) held in Rio in 1992 as well as for the establishment of Agenda 21 and documents issued later under the UNCED umbrella.

Key words in the above definition are *needs* and *future generations*. Accordingly, sustainable development policies aim at satisfying needs, i.e., enhancing the quality of human life, while preserving assets for the future, i.e., without exceeding the carrying capacities of the supporting resource base. Quality of human life may be measured with indicators such as health, income and education, although quantitative metrics to measure those indicators are not always obvious. The second part of the equation is even less straightforward, as the notion of resource base incorporates not only natural resources but also human resources that substitute to them, e.g., knowledge and technology may substitute raw materials.

Several international organisations, including the United Nations through its Commission on Sustainable Development (CSD) and UNCED, and the OECD, have developed frameworks for assessing sustainability which helped in clarifying the Bruntland concept. Their application, however, has not been widely spread. The three-pillar model adopted by OECD (OECD, 2001a), attempts to describe sustainable development as a combination of three elements or dimensions: economy, society and environment. The policy guidance issued from the application of this model focuses on integrating economic, environmental and social aspects within a global assessment.

Based upon this model, Figure 3.1 provides a schematic representation of the three dimensions of sustainable development. The time and geographic axes simulate the inter-generational and intra-regional equity context. Other schematic representations (e.g., OECD, 2001a) emphasize the interactions between the economic, social and environmental factors that link the three dimensions of sustainable development. For example, education (society) affects productivity (economy), atmospheric pollution (environment) affects health (society) and income distribution (economy) affects welfare (society).

Figure 3.1 Schematic representation of the central aspects of sustainable development, based on the definition of the Brundtland Commission
(Modified from SDC & ARE, 2004)



A key challenge for implementing sustainable development policies is to address the three dimensions in a balanced way, considering their interactions and, whenever necessary, making relevant trade-offs. In this connection, it should be noted that the interdependency of the three dimensions prevents the development of independent indicators for each aspect and increases the importance of judgemental evaluation in the global assessment.

3.2 Indicators

The implementation of an assessment based on the sustainable development approach requires the establishment of indicators related to economic, environmental and social aspects. The evaluation of alternative options – for example in the energy sector different electricity generation technologies and chains – will be based upon a comparison of metrics measuring the indicators for each option.

There is no unique set of indicators that would be relevant for all applications. The selection of indicators is guided by the scope of the assessment, e.g., indicators relevant in the energy sector will differ from those adapted to agriculture and indicators in the field of nuclear fuel cycle would not be relevant for overall energy system assessment. The objective and target audience of the assessment are important also in the selection of indicators. Analysts, corporate managers and governmental policy makers will require different sets of indicators.

The process of selecting indicators is an integral part of the assessment and should be carried out in cooperation with interested parties if applicable to ensure that the results will be accepted by stakeholders. A key requirement in this connection is to reach an agreement on the set of indicators and on the metrics to be used to measure those indicators, through open dialogue and discussions if needed.

One of the aspects of indicators deserving special attention is their quantification. Ideally, the indicator needs to be formulated in such a way that it can be expressed as a numeric value. It should be noted in this regard that criteria related to the social dimension of sustainability are often not expressible in a fully quantitative manner.

Another important requirement is the availability of data. An indicator should be measurable, i.e., information on its value should be accessible to the analyst through statistics, already existing or that can be collected reasonably easily.

Extensive literature has been published on indicators of sustainable development in general and on those adapted to energy system assessment in particular. The following review of desirable characteristics for indicators is drawn from work carried out in the framework of the European Commission NEEDS (New Energy Externalities Development for Sustainability) project at the Paul Scherrer Institute (Burgherr, 2005). It lists the major characteristics of indicators in terms of scientific robustness, functional relevance and practical ease of implementation.

Scientific

- *Measurable and quantifiable:* adequately reflect the phenomenon intended to be measured.
- *Meaningful:* appropriate to the needs of the user.
- *Clear in value*: distinct indication of which direction is good and which is bad.
- *Clear in content:* measured in understandable units that make sense.
- *Appropriate in scale:* not over or under aggregated.
- *No redundancy or double counting:* indicators are not overlapping in what they measure.
- *Robust and reproducible:* indicator measurement is methodologically sound, fits the intended purpose and is repeatable.
- *Sensitive and specific:* indicators must be sensitive to changes in the system under study and, ideally, respond relatively quickly and noticeably.
- *Verifiable:* external persons or groups should be able to verify an indicator.
- *Hierarchical:* to allow a user to understand the level of detail necessary.

Functional

- *Relevant:* for all stakeholders involved.
- *Compelling:* interesting, exciting and suggestive of effective action.
- *Leading:* so that they can provide information to act on.
- *Possible to influence:* indicators must measure parameters that are possible to be changed.
- *Comparable:* if the same indicators are used in several systems, they should provide usable results.
- *Comprehensive:* the indicator set should sufficiently describe all essential aspects of the system under study.

Pragmatic

- *Manageable:* not too many to handle; also important in view of interactions with users and stakeholders.
- *Understandable:* possible to be understood by stakeholders.
- *Feasible:* measurable at reasonable effort and cost.
- *Timely:* reasonably easy to collect and compile without long delays.
- *Coverage of the different aspects of sustainability*: indicators address economic, environmental and social dimensions.
- *Allowing international comparison:* to the extent necessary, i.e. in accordance with specific study objectives.

The relative importance of each characteristic depends on the objectives and scope of the assessment to be carried out and on the audience for the results. In particular, analysts and researchers will focus on details and comprehensiveness while policy makers will require aggregated, synthetic indicators providing messages easily understood by civil society stakeholders.

The debate on the benefits and drawbacks of aggregated indicators versus extended sets of detailed indicators is beyond the scope of this report. In a nutshell, aggregated indicators are more suitable at the policy making level but should be interpreted with great care to avoid misleading "simple" messages. On the other hand, large sets of detailed indicators are suitable for analysts and corporate managers but may not provide the right signals if they are not properly prioritised.

3.3 Framework and indicators for the energy/electricity sector

The sustainable development framework can be applied in the energy sector for various purposes such as assessing: the overall sustainability performance of an energy system, local, national or regional; alternative options within an energy system, e.g., coal versus nuclear for electricity generation; or alternative technologies, e.g., different nuclear reactor types or fuel cycle options.

The sustainable development framework applied with the relevant indicators allows, in principle, to integrate all the economic, social and environmental aspects of energy systems in a comprehensive holistic assessment. Derived from the concept described above, sustainability indicators and metrics form the basis for a systematic, comparative evaluation covering the risks and benefits of various energy/electricity supply options.

Previous studies have demonstrated that even if the evaluations relate exclusively to energy/electricity systems, the objectives and scope of the study and the boundaries of the system analysed should be defined precisely in order to identify a set of relevant indicators. This introduces an inherent limit to carrying out generic evaluations and studies. Lessons learnt from past studies include also the need to be aware of difficulties to obtain accurate, reliable data for some indicators.

Different sets of indicators have been proposed by international and national organisations for assessing the sustainability of energy systems and they have received various degrees of validation/approval by analysts or other stakeholders. The most comprehensive examples include the coordinated effort by the United Nations (UNDESA, 2001a,b,c) and the OECD project on sustainable development (OECD, 2001b); previous work of the Nuclear Energy Agency (NEA, 2000; 2002) and of the International Atomic Energy Agency (IAEA, 2003) focused on nuclear energy; the study carried out in Germany (Enquête Commission, 2002) and the activities of PSI in the field of electricity supply technologies (Hirschberg *et al.*, 2004) cover electricity systems.

A recent interagency effort (IAEA, 2005) led by the IAEA in cooperation with UNDESA, IEA, the Statistical Office of the European Communities (Eurostat) and the European Environment Agency (EEA) produced a core set of energy indicators for sustainable development. The 30 indicators are classified according to the three major dimensions of sustainability: economic (16 indicators), environmental (10 indicators) and social (4 indicators). Within each group, indicators are then arranged by themes and sub-themes. Overall, this core indicator set is consistent with and supplementary to the UNCSD indicator framework. However, because they are not technology-specific, they cannot be applied to assess and compare alternative technological options and, therefore, are not directly relevant in the field of nuclear energy.

The survey of indicator sets carried out at the Paul Scherrer Institute in the context of the GaBE project (Hirschberg *et al.*, 2004) and of the NEEDS project (Burgherr, 2005) led to the following main findings:

- The sets of indicators have different scope and focus ranging from sustainable development in general through sustainable development in the energy sector to sustainable development of specific energy carriers.
- The sets of indicators originating from international organisations are not suitable for comparing sustainability attributes of major energy carriers, with appropriate differentiation between technologies.
- Economic and environmental indicators are relatively well developed but social indicators are poorly developed and highly subjective in some cases.
- Most of the sets are primarily based on directly available, simplistic indicators. There are major problems with consistency.
- Few efforts have been made towards aggregation of indicators to support decisions.
- A set of widely accepted, technology- and application-specific, harmonised numerical indicators is not available from earlier studies. A broad knowledge base is a prerequisite for the establishment of such indicators.

Following the survey, and based on feedback from sustainability assessments in different contexts and countries including China, Germany and Switzerland, a set of technology-specific criteria and indicators was defined by the PSI after discussions with other researchers and stakeholders (Hirschberg *et al.*, 2004). This proposed set is comprehensive but concise enough to be applicable in case studies. However, it is not universal and, because it was developed in the context of a national study to assess an existing electricity system, it does not include indicators specifically designed to address technology progress and development.

The three dimensions of sustainable development were considered in the proposed set of indicators given in Table 3.1. It should be noted that allocation of specific impact areas and the associated indicators to the three dimensions of sustainability involves judgements and some elements of arbitrariness. For example, impact area "Resources" includes some ecologic indicators, which affect the overall efficiency of systems and thus have an impact on economy. Health effects are in some studies considered to be a part of the ecological rather than the social dimension.

Table 3.1 Proposed set of technology-specific indicators (Hirschberg *et al.*, 2004)

Dimension	Impact area	Indicator	Unit
Economy	Financial requirements	Production cost	*c/kWh*
		Fuel price increase sensitivity	*Factor*[a]
	Resources	Availability (load factor)	%
		Geopolitical factors	*Relative scale*
		Long-term sustainability: Energetic resource lifetime	*Years*
		Long-term sustainability: Non-energetic resource consumption	*kg/GWh*
		Peak load response	*Relative scale*
Environment	Global warming	CO_2-equivalents	*tons/GWh*
	Regional environmental impact	Change in unprotected ecosystem area	*km^2/GWh*
	Non-pollutant effects	Land use	*m^2/GWh*
	Severe accidents	Fatalities[b]	*Fatalities/GWh*
	Total waste	Weight	*tons/GWh*
Social	Employment	Technology-specific job opportunities	*Person-years/ GWh*
	Proliferation	Potential	*Relative scale*
	Human health impacts (normal operation)	Mortality (reduced life-expectancy)	*Years of lfe lost/GWh*
	Local disturbance	Noise, visual amenity	*Relative scale*
	Critical waste confinement	"Necessary" confinement time	*Thousand of years*
	Risk aversion	Maximum credible number of fatalities per accident	*Max fatalities/ accident*

a. Increase of production costs due to doubling of fuel costs.

b. Expected damages due to severe accidents, expressed in fatalities per unit of energy.

The environmental indicator associated with severe accidents is the specific (i.e., per unit of electricity generated) number of fatalities resulting from such accidents. This might seem to be an inconsistency, but the reason for this choice is that a measure of accident-related environmental damage, which could be applied to all technologies, is difficult to establish. Thus, mortality due to accidents serves here as a surrogate for the corresponding environmental effects.

Many other issues raised by the selected indicators need to be addressed. The list presented in the table is the result of work in progress and will be discussed further. Improvement will be achieved through research as well as dialogue with stakeholders. As noted above, the social indicators are the most controversial and difficult to define, select and measure. Difficulties with the measurement of social aspects for specific technologies occur both on the conceptual and the empirical level. One possibility to overcome this problem is the use of participative or recursive analysis. The integrated project NEEDS undertaken within the sixth Framework Programme of the European Commission will cover this topic.

An important finding from previous studies is that the selection of indicators is driven by the scope and objectives of the study and depends on the boundaries of the system to be assessed. The set of indicators relevant for assessing options for electricity generation in a country might not be adequate for an evaluation of alternative options by a utility for a given project. Therefore, each study should start by a review of relevant indicators and a selection of the best set in the specific context of the assessment to be carried out.

References

The list of references provided below is not exhaustive. It is limited to the published literature directly used in the chapter. Many of the references provided contain more comprehensive lists of articles, reports and books covering a broader range of outcomes from past and ongoing research on the subject matter.

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Chapter 4

ILLUSTRATIVE RESULTS OF ASSESSMENTS

4.1 Introduction

The results presented in this chapter are drawn from information available in published studies and established databases. They illustrate the application of the framework and methodology described in Chapter 3 to specific electricity generation chains and systems by presenting sets of values for some indicators which were obtained with consistent assumptions adopted in each source study. Each set of results was obtained – in the original study – based on technology characteristics, economic parameters and other needed input data corresponding to the context of the case study.

The technologies evaluated vary from study to study; for example coal chains for generating electricity considered in the different studies quoted below are not identical. Similarly the economic assumptions adopted, including discount rate, currency and year of reference, vary according to the context of each study. Therefore, while comparisons provided for each indicator are internally consistent, the results from different studies, given as published and not harmonised, are not comparable.

Harmonisation of results from different studies was beyond the scope of the present project and in most cases would be impossible and meaningless in the light of the country and case specific characteristics of the assumptions and input data. The results presented below are essentially illustrative and it is not possible to draw global conclusions based on multi-criteria analysis from the examples provided in this chapter for various indicators. Chapter 5 provides insights on the use of external costs as a means to aggregate indicators, and on multi-criteria analysis in support to decision-making.

The results presented in this chapter do not include all the indicators listed in Table 3.1 but they cover the three dimensions of sustainable development. Examples of economic indicators include generation costs, measures of security of supply and resource base longevity. In the domain of environmental indicators, the examples provided include atmospheric emissions and solid waste volumes. The social indicators, as noted in Chapter 3, are more difficult to measure and assess than the other indicators. A few examples are given covering employment, proliferation risk and impacts of energy chains on human health. In this connection, it may be noted that several indicators considered as environmental provide insights on social aspects through correlation between, for example, air quality, human health and quality of life.

In all the studies on which this chapter is based, the quantitative indicators were estimated through a systematic, multi-disciplinary, bottom-up methodology for the assessment of energy systems. This applies in particular to the complex environmental indicators. The overall approach is process-oriented, i.e., the technologies of interest and their features are explicitly represented in the models used to estimate burdens and eventually impacts. The implementation and applications of the various assessment methods relies on principles adopted in life cycle assessment (LCA) including for the evaluation of non-environmental indicators, for which, whenever considered important, the full energy chain is considered and not only the power plant.

For more details on the assumptions, data bases and methodologies used to obtain the results summarised below the reader is invited to refer to the original studies listed in the reference section.

4.2 Economic indicators

4.2.1 Generation costs

The most obvious economic indicator for electricity generation systems is the total cost of generation. However, although it is trivial to calculate, it is not easily accessible to the analysts for power plants in operation because market competition prevents producers from disclosing cost data fully. On the other hand, many national and international studies provide projected cost estimates, calculated for plants to be commissioned in the future. It is a relevant indicator in the context of the present report as it provides guidance for national energy policy and electricity system expansion planning at the utility level.

Although all the examples given below refer to levelised costs of generating electricity averaged over the lifetime of the power plants, they are not comparable from one study to the other. The main reasons are differences in assumptions regarding discount rate, availability/load factor and economic lifetime; furthermore, some studies, such as the report of the Massachusetts Institute of Technology (MIT, 2003), take into account taxes and risk related premium on cost of capital while others don't. Last but not least, the fossil fuel prices assumed in each study correspond to different dates and different country or region circumstances.

The results are presented in the following tables as given in the source studies, i.e., in different monetary units of various dates. No attempt was made to convert costs in the same currency of a given date because (see IEA and NEA, 2005) it is not only very complicated but also potentially misleading.

The generation costs provided by the MIT study cover coal, gas and nuclear power plants in the United States estimated taking into account the composite marginal income tax rate, assumed to be 38%, applied to the taxable income of the electricity producer. More detail on the "merchant" cost model used and on the assumptions adopted are given in the MIT report (MIT, 2003).

Table 4.1 Electricity generation costs in the United States (US cent of 2002/kWh)

Pulverised coal	CCGT low*	Gas medium*	Gas high*	Nuclear	Nuclear **	Nuclear ***
4.2	3.8	4.1	5.6	6.7	5.5	4.2

* Refers to gas price.

** Construction cost reduced by 25%.

*** Cost of capital for nuclear similar to that for gas/coal plants.

The results presented in Table 4.1 are given for low, medium and high gas price assumptions, respectively 3.77, 4.42 and 6.72 USD/MC F,[1] and for three different cases regarding capital cost of nuclear power plants, the base case corresponding to an overnight capital cost for nuclear of 2 000 USD/kWe.

1. MCF = million cubic feet.

The GabE study carried out by Paul Scherrer Institute (PSI) provides comparative production costs for different electricity generation technologies under German conditions (Hirschberg *et al.*, 2004a, p. 63). The results, shown in Table 4.2, are not easily comparable with those of other studies because they relate to the existing electricity generation mix in operation in Germany at the time, i.e., around 2003, which includes, for example, nuclear power plants with a capital cost largely amortised. Also, for hydro and solar photovoltaic, the back-up costs are not accounted for.

Table 4.2 Electricity generation costs in Germany (€ cent/kWh)

Lignite	Hard coal	Oil	Gas	Nuclear	Hydro	Wind	Solar PV
3.3	3.0	3.1	3.6	2.1	7	7	60

Cost estimates provided by the United Kingdom Department of Trade and Industry in the context of the OECD study (IEA and NEA, 2005) cover various options and give ranges of values taking into account uncertainties on future performance of the technologies considered. The estimates presented in Table 4.3 were calculated at 10% discount rate for plants to be commissioned in 2010 and are expressed in British pence (p) of mid-2003.

Table 4.3 Electricity generation costs in the United Kingdom (p of 2003/kWh)

Coal	Gas	Nuclear	Small hydro	Onshore wind	Offshore wind	Waste	Landfill gas
3.6/4.0	2.3/2.4	2.8/4.3	1.6/1.9	3.2/4.2	4.5/5.7	2.5/3.0	3.3/3.9

The most recent levelised generation cost estimates for Finland (Tarjanne, 2006) were based on current gas prices on the European market and, therefore, show a large competitive margin for nuclear versus gas (see Table 4.4). According to Finnish conditions, the costs were calculated for a real interest rate of 5% for all plants. The generation costs for wood and wind do not take into account subsidies; wind power plants are assumed to operate at full power 2 200 hours per year and backup-power cost is not taken into account.

Table 4.4 Electricity generation costs in Finland (€ of 2006/MWh)

Wood	Peat	Coal	Gas	Nuclear	Wind
51.24	55.03	51.97	51.97	25.91	45.48

The main results from the international survey published by OECD on projected costs of generating electricity (IEA and NEA, 2005) are summarised below. The technologies and plant types covered by the study include units under construction or planned that could be commissioned in the respondent countries between 2010 and 2015. Construction, operation and maintenance and fuel cost data were provided by participating experts, together with technical characteristics of the plants.

The costs of generating electricity were calculated using the levelised lifetime cost approach and generic assumptions such as economic lifetime of 40 years, average load factor for base-load plants of 85% and discount rates of 5 and 10%. Details on the input data and assumptions adopted for calculating levelised costs of generating electricity are provided in the publication.

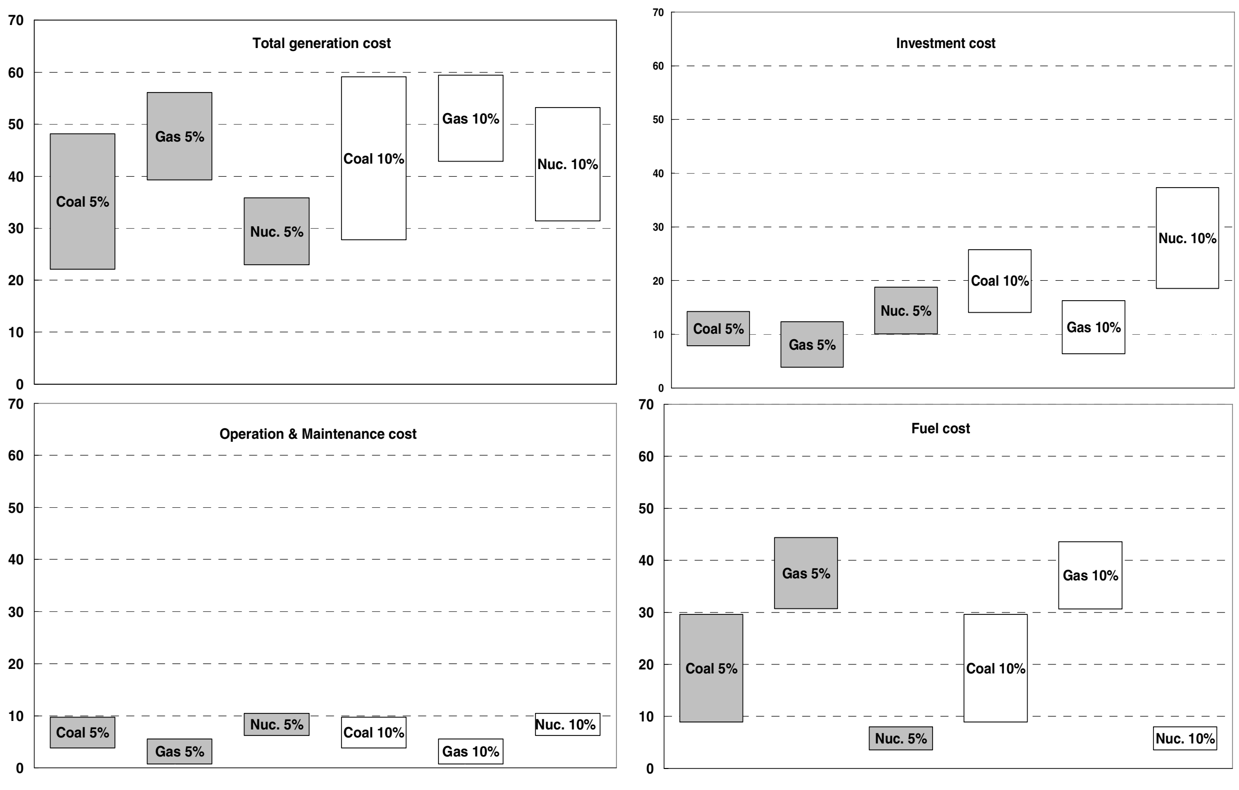
Table 4.5 summarises the ranges of levelised costs, excluding the 5% highest and 5% lowest values, for coal, gas and nuclear power plants at 5 and 10% discount rates. The levelised costs are given for wind power plants also, not taking into account the backup power needed to compensate for the intermittent availability of wind power plants.

Table 4.5 Ranges of electricity generation costs (€/MWh)

At 5% discount rate				At 10% discount rate			
Coal	Gas	Nuclear	Wind	Coal	Gas	Nuclear	Wind
22/48	39/56	23/36	35/90	28/59	43/59	31/53	45/125

Figure 4.1 shows cost ranges for coal, gas and nuclear power plants. It should be stressed that the ranges given in the table and shown in the figure reflect costs in different countries and for different technologies within the same fuel class. The difference in cost structure for each technology is illustrated by the ranges of investment, operation and maintenance (O&M) and fuel costs.

Figure 4.1 Range of levelised costs for coal, gas and nuclear power plants (USD/MWh)



4.2.2 Fuel price sensitivity

The sensitivity of generation cost to fuel price increase is an important factor for the medium and long-term stability of electricity prices which, in turn, has an impact on economic performance of a country or a company.

The OECD study (IEA and NEA, 2005) provides the structure of electricity generation costs for the plants considered (see Figure 4.1). Using those cost structures to estimate the sensitivity to a doubling of fuel prices gives the total generation cost increases, in percentage, shown in Table 4.6 for coal, gas, nuclear and wind/solar power plants.

Table 4.6 Impact of a doubling in fuel prices on generation costs (%)

Coal	Gas	Nuclear		Wind/Solar
		U price	Fuel cycle cost	
40	75	4	15	0

For nuclear power plants, the sensitivity was calculated for uranium price increase and for total fuel cycle cost increase but it should be noted that fuel cycle services, delivered by industrial facilities, are less volatile than those of raw materials.

The values provided in Table 4.6 are indicative only, as they are calculated on average generation costs for a basket of plants including various technologies and located in different countries. However, they illustrate general trends. They show a significant difference between fossil fuels on the one hand and nuclear power and renewable sources on the other hand. They highlight the generation cost stability offered by renewable sources – and to a lesser extent by nuclear power – irrespective of uncertainties on fossil fuel market price volatility.

4.2.3 Availability factor

When considering state-of-the-art power plants for base-load generation, availability factor is not a discriminator. Coal, gas and nuclear power plants can achieve availability factors above 85%. In the case of power plants relying on intermittent renewable sources such as wind and solar, availability factors depend mainly on local conditions and are not technology specific. The load factors range between 10 and 25% for solar energy and between 15 and 45% for wind energy. This calls for a large non-renewable back-up capacity or secured electricity imports, particularly in winter when the demand is generally high. However, some countries such as Denmark and Germany have demonstrated that high shares – some 25% of total generation capacity – of wind capacity connected to the network are viable.

4.2.4 Security of fuel supply

Security of supply could be included in the social, or even environmental, indicators as well as considered as an economic indicator. It is addressed in the economic indicator section of this report to be consistent with the list provided in Table 2.1.

In a broad sense, security of energy supply may be defined as the lack of vulnerability of the system considered (e.g., national economy or company balance sheet) to volatility in volume and price of imported energy products such as oil and gas. However, a precise definition of the concept specifying its boundaries is not easy to find. Security of energy supply has economic, social and political dimensions at the same time. Energy system analysts and economists can define the economic aspects but the social and political dimensions are more difficult to capture.

In the context of the present report, which focuses on the nuclear energy chain for electricity generation, physical disruptions caused by insufficient transmission capabilities or price spikes which might result from market mechanisms are not covered. These issues need to be addressed by policy makers dealing with energy systems at the national or regional level but are not a discriminator for selecting an electricity generation option.

Although some indicators to measure security of supply have been proposed by economists or other experts (IEA and NEA, 1998), there is no consensus on the relevant indicator or on a set of relevant indicators and more research is necessary on quantifying benefits of security of supply in order to support policy making. In the meantime, decision makers generally rely on a basket of parameters and/or qualitative assessments.

A number of energy dependency indicators exist which have been measured, reported and stored in data bases together with other energy indicators. For example, it is easy to find time series covering, for each imported energy source, ratios of domestic supply versus total requirement and respective shares of each foreign supplier in total supply. The level of strategic inventories and physical capacities of storage are also relevant indicators monitored by some countries and international organisations. However, indicators of security of energy supply should represent a degree of risk and the risk associated with dependency varies according to the geopolitical situation of the supplier and importer countries as much as, or even more than, on the size of imports.

Geopolitical distribution of primary fuel resources and production capacities is one of the measures of security of supply. It is generally considered that a large number of potential suppliers facilitates diversity of supply and limits the risks of supply disruption for physical or political reasons. Beyond the value of diversity, however, the evaluation of the reliability of a supplier country or region is largely subjective, depending on non-quantitative socio-political factors. The geographic distributions of fossil fuel and uranium resources, and their productions in 2005, are given in the tables below to illustrate this indicator for coal, oil, gas and uranium. Obviously renewable energy sources are 100% domestic and security of supply is not an issue for their development.

Tables 4.7 to 4.9 provide data on coal, oil and gas drawn from the latest BP Statistical Review (BP, 2006); Table 4.10 gives similar data for uranium drawn from the latest Red Book (IAEA and NEA, 2006).

Table 4.7 Geographic distribution of proven gas reserves and production

Country	**% of proved reserves**	**% of 2005 production**
United States	3	19
Total OECD	*8.5*	*39*
Venezuela	2.5	1
Algeria	2.5	3
Nigeria	3	1
Iran	15	3
Qatar	14.5	1.5
Saudi Arabia	4	2.5
Russian Federation	26.5	21.5

Table 4.8 Geographic distribution of proven oil reserves and production

Country	% of proved reserves	% of 2005 production
United States	2.5	8
Total OECD	*6.5*	*24*
Venezuela	6.5	4
Libya	3.5	2
Nigeria	3	3
Iran	11.5	5
Iraq	9.5	2.5
Kuwait	8.5	3.5
Saudi Arabia	22	13.5
United Arab Emirates	8	3.5
Kazakhstan	3.5	1.5
Russian Federation	6	12

Table 4.9 Geographic distribution of proven coal reserves and production

Country	% of proved reserves	% of 2005 production
Australia	8.5	7
Poland	1.5	2.5
United States	27	20
Total OECD	*41*	*35*
South Africa	5.5	5
China	12.5	38.5
India	10	7
Kazakhstan	3.5	1.5
Russian Federation	17.5	4.5
Ukraine	4	1.5

Table 4.10 Geographic distribution of uranium resources and production

Country	% of resources*	% of 2005 production
Australia	24	22
Canada	9.5	28.5
United States	7	2
Total OECD	*43*	*53.5*
Brazil	6	1
Namibia	6	7
Niger	5	8
South Africa	7	2
Kazakhstan	17	10
Russian Federation	3.5	8
Uzbekistan	2.5	5.5

* Total identified resources recoverable at less than 130 USD/tU.

For OECD countries, reliable and continuous supply of oil and gas depends on countries outside OECD including the Middle East and Russian Federation. The United States is a major producer but its reserves represent only a few percent of the world total. For coal, security of supply is a lesser concern due to the vast amount of reserves and the geopolitical distribution of suppliers is more balanced than for hydrocarbons.

The geopolitical distribution of uranium resources and production, on the other hand, offers guarantees against risk of disruption. Known uranium resources are found in significant quantities in countries as diverse as Australia, Canada and United States, in OECD, Kazakhstan and Russian Federation, in countries in transition, and Namibia, Niger and South Africa in developing countries (Table 4.10). The two major producers, Canada and Australia with 28.5% and 22% of the total respectively, are OECD countries, and most producing countries contribute less than 10% to the total.

4.2.5 Lifetime of fuel resources

The lifetime of primary energy resources is a measure of the period during which this resource can be exploited. Ideally, it would be desirable to know the real lifetime of resources but it can be evaluated only with assumptions on the evolution of demand and production. Therefore, the indicator usually referred to is the ratio of reserves to annual production in the latest year for which data are available.

Table 4.11 Ratio reserves/production 2005 (years)

Coal	Oil	Gas	Uranium
155	41	65	85

According to Table 4.11, providing the ratios for coal, oil, gas and uranium, coal could be relied upon for more than a century and a half, provided carbon emissions could be mitigated while oil would be exhausted in less than 50 years and gas in 65 years. Uranium would last less than a century. This indicator provides some insight on the duration of resources with present technology.

However, this static ratio does not take into account future evolutions of consumption and production and ignores potential discoveries of additional resources. Consumption may increase or decrease depending on many factors including economic growth, technological and behavioural changes. Resources may increase through exploration, better recovery techniques, and price escalation which shifts non-economic deposits into economically viable resources.

The ratio of identified resources to current production is even less relevant in a long-term perspective in the case of uranium and nuclear energy than in the case of fossil fuels because technology progress can make a drastic difference in uranium requirements per unit of electricity generated by nuclear power plants. Reprocessing of spent fuel followed by recycling of fissile materials in fast neutron reactors can, theoretically, multiply by two orders of magnitude the amount of energy produced by one tonne of uranium as compared to thermal reactors operated once through (NEA, 2006). Around 50 to 60 is a more realistic range of multipliers, taking into account transition from thermal to fast neutron systems and process losses at various fuel cycle steps.

Table 4.12 illustrates the impact of technology on the lifetime of uranium resources (IAEA and NEA, 2006) if used to produce the nuclear electricity generated in 2004, i.e., 2 640 TWh, with two different reactor and fuel cycle options.

Table 4.12 Lifetime of uranium resources (years)

Technology	Identified resources ~4.7 MtU	Total conventional resources ~ 14.8 MtU	Total conventional resources plus phosphates ~ 36.8 MtU
LWRs once through	85	270	675
Progressive introduction of FBRs*	4 250	13 500	33 750

* It is assumed that the progressive introduction of fast breeder reactors (FBRs) multiplies by 50 the amount of electricity generated by 1 tonne of uranium.

Also, uranium has been used for less than half a century and more resources may be found if exploration efforts increase. Very good uranium mines show concentrations of uranium in the ore body of 10% and beyond. Current mines typically have concentrations in the range 0.1-10%. Extraction from ore bodies with lower concentrations is not economic today but could become more attractive in the future if uranium prices would continue to rise. Eventually uranium from phosphates and from sea water could complement the resource base.

While potential exploitation of resources characterised by low concentrations has economic and ecologic implications that need to be investigated in detail, availability of uranium is definitely not the most critical factor that could jeopardize the long term viability of nuclear energy.

4.2.6 Use of energy resources

Fossil resources have been selected as an indicator of energy product use due to their relative scarcity and usefulness within other sectors than energy supply. This has a direct bearing on the issue of long-term energetic sustainability, having in mind the need to preserve fossil resources also for chemical and other non-energetic uses.

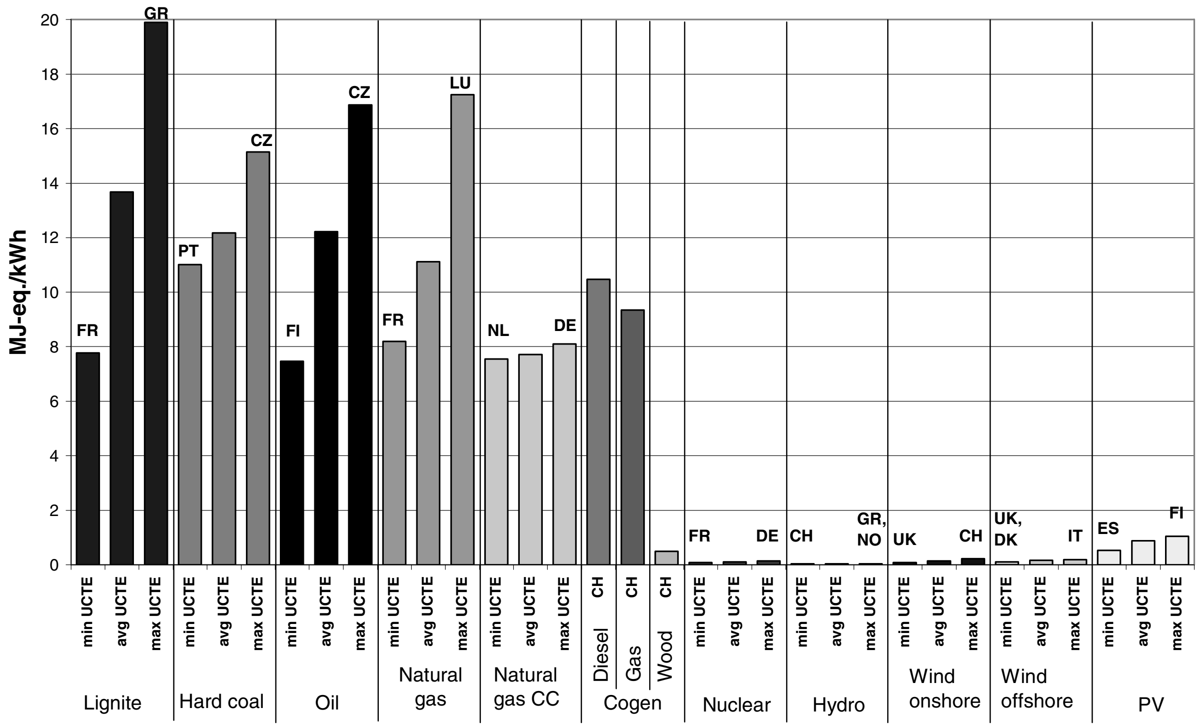
The consumption of fossil fuels by different energy chains is illustrated in Figure 4.2 drawn from the studies carried out by PSI (Dones *et al.*, 2004a and 2004b)[2] covering the member countries of the Union for the Coordination of Transmission of Electricity (UCTE)[3] and some other European countries, e.g., the United Kingdom.

The use of fossil resources, measured in MJ-equivalents of primary energy, is shown for various electricity generation chains. The consumption is naturally much higher for fossil chains, using coal, gas or oil as fuel at the power plant, than for nuclear and renewable chains using fossil fuels as a secondary or lower rank input. Among the fossil chains, lignite has the worst performance though hard coal and oil are comparable. Natural gas chains with combined cycle power plants have the lowest consumption among fossil chains due to their high efficiencies.

2. Details on the methodology and scope of those studies are provided in section 4.3 below on environmental indicators.
3. All figures shown refer to the Member Countries of UCTE in year 2000, namely: Austria, Belgium, Bosnia-Herzegovina, Croatia, Denmark (associated member), France, Germany, Greece, Italy, Luxembourg, Former Yugoslav Republic of Macedonia, the Netherlands, Portugal, Slovenia, Spain, Switzerland, and Serbia and Montenegro. The CENTREL countries Czech Republic, Hungary, Poland and Slovak Republic have officially joined UCTE in 2001.

Renewable sources and nuclear indirectly use fossil fuels for heat and electricity consumption within their chains. Hydro power has the lowest consumption, followed by nuclear and wind, which are comparable. Wood cogeneration and PV show the worst performance among renewable sources, but still one order of magnitude below fossil chains.

Figure 4.2 Requirement of fossil resources for selected energy chains

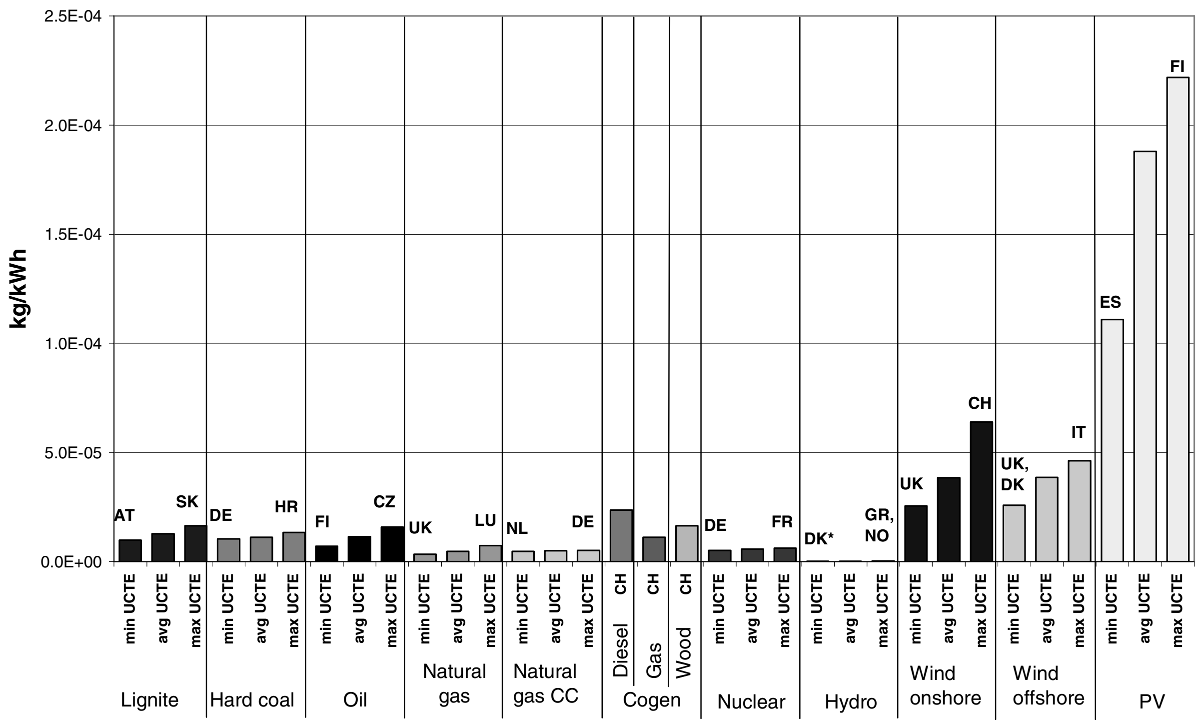


4.2.7 Use of non-energetic resources

The consumption of non-renewable natural resources other than fossil fuels or uranium is a measure of the pressure of an energy system on the environment, and this is why it is included in economic indicators. Copper was chosen as a reference material to represent limited metal resources in the GaBe study but consumptions of other materials could also be used.

Figure 4.3 shows a comparison of requirements of copper for different electricity generations chains in the UCTE countries in 2000 (Dones *et al.*, 2004a and 2004b). The PV chain shows the highest requirements by far, exceeding all other chains by more than a factor of five. The second worst performer is wind power; copper consumption for offshore and onshore turbines is in the same range. Fossil fuel chains, nuclear, and wood cogeneration have comparable requirements of copper and are better than PV by a factor of about 10. Hydro power shows the lowest needs for copper.

Figure 4.3 Requirement of copper for selected energy chains



4.3 Environmental indicators

The LCA approach used for generating most indicators is based, as far as environmental indicators are concerned, on a systematic method for the establishment of energy and material balances of the various energy chains. LCA utilises process chain analysis specific to the types of fuels used in each process and allows for the full accounting of burdens such as emissions, also when they take place outside national boundaries. LCA considers not only direct emissions from power plant construction, operation and decommissioning but also the environmental burdens associated with the entire lifetime of all relevant processes upstream and downstream within the energy chain. This includes exploration, extraction, processing and transport, as well as waste treatment and storage. The direct emissions include releases from the operation of power plants, mines and processing factories, transport and building of machines. In addition, indirect emissions originating from materials manufacturing, from energy inputs to all steps of the chain and from infrastructure, are covered. Detailed environmental inventories (i.e. burdens such as emissions or wastes) for current and future energy systems during normal operation have been established for a wide spectrum of European countries, with the highest level of detail for Switzerland (Dones *et al.*, 2004a and 2004b). Selected environmental inventories (burdens) may be used directly as indicators or may serve as input to health and environmental impact analysis.

The results presented below are based on the Ecoinvent database (Dones *et al.*, 2004a and 2004b; Ecoinvent Centre, 2004). For fossil fuel, nuclear and hydro generation chains, average and best and worst UCTE country performances are displayed in the figures. Whenever available, results from Chinese energy chains (Dones *et al.*, 2003) are included in the comparisons.

Cogeneration systems are representative for the Swiss conditions; the results for these systems were generated employing energy allocation. The cogeneration plant burning wood chips is equipped with control systems for reducing particle and NO_x emissions.

The assessments of wind and PV systems are based on a 800 kWe onshore turbine, a 2 MWe offshore plant, and a polycrystalline PV panel, mounted on a slanted roof. They are assumed to be installed at different European sites, leading to minimum and maximum estimates depending on different load factors. In the case of onshore wind turbines, an average German site with a capacity factor of 0.2 represents average UCTE conditions. Possible onshore sites in United Kingdom with a capacity factor of 0.3 represent best European conditions; sites in Switzerland with a capacity factor of 0.12 represent worst conditions. Average offshore generation is based on results from the Baltic Sea at a site with a capacity factor of 0.3. Capacity factors of 0.45, chosen as best European conditions, are possible in the sea off United Kingdom and Denmark. The Mediterranean around Italy is chosen as worst European offshore site with a capacity factor of 0.25. For roof-top PV systems, a Swiss yield of 885 kWh/kW_p is assumed as representative for average yearly European irradiation. Sites in Spain and Finland with yields of 1 500 kWh/kW_pa and 750 kWh/kW_pa,[4] respectively, are assumed as representative for best and worst performance within Europe.

4.3.1 Greenhouse gas emissions

Greenhouse gas (GHG) emissions are an indicator of global environmental impact owing to their role in global warming and climate change. Figure 4.4 shows a comparison of GHG emissions for different electricity generation chains.

GHG emissions are expressed in kg CO_2 equivalent, taking into account the warming potential of each gas. Lignite has the highest GHG emissions among all analysed energy chains. UCTE average is slightly above 1.2 kg CO_2-eq./kWh; differences between country averages are significant.

Hard coal shows only slightly lower GHG emissions than lignite with a UCTE average of about 1.07 kg CO_2-eq./kWh. Differences between various UCTE country averages are smaller than for lignite. Average GHG emissions of the Chinese hard coal chain are between European average and Czech Republic average.

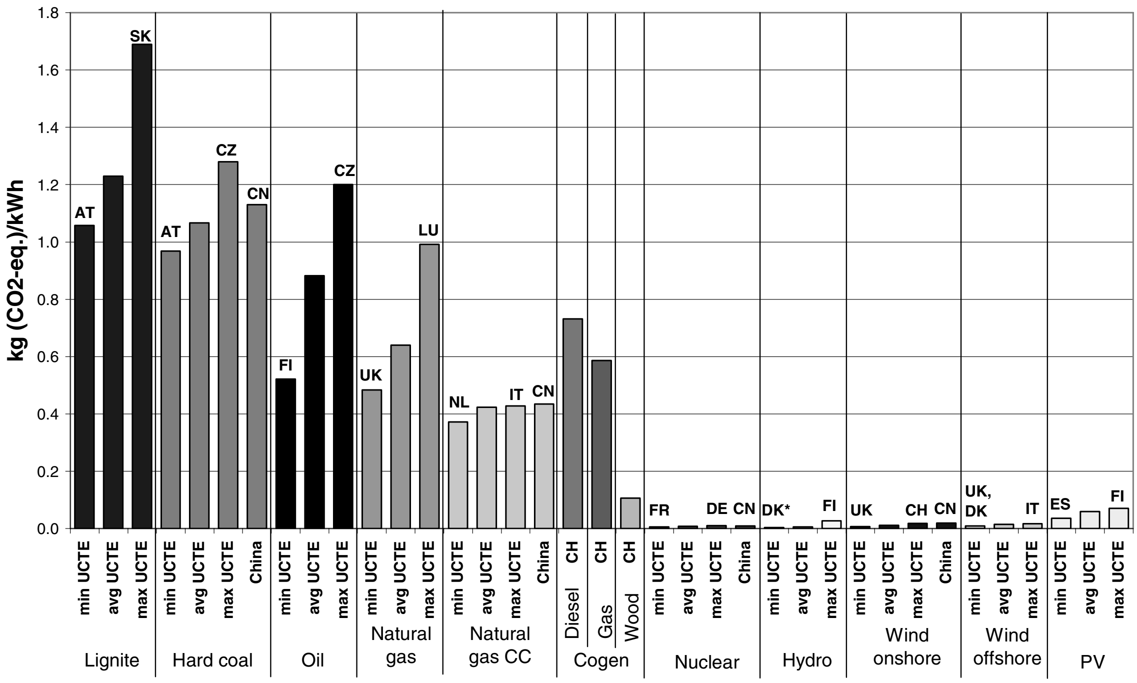
UCTE average GHG emissions from the oil chain are about 0.9 kg CO_2-eq./kWh. Country averages differ remarkably with Finland on the low end of the scale and Czech Republic on the upper end.

The natural gas chain has the lowest GHG emissions among fossil systems. UCTE average is slightly above 0.6 kg CO_2-eq./kWh. The analysis of natural gas combined cycle plants indicates what can be achieved with best technology today. UCTE average is about 0.4 kg CO_2-eq./kWh. It should be noted that the above estimates correspond to a region where gas/methane leakages are very small.

In general, direct power plant CO_2 emissions dominate GHG emissions of fossil systems and are also responsible for differences between European country averages of fossil electricity generation.

4. Data for site specific yields of photovoltaic electricity generation were retrieved from http://re.jrc.cec.eu.int/pvgis/pv/imaps/imaps.htm (10.12.2005).

Figure 4.4 Greenhouse gas emissions of selected energy chains



GHG emissions of nuclear and renewable energy chains are between one and two orders of magnitude below emissions of fossil chains. Among renewable sources, hydro and wind have better performance than PV and wood cogeneration. UCTE averages are about 8 g CO_2-eq./kWh for nuclear, 5 g CO_2-eq./kWh for hydro, 11 g CO_2-eq./kWh for onshore wind, 14 g CO_2-eq./kWh for offshore wind plants, 60 g CO_2-eq./kWh for PV and 100 g CO_2-eq./kWh for wood cogeneration.

4.3.2 Other atmospheric emissions

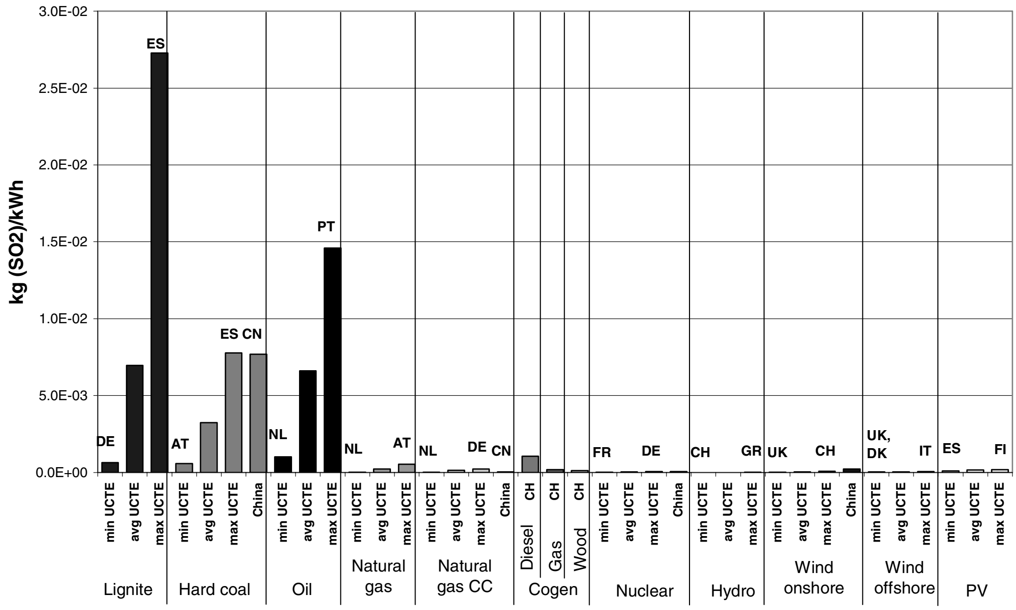
While greenhouse gas emissions have a potential worldwide impact through global warming and climate change, SOx, NOx and particulate matters have regional or local impacts. Illustrative results are shown in Figures 4.5 to 4.7, drawn from the same studies as the GHG emission data.

SO_2 emissions

Direct power plant emissions dominate SO_2 emissions of the fossil chains and depend on the sulphur content of the fuel and the emission control measures adopted. Lignite and oil with UCTE averages of about 7 g/kWh have the highest SO_2 emissions. Country averages differ considerably, the factor between the best and the worst performing country can reach values of nearly 30. UCTE average for hard coal is about 3 g/kWh. The best performing countries show that relatively low SO_2 emissions are possible even for coal and oil power plants.

The natural gas chain with an UCTE average of about 0.2 g/kWh has the lowest SO_2 emissions among fossil systems. Combined cycle plants show only small advantages. SO_2 emissions of nuclear and renewable chains (barely visible in Figure 4.5) are between one and two orders of magnitude below UCTE average emissions of fossil chains. Among renewable sources, hydro and wind have better performance than PV and wood cogeneration.

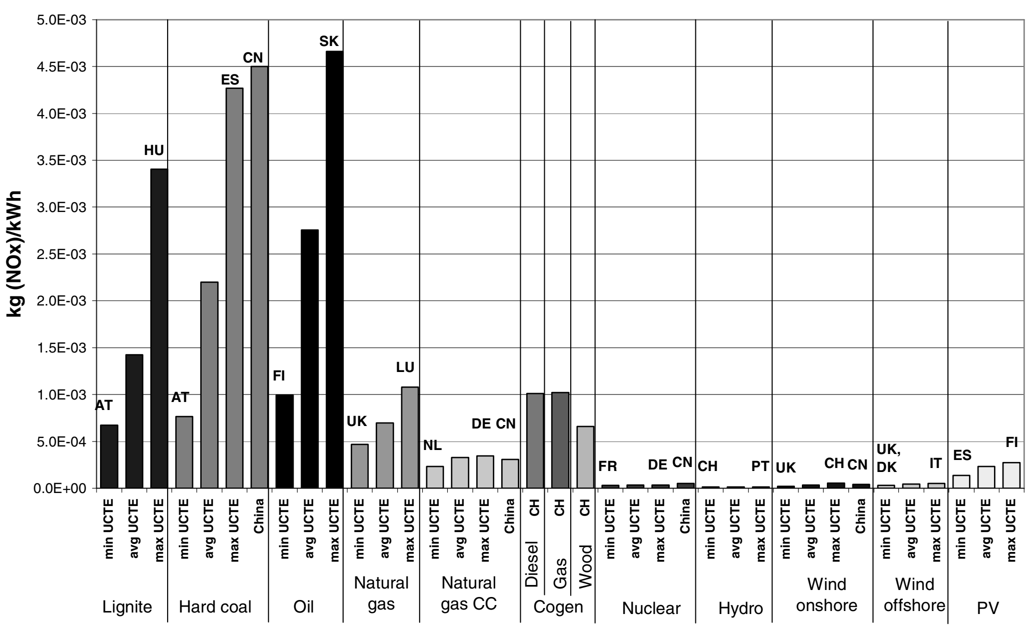
Figure 4.5. SO_2 emissions of selected energy chains



NO_x emissions

Oil has the highest NO_x emissions among all analysed energy chains (see Figure 4.6). UCTE average is about 2.8 g/kWh; differences between country averages are significant.

Figure 4.6 NO_x emissions of selected energy chains



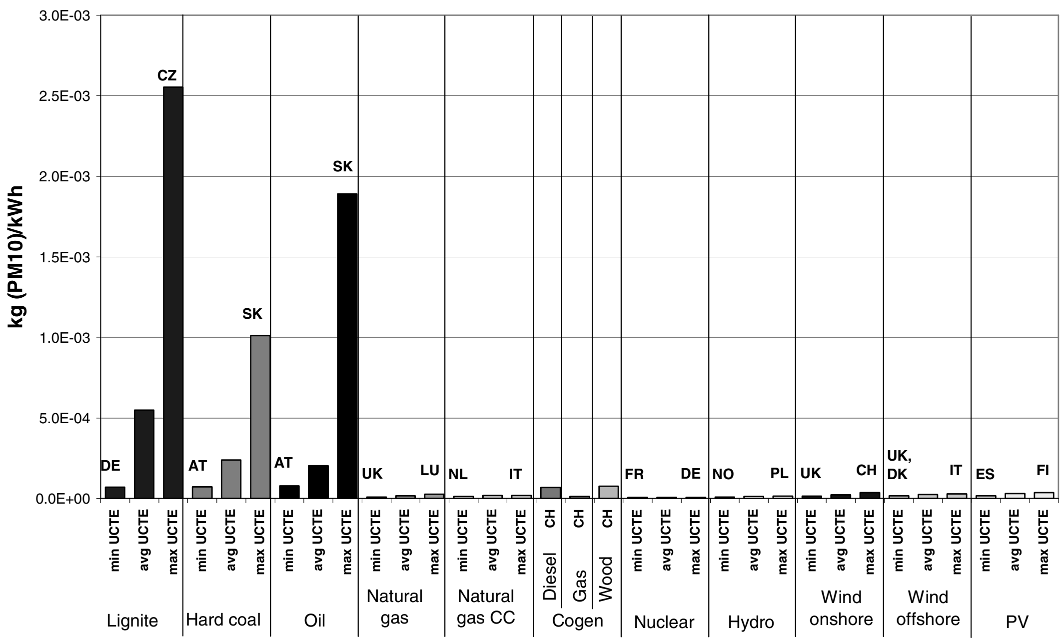
NO_x emissions from the hard coal chain are only slightly lower with a UCTE average of about 2.2 g/kWh. Similar to the oil chain, differences between UCTE country averages are remarkable. The Chinese hard coal chain performs slightly worse than the worst UCTE countries. Due to lack of long transport distances, which are responsible for an important part of NO_x emissions in case of oil and hard coal chains, NO_x emissions of lignite chains are in general lower. UCTE average is below 1.5 g/kWh.

The natural gas chain has the lowest NO_x emissions among fossil systems. UCTE average is about 0.7 g/kWh for gas-fired plants and about 0.3 g/kWh for gas combined cycle plants (CCGT). NO_x emissions of nuclear, hydro and wind technologies are between one and two orders of magnitude below emissions of fossil chains. Emissions from PV are above this level and roughly comparable to CCGT plants. Wood cogeneration reaches emission levels comparable to well performing conventional fossil chains.

PM_{10} emissions

PM_{10} are a significant air pollutant responsible for health damages, e.g., lung disease. Direct power plant PM_{10} releases which depend on pollution control measures, dominate the fossil chains, but fuel supply contributes also importantly to total PM_{10} releases. The lignite chain with a UCTE average of about 0.5 g/kWh shows the worst performance (see Figure 4.7). Hard coal and oil UCTE averages are in the order of 0.25 g/kWh. Country averages differ considerably for these three fuels; even a factor of 25 between the best and the worst country is possible.

Figure 4.7 PM_{10} releases of selected energy chains

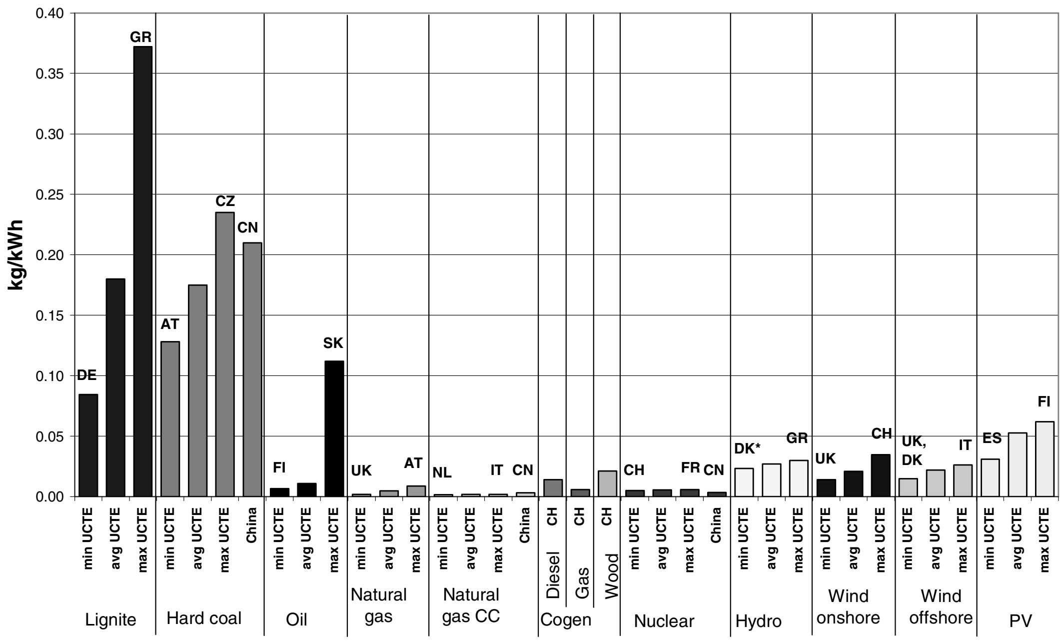


PM_{10} releases from the natural gas, nuclear and renewable chains, except wood cogeneration, are between one and two orders of magnitude below UCTE average emissions of fossil chains. Among renewable sources, hydro has a better performance than wind and PV, which are in the same range, and wood cogeneration, which is comparable to the best performing coal and oil chains.

4.3.3 Solid waste

The production of non-radioactive waste by different energy chains is illustrated in Figure 4.8. It should be noted that various waste types with different characteristics are aggregated. This includes many single species disposed of, as or in: hazardous waste, incineration, inert material landfill, land farming, municipal incineration, lignite ash, residual material landfill, sanitary landfill, underground deposits. The masses as such are not an indication of the risks associated with the wastes. No weighting is applied here to account for the potential harm of each waste type.

Figure 4.8 Production of non-radioactive waste for selected energy chains

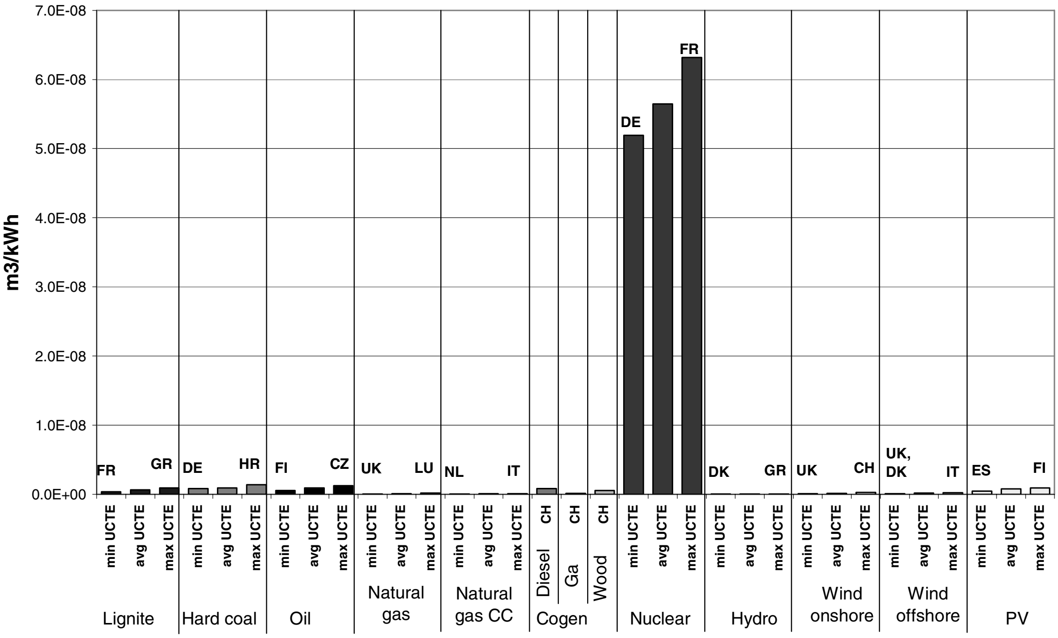


Hard coal and lignite chains with UCTE averages of about 0.18 kg/kWh produce the highest amounts of non radioactive waste. Within the lignite chain, ashes from power plant operation are dominant; the main part in hard coal chains originates in tailings from mining since an important fraction of hard coal ash is recycled, e.g., into concrete and highway pavement. The performance of the Chinese hard coal chain is between UCTE average and the worst UCTE performer.

Natural gas chains, particularly combined cycle gas plants, and nuclear chains produce the lowest amounts of non-radioactive waste. Waste amounts of wood cogeneration, hydro and wind are about one order of magnitude higher and solar photovoltaic performs slightly worse than those chains.

Only the nuclear chain produces significant amounts of radioactive waste directly; for all other chains some radioactive waste is produced indirectly predominantly owing to nuclear electricity inputs to the chain, although coal ash often contains significant radioactivity. Figure 4.9 shows the volumes occupied by low, middle, and high level waste, including containment in underground geological repositories. Results for single countries are not much different from UCTE average. Due to differences in modelling of the chains, Chinese results could not be included in this comparison.

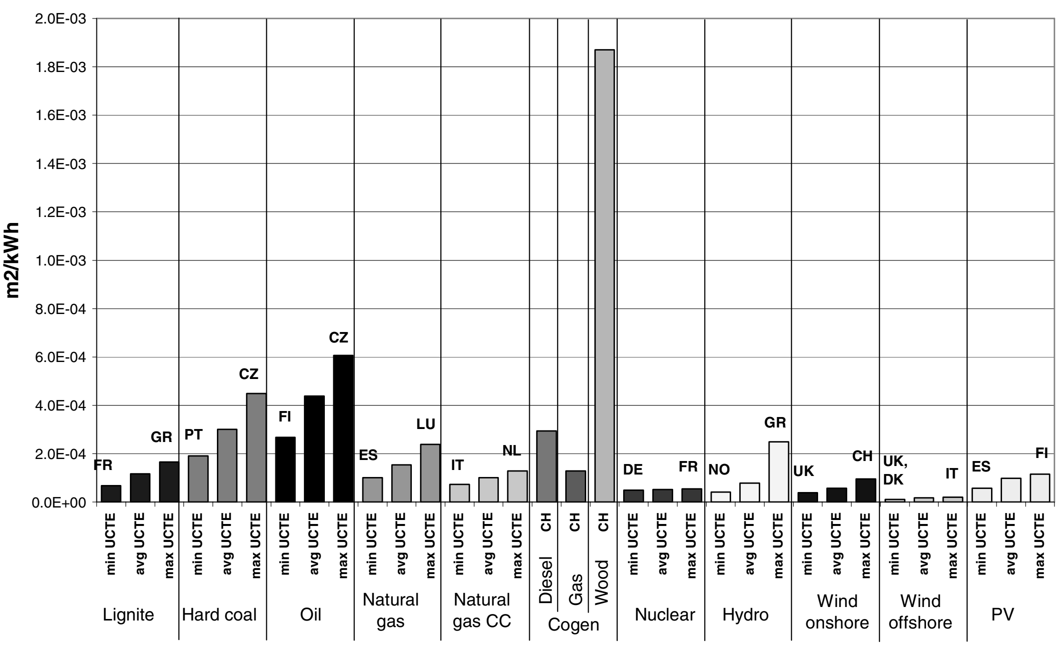
Figure 4.9 Production of radioactive waste for selected energy chains



4.3.4 Land use

Land use shown in Figure 4.10, measured in m^2/kWh, refers to all surfaces which are transformed from the original into a different state as a consequence of human activities within the energy chains.

Figure 4.10 Land use of selected energy chains



Due to forestry for wood harvesting, wood cogeneration requires by far the most extensive land use. Next come oil and hard coal chains. Exploitation and production of oil as well as hard coal mining require substantial areas. Natural gas, lignite, and PV show similar results in the middle of the range. Country specific differences in the averages of fossil chains originate mostly in different efficiencies of the power plants and in different origins of the fuels. Nuclear, hydro and onshore wind perform well; the lowest value is for offshore wind.

4.3.5 Accident risks

This section builds primarily on ENSAD (Energy-related Severe Accident Database), a comprehensive database on severe accidents with emphasis on the energy sector, established by PSI (Hirschberg *et al.*, 1998) and successively extended in the last years. The extensions were enabled through projects supported by the electrical industry (Hirschberg *et al.*, 2003a; Hirschberg *et al.*, 2003b), by the European Commission (Burgherr *et al.*, 2004) and by the Swiss gas industry (Burgherr and Hirschberg, 2005). The database allows comprehensive analyses of accident risks, which are not limited to power plants but cover full energy chains, including exploration, extraction, processing, storage, transport and waste management. The experience-based results are supplemented by use of Probabilistic Safety Assessment (PSA) when evaluating nuclear energy.

ENSAD contains currently 18 400 accidents of which about 89% occurred in the period 1969-2000. Man-made accidents (12 943) represent 70.3% of the total, whereas natural disasters (5 457) represent less than 30%. Energy-related accidents amount to 6 404, representing 34.8%, of the total and 49.5% of man-made accidents. Among the energy-related accidents 3 117 (48.7%) are severe[5] of which 2 078 have 5 or more fatalities. Non-energy-related accidents and natural disasters are of secondary priority within ENSAD. Consequently, the corresponding data are generally less complete and of lower quality than the ones provided for the energy-related accidents.

Table 4.13 Summary of ENSAD records for accidents with at least five fatalities

Energy chain	OECD		EU15		non-OECD	
	Accidents	*Fatalities*	*Accidents*	*Fatalities*	*Accidents*	*Fatalities*
Coal	75	2 259	11	234	102 1 044 [a]	4 831 18 017 [a]
Oil	165	3 789	58	1 141	232	16 494
Natural gas	80	978	24	229	45	1 000
LPG	59	1 905	19	515	46	2 016
Hydro	1	14	0	0	10	29 924 [b]

a. First line without China, second line with China.

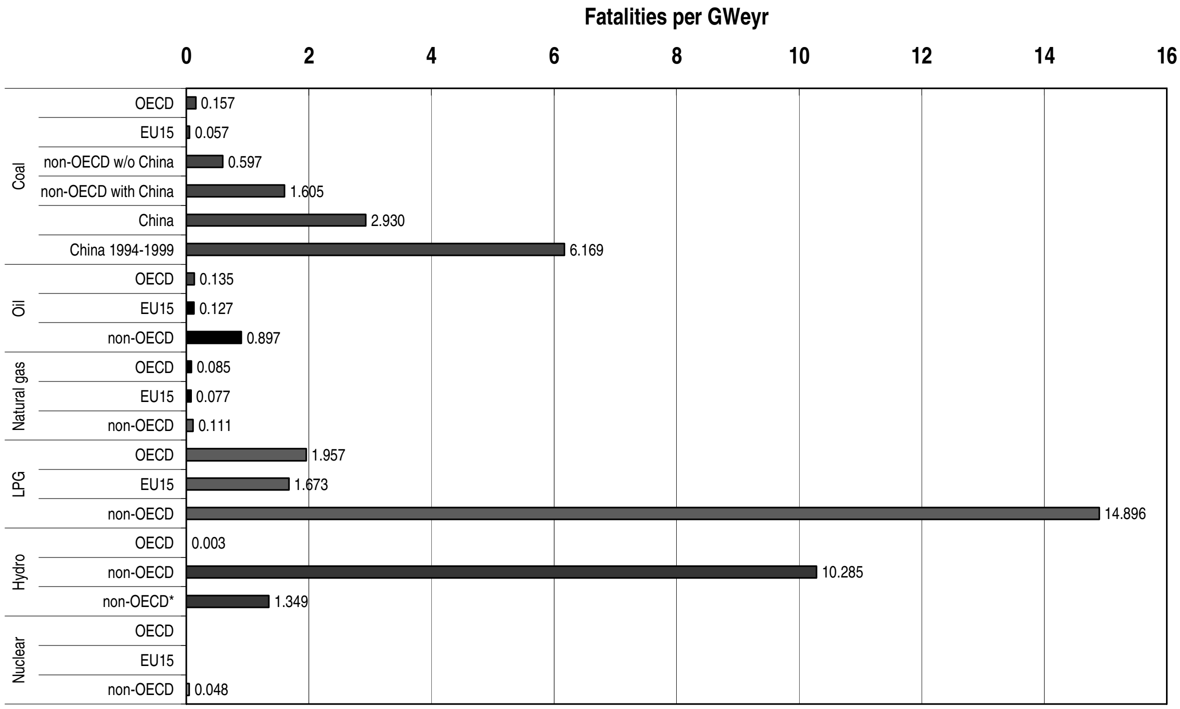
b. Banqiao and Shimantan dam failures together caused 26 000 fatalities.

A partial overview of statistical information on severe accidents in various energy chains is provided in Table 4.13. Evaluations and analyses are most detailed for fatalities because information on other indicators such as injured, evacuees or economic costs was not available to a similar level of completeness. However, aggregated indicators could still reveal some general trends.

5. Based on the literature there is not single definition of severe accident. The ENSAD uses seven criteria to define a severe accident: at least 5 fatalities, or at least 10 injured; or at least 200 evacuees; or extensive ban on consumption of food; or releases of hydrocarbons exceeding 10 000 tonnes; or enforce clean-up of land and water over an area of at least 25 km^2; or economic loss of at least 5 million USD of 2000.

Based on the ENSAD, selected aggregated accident indicators have been generated and compared. The approach used accounts for contributions from all stages of the energy chains that were analysed. The comparison of different energy chains was based on normalized indicators combining consequences (e.g., number of fatalities) and output of the chains (e.g., electricity generation), and also on the estimated accident-related external costs for selected technologies. Figure 4.11 shows results in terms of fatalities per $GW_{e.}$year, differentiating between OECD, EU-15, non-OECD countries and when available China.

Figure 4.11 Severe accident indicators for OECD and non-OECD countries for the period 1969-2000



* Hydro with and without Banqiao and Shimantan dam failures.

The statistical basis of the indicators may differ radically for different energy chains. For example, 1 221 severe accidents with immediate fatalities are accounted for in the indicators for the coal chain and only one for the nuclear chain (Chernobyl). It should be noted that only immediate fatalities were considered in Figure 4.11; latent fatalities, of particular relevance for the nuclear chain, are treated separately (see below). For other chains latent fatalities are not estimated.

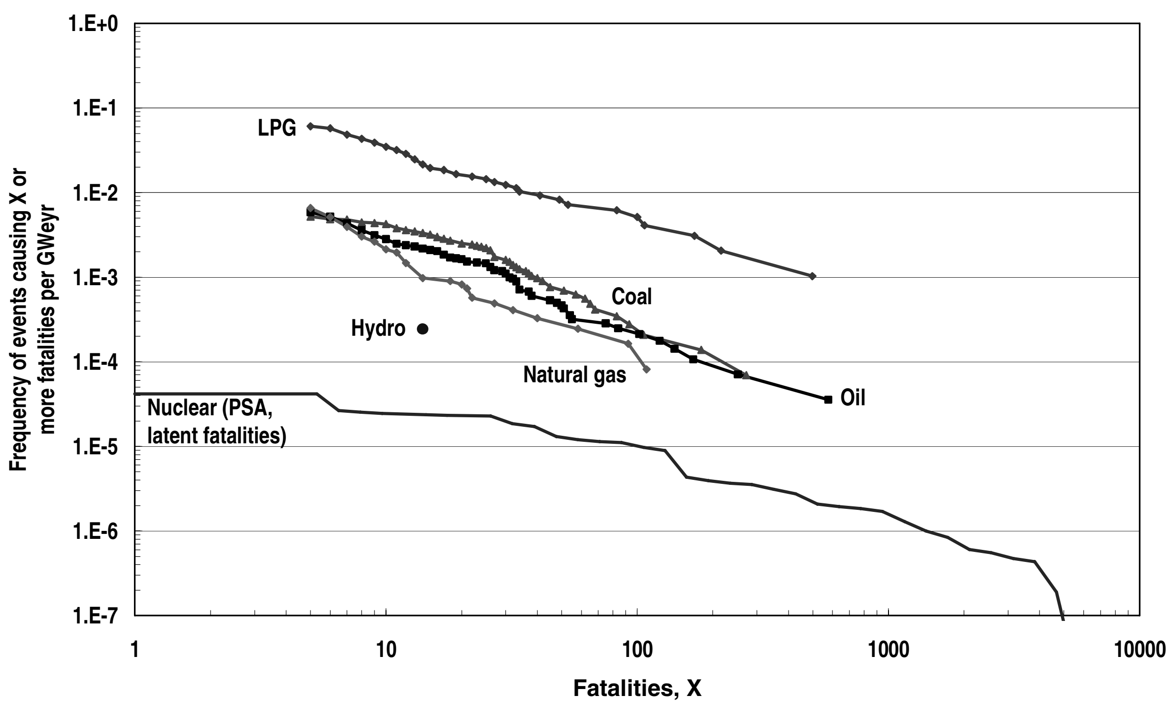
Significant differences exist between the aggregated fatality rates assessed for the various energy carriers. Generally, the immediate fatality rates for all considered energy carriers are significantly higher for the non-OECD countries than for OECD countries. In the case of hydro and nuclear the difference is dramatic. The recent experience with hydro in OECD countries points to very low fatality rates, comparable to the representative PSA-based results obtained for nuclear power plants in Switzerland and in the United States.

Further analyses carried out based on ENSAD for the world-aggregated results (OECD and non-OECD taken together) show that aggregated immediate fatality rates are much higher for the fossil fuel chains than for the fossil-fuelled power plants alone. The highest fatality rates are related to LPG and hydro, followed by coal, oil, natural gas and nuclear.

In the case of nuclear, the estimated latent fatality rate solely associated with the only severe (in terms of immediate fatalities) nuclear accident (Chernobyl), clearly exceeds all the above mentioned immediate fatality rates. In view of the drastic differences in design, operation and emergency procedures of the Chernobyl plant, the Chernobyl-specific results are not relevant for OECD or most non-OECD countries. Given the lack of statistical data, results of state-of-the-art probabilistic safety assessments (PSAs) for western plants are used as the reference values (see Hirschberg *et al.*, 1998 for details) for estimating consequences of severe accidents.

Figure 4.12 shows the frequency-consequence curves for OECD countries. The curves for coal, oil, natural gas, LPG and hydro are based on historical accidents and show immediate fatalities. For the nuclear chain, since there is no historic data, the theoretical curve results from the plant-specific Probabilistic Safety Assessment (PSA) for a Swiss nuclear power plant. This reflects latent fatalities from long-term health damage associated with the release of radioactive materials (Burgherr *et al.*, 2004). The curves reflect the ranking of the various chains but also provide an indication of the chain-specific maximum extent of damage that has or may occur.

Figure 4.12 Comparison of frequency-consequence curves for full energy chains in OECD countries for the period 1969-2000



4.4 Social indicators

The social dimension is the most difficult to quantify and it is no trivial matter even to agree on which aspects can/should be included. There is quite a broad experience with criteria and indicators addressing social conditions in specific countries. Also, social aspects of energy supply in general are easier to address than technology-specific attributes which may be controversial. Currently, criteria and indicators used for characterisation of specific technologies are partially intuitive and partially based on the experiences gained through interactions with stakeholders. There is no consensus on a standard set of such attributes and it is unlikely that a broad agreement will be established in the near future.

Progress with quantification and implementation of social indicators is expected within the ongoing EU Integrated Project NEEDS (http://www.needs-project.org/); this effort is pursued within the Research Stream "Technology Roadmap and Stakeholder Perspectives", coordinated by the Paul Scherrer Institute. Examples of criteria of interest include: political stability, socially acceptable developments, impacts on settlements and landscape quality, social components of economic impacts and social components of risks including physical security. Some of the indicators are relatively straightforward, for example direct employment effects; others are not easily defined and may be very cumbersome to quantify. Possibly, partial results may become available in 2007. The following sections provide a few examples of social indicators quantified in the past.

4.4.1 Employment

The differences between the various energy chains in terms of job creation may be significant but their overall influence on the level of employment is of secondary importance as compared with other factors affecting the national or global economy. Promotion of work-intensive options, such as solar PV, may create new work opportunities within some sectors of economy but reduce employment globally because other sectors may lose their competitiveness due to higher energy costs and prices as labour intensive options will be more expensive.

Studies typically indicate that programmes strongly promoting renewable energy sources lead to a slight increase of gross domestic product (GDP) as well as a small increase in the number of job opportunities. However, job creations are mainly local or regional with employment increases relatively modest in absolute terms. Large centralised options, particularly nuclear and to some extent large hydro, lead to regional stimulation of employment though the effects are mostly concentrated during the construction phase. The job quality offered by various energy chains may differ depending of the technologies relied upon.

The estimates of direct technology-specific job opportunities for Germany in (Hirschberg *et al.*, 2004a) show that nuclear and lignite have the lowest values with wind being about twice as work intensive. Natural gas, coal and hydro are in the middle range while solar photovoltaic is by far the most work intensive (40 times more than nuclear). In contrast to fossil energy sources, where fuel provision is the dominant contributor to work opportunities, nuclear and renewable sources offer jobs mainly in plant construction including, in the case of renewable sources, manufacturing of components.

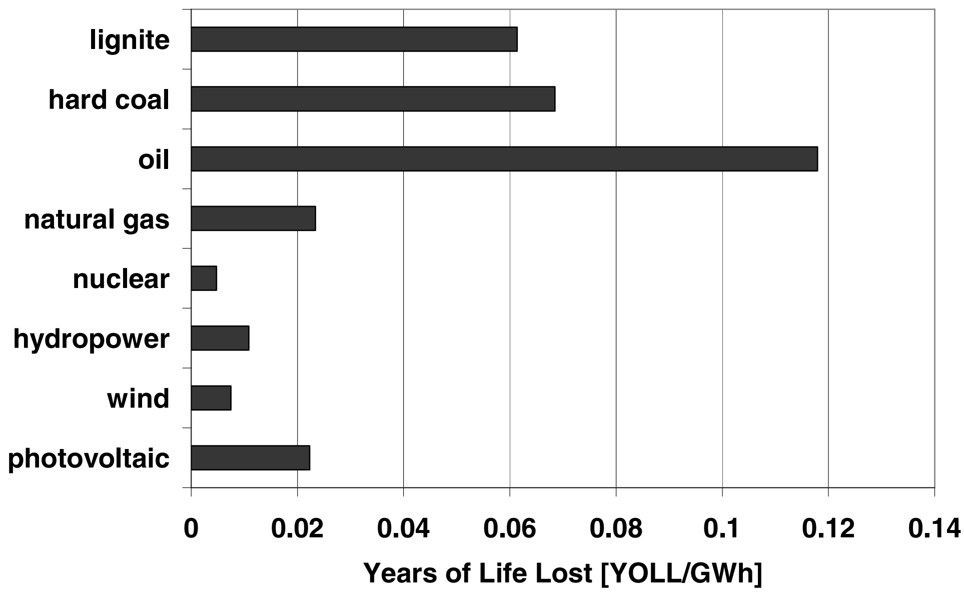
4.4.2 Human health impacts from normal operation

Human health impacts due to normal operation may be represented by "mortality", defined by reduced life expectancy calculated in terms of Years of Life Lost or "YOLL". Mortality is the major contributor to total external costs (see Chapter 5) but various morbidity effects add to the total health impacts. Morbidity effects can be assessed but they are difficult to aggregate in a fully objective manner because their end results, i.e., years of life lost, and their values, estimated in monetary terms, vary dramatically according to local conditions, e.g., population density, lifetime expectancy, medical support available to affected population.

The basis for the assessment of health effects is the methodology developed within the European ExternE project initiated in the mid-1990s and refined in successive phases (see for example Friedrich *et al.*, 2004). The methodology was updated in 2005 (Bickel and Friedrich, 2005).

Figure 4.13 shows as an example mortality resulting from the emissions of major pollutants, specific for the current German energy chains (Hirschberg *et al.*, 2004a). The emissions are consistent with the German emission inventories shown earlier in some of the figures in this chapter; also radioactive emissions have been taken into account.

Figure 4.13 Mortality associated with normal operation of German energy chains in the year 2000



Nuclear, wind and hydro have very low mortality due to normal operation. Mortality for the natural gas and the solar PV chains are comparable. The fossil systems other than natural gas exhibit much higher impacts than the other options. It is worthwhile noting that for all chains mortality due to accidents is practically negligible as compared with the corresponding effects of normal operation.

Mortality due to air pollution strongly depends on location which determines the number of persons affected by the emissions and technology which determines the amount of emissions. The number of YOLL per tonne of SO_2 emitted in China is on average almost seven times higher than the average for the European Union mainly because of the drastic difference in population densities around power plants. Taking the current conventional coal plant in the largest city of the densely populated Shandong province and the associated rest of the coal chain, use of low sulphur coal reduces the YOLL per GWh by a factor of 1.7; implementation of scrubbers with 95% SO_2 removal efficiency by a factor of 4.4; replacement by an advanced coal plant (AFBC) by a factor of 8.0; replacement by IGCC by a factor of about 13; replacement by natural gas CCGT plant by a factor of about 52 and by a nuclear power plant by a factor of 63 (Hirschberg *et al.*, 2003c and 2004b).

Mortality effects due to anthropogenic emissions within EU-25 in 1998 correspond to about 2.2 million YOLL, of which 22% are due to electricity generation, cogeneration and district heating plants (Friedrich et al., 2004). The results for China in 1998 are (Hirschberg *et al.*, 2003c and 2004b): 9.1 million YOLL with a 23% share from the power sector.

4.4.3 Waste confinement

The *necessary confinement time* of the most hazardous waste may be included among social indicators. It can be seen as a complementary attribute to the mass, implicitly encompassing the potential harm from hazardous waste. However, the notion is subjective and there is no consensus on its definition.

For example, waste from the coal and solar PV chains involve toxic metals such as arsenic, cadmium and lead which remain indefinitely potentially harmful. Therefore, in theory, there are no temporal boundaries for the estimation of the corresponding health impacts. However, current norms and regulation do not reflect the necessity for their long-term stewardship.

On the other hand, the necessity of extremely long confinement times for long-life high-level radioactive waste raises public concerns. This leads to acceptance goals formulated by regulators that the annual individual doses should at no point of time exceed levels that are very small compared to those due to natural radiation and man-made sources.[6]

Like for other social indicators, more research is needed to identify relevant criteria taking into account inter-generational equity and distribution of risks and benefits. As a proxy, the use of risk aversion coefficients could help decision making.

4.4.4 Proliferation risks

Proliferation resistance and physical protection of facilities and materials used in the nuclear energy chain for electricity generation are a major concern for policy makers and civil society. This concern is unique to the nuclear chain and has motivated the implementation of intrinsic and extrinsic measures to avoid that sensitive nuclear materials, e.g., highly enriched uranium or plutonium, or technologies, e.g., enrichment, developed for civilian purposes could be diverted for military and/or terrorist use. Enhancing proliferation resistance and physical protection are essential goals for advanced nuclear energy systems.

The most important instrument for discouraging diversion and misuse of nuclear materials or technologies is the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) of 1970 that commits 189 countries and carries an explicit commitment by the non-nuclear-weapon States to receive the benefits of peaceful nuclear technology in return to agreeing to forego nuclear weapons. The compliance with those commitments is verified by the International Atomic Energy Agency (IAEA) through its safeguards system. The effectiveness of safeguards controls has been demonstrated by years of experience, although no system can ensure absolute prevention. Safeguards controls have been strengthened recently to cover detection of clandestine diversion and/or production of sensitive materials.

The international safeguards regime aiming at preventing proliferation of nuclear weapons creates some constraints on nuclear fuel markets associated with declaration, controls and verification of the peaceful uses of nuclear materials. The framework implemented under the auspices of the IAEA does provide, however, a well defined set of stable rules. Within this framework, complemented by national laws and regulations, nuclear materials for peaceful uses can be traded freely between countries and operators.

6. As an example, the limiting dose according to the Swiss requirements is 0.1 mSv; for reference, the total average yearly exposure in Switzerland due to natural and man-made sources is about 4 mSv.

The proliferation and terrorist threats, however, are linked with the political context, international security and the perceived strategic role of nuclear weapons. Improving international relations to the point where States and political groups will not look to nuclear weapons as instruments for defending their territories or convictions is the policy goal that would render concerns about proliferation resistance and physical protection obsolete.

In the meantime, advanced nuclear energy systems incorporate intrinsic measures to enhance proliferation resistance and physical protection. Such measures aim at impeding the diversion or undeclared production of nuclear materials or misuse of technology and the theft of materials suitable for nuclear explosives or radioactivity dispersal devices as well as the sabotage of facilities.

4.4.5 Risk aversion

The need to reflect explicitly risk aversion in the assessment of consequences from severe accidents has been recognised in most recent studies on the assessment of energy systems. This necessity results from the discrepancy between the social acceptability of a risk and the estimated value of the damages caused by a severe accident to humans and the environment. When assessment is made using external costs, risk aversion can be integrated within the evaluation of the external cost of a severe accident through a risk coefficient (see Chapter 5). In that approach, valuation of risk aversion strongly depends on stakeholder preferences.

Within the framework described in Chapter 3, the risk aversion indicator provided in Table 3.1 is the "Maximum credible number of fatalities per accident". It can be used as a surrogate for risk aversion towards low-probability high-consequence accidents (Hirschberg *et al.*, 2004a). The indicator values may be established using frequency-consequence curves shown in Figure 4.12. However, the maximum credible consequences depend not only on the technology but also on the location and many parameters such as population density, wind direction and speed, and climate conditions have significant impacts on them.

For fossil fuel chains, historical frequency-consequence curves for non-OECD countries (Burgherr *et al.*, 2004) can be used rather than those for OECD countries to obtain the maximum credible values. For nuclear systems, the results of Level III PSA are most appropriate to provide a maximum. In the case of hydro, adjustments of generic experience data may be necessary depending on the application case (population down-stream). In densely populated areas in OECD the extent of consequences of hypothetical extreme accidents is largest in the case of nuclear, followed by hydro, oil, coal[7] and gas. Accidents in renewable energy chains are quite limited in terms of consequences.

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Chapter 5

EXTERNAL COSTS AND MULTI-CRITERIA DECISION ANALYSIS

External cost evaluation and multi-criteria decision analysis (MCDA) are decision aiding tools aiming at integration and/or aggregation of indicators to provide synthesised messages to decision makers. Both approaches have advantages and drawbacks and may be used alternatively or together, when possible, depending on the scope and objectives of the decisions to be taken.

5.1 External costs

In order to understand the relevance of externalities in the decision-making process, it is important to recognise what is an externality and to assess the limits of external cost valuation. An externality exists when some negative or positive impact is generated by an economic activity and imposed on third parties without being priced by the market (Pearce, 2002). If the inventory of externalities could be exhaustive and if their value could be estimated in an accurate and reliable manner, the internalisation of external costs would lead to the best choice. Unfortunately, those two conditions are seldom met and this sets the limits of relevance of external costs in the decision-making process.

However, robust approaches have been developed, refined and implemented during the last decade to identify externalities and to value them. The "impact pathway approach", established and implemented in the ExternE Project of the European Commission (EC, 1995a), is widely accepted as the state-of-the-art methodology for the assessment of external costs. During recent years, major efforts have been made to improve the methodological basis for external cost assessment, with emphasis on fossil energy chains, and health and environmental burdens (Friedrich *et al.*, 2004; Rabl *et al.*, 2005; Bickel and Friedrich, 2005).

It should be noted that the applications available for nuclear energy chains (see for example EC, 1995b) have not been refined and updated to the same extent as for fossil fuel chains. Consequently, the existing studies show some deficits with regard to the accounting for life cycle effects, treatment of severe accidents in accordance with state-of-the-art probabilistic safety assessments (PSAs) and representation of technological and structural improvements in the nuclear technology. Appropriate, state-of-the-art treatment of these issues is not expected to significantly increase the currently low estimates of external costs but would improve the robustness of the results.

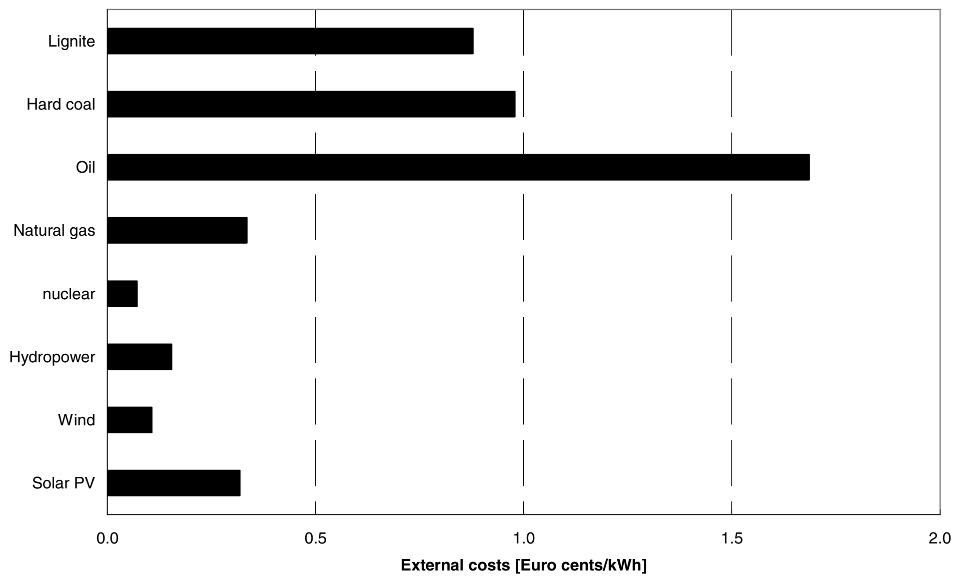
5.1.1 External costs resulting from environmental burdens

The focus of externality assessments has been environmental burdens, covering impact assessment through the impact pathway and LCA approaches, and valuation of damages through various approaches, e.g., willingness to pay or damage cost estimates. In this framework, estimates of external costs are dominated by health effects (mortality and morbidity) and the highly uncertain damage costs due to global warming.

A few results are presented in some detail below but valuable information on other energy chains and country specific cases may be found in many other studies. For example, estimates of externalities of energy in different countries of Europe are provided in Volume 10 of the ExternE study series (EC, 1999). Also, detailed results of the implementation of the ExternE methodology in Sweden are provided in a detailed report issued by the Stockholm Environmental Institute (Nilsson and Gullberg, 1998).

The main results of the study carried out by PSI on German electricity systems (Hirschberg *et al.*, 2004) are presented in Figure 5.1 showing external costs for different options, not taking into account the cost of global warming. The ranking of options not surprisingly is the same as illustrated in Figure 4.13 showing mortality/years of life lost per unit of electricity generated.

Figure 5.1 Average external costs of electricity generation in Germany



In a recent study carried out in the framework of the ExternE project/policy applications (Dones *et al.*, 2005), average external costs for current and advanced electricity systems have been estimated as well contributions to those costs of the individual pollutants. The results were obtained by combining the most detailed inventories in the LCA ecoinvent database (www.ecoinvent.ch), extended to selected new technologies, with damage factors based on the impact-pathway approach. The ecoinvent database, developed and implemented by the Swiss Centre for Life Cycle Inventories, includes energy systems, materials and metals, waste treatment and disposal, transport systems, chemicals, and agricultural products. About 2 750 processes, reflecting European conditions around the year 2000, have been considered, of which about half are energy-related. The cumulative environmental burdens calculated for the processes reflect all interactions within the economic system modelled in ecoinvent. These calculated inventories do not contain explicit information on the location of the contributing emission sources. Therefore, the external costs are calculated based on damage factors for emissions occurring in an average location in Europe (EU15).

Three new power technologies were investigated. For the coal chain, the pressurised fluidised bed combustion (PFBC) technology, expected to be commercially available by 2010, was assessed. For hydrocarbons, the already available CCGT technology was evaluated. For nuclear, the system analysed is based on an advanced light water reactor (ALWR) with better net efficiency (around 35% or more) than current LWRs, longer lifetime (60 years against 40 years), reduced material intensity for construction of the power plant, and higher fuel burn-up. Furthermore, only energy-efficient enrichment processes, such as gaseous centrifugation, were assumed. For solar photovoltaic substantial reductions of the inventories of materials required were assumed.

Figure 5.2 External costs of electricity systems

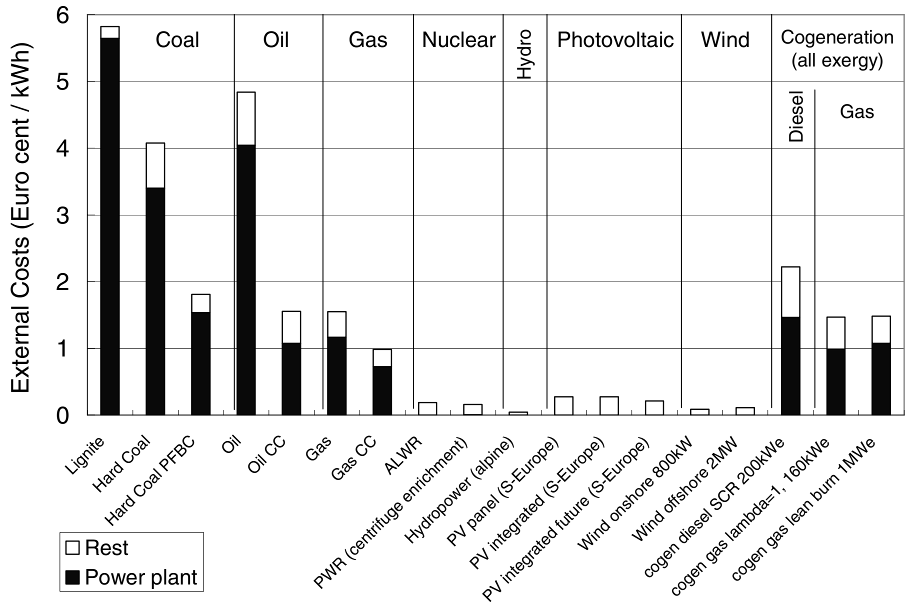


Figure 5.3 Contributions of different burdens to external costs of electricity systems

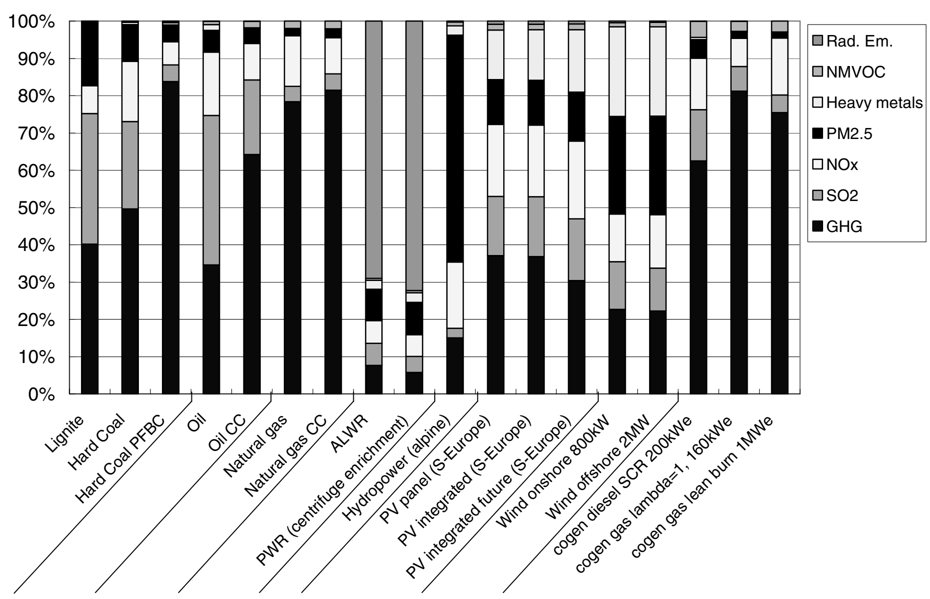


Figure 5.2 provides an overview of external costs obtained for the various electricity systems considered, showing the respective contributions from the power plant and from the rest of the chain. The relative contributions of the various burdens to total external costs are shown in Figure 5.3.

Among the electricity systems considered in the study, renewable sources and nuclear exhibit the lowest external costs, while those for fossil technologies are substantial in comparison with internalised electricity production costs. External costs for advanced fossil systems are strongly reduced as compared with those of current systems and are dominated by estimated costs of global warming. Sensitivity analyses, addressing major uncertainties in impacts and monetary evaluation, show that the ranking of technologies remains quite robust in spite of the large uncertainties involved.

The low external costs of nuclear chains result from a combination of factors. Occupational health effects are largely eliminated and internalised in generation costs through radiation protection norms and regulation. Also, within OECD countries, decommissioning and waste management costs are internalised already through regulation. While there are some uncertainties on the real costs of final disposal of high-level radioactive waste (HLW), which can be fully resolved only by full-scale demonstration of HLW repositories, the uncertainties in quantification of many non-nuclear externalities, such as GHG damage costs, are generally much larger.

5.1.2 External costs of severe accidents

Estimating external costs of severe accidents is more controversial than estimating those resulting from air pollution, mainly owing to the social dimension of the damages they cause and to risk aversion which affects significantly their impact as perceived by civil society. Regarding the specific case of severe nuclear accident the study carried out on the French nuclear chain in the context of the ExternE project suggested a multiplying factor of around 20 to reflect risk aversion in the external cost estimate (see Schieber and Schneider in OECD, 2002).

The ExternE/NewExt Project of the EU (Burgherr *et al.*, 2004) investigated external costs of major accidents in non-nuclear fuel chains. Key results from that study are summarised in Table 5.1 which shows the damage and external costs for immediate fatalities associated with sample energy systems, including fuel cycles, obtained on the basis of historical experience with accidents in OECD and non-OECD countries. The damage costs correspond to the total cost of major accident consequences in each case while the external costs correspond to the part of the damage costs not internalised by producers and, thereby, not supported directly by the consumer but rather society as a whole.

The costs were estimated taking into account severe accidents with at least five immediate fatalities and assuming a central value of 1.045 million €[1] for "Statistical Life". For the nuclear chain, the costs reported in Table 5.1 are based on the Chernobyl accident for non-OECD countries and on PSA for a Swiss plant for OECD countries.

The very low expected value of damages due to hypothetical severe nuclear accidents is a consequence of the safety measures implemented. Although it is difficult to estimate precisely the costs of safety measures integrated in the design of reactors and other nuclear facilities, those costs are undoubtedly significant and contribute to the capital intensity of nuclear energy. The extensive and frequently costly post Three Mile Island and post Chernobyl back-fitting required for bringing down

1. For more in depth discussion on value of statistical life and year of life lost, see (Pearce, in OECD 2002).

the core damage frequencies to the low levels imposed by safety regulations are going a long way towards internalisation of severe accident costs.

Table 5.1 Full chain damage costs and external costs of severe accidents

Energy chains	Reference countries	Damage costs €2002/MWh			External costs €2002/MWh		
		Occupational	Public	Total	Occupational	Public	Total
Coal	*OECD*	1.7E-3	1.2E-5	1.7E-3	3.4E-4	6.1E-6	3.5E-4
	non-OECD w/o China	6.5E-3	4.3E-5	6.5E-3	3.2E-3	3.5E-5	3.3E-3
	China (1994-1999)	1.2E-2	ng[3]	1.2E-2	6.1E-3	ng[3]	6.1E-3
Oil	*OECD*	9.9E-4	9.0E-4	1.9E-3	2.0E-4	4.5E-4	6.5E-4
	non-OECD	1.8E-3	1.1E-2	1.3E-2	9.1E-4	8.7E-3	9.6E-3
Natural gas	*OECD*	2.2E-4	4.4E-4	6.6E-4	4.5E-5	2.2E-4	2.6E-4
	non-OECD	3.3E-4	5.9E-4	9.2E-4	1.6E-4	4.7E-4	6.3E-4
Hydro	*OECD*	ng[3]	4.1E-5	4.1E-5	ng[3]	2.0E-5	2.0E-5
	non-OECD	ng[3]	1.2E-1	1.2E-1	ng[3]	9.8E-2	9.8E-2
	non-OECD w/o Banqiao/Shimantan	ng[3]	1.6E-2	1.6E-2	ng[3]	1.3E-2	1.3E-2
Nuclear	*OECD*[1]	ng[3]	ng[3]	ng[3]	ng[3]	ng[3]	ng[3]
	non-OECD[2]	5.7E-4	ng[3]	5.7E-4	2.9E-4	ng[3]	2.9E-4

1. Based on PSA for a Swiss plant.
2. Based on the Chernobyl accident.
3. ng = negligible.

The assessed costs resulting from injuries and evacuations are generally much less significant than those associated with fatalities but their evaluation is based on a less-complete statistical data base. The central estimate of oil spill damage costs is 3.7E-3 €2002/MWh for OECD and 5.5E-3 €2002/MWh for non-OECD, with the maximum estimates, shown in Table 5.1, one order of magnitude higher. Other types of economic damages due to accidents were assessed and expressed in terms of damage costs but the basis is too heterogeneous to allow a reasonably consistent comparison. Globally, based on the results from studies carried out so far, external costs associated with severe accidents are quite insignificant when compared to the external costs of air pollution.

In an earlier study (Hirschberg *et al.*, 1998) the accident damage costs based on PSA for a Swiss nuclear power plant were estimated and the results showed that they were dominated by the costs of latent fatalities which are not taken into account in Table 5.1. In that study the mean value – including damage costs of non-health effects – was assessed at 1.2E-3 USD/MWh, with 5^{th} and 95^{th} percentiles at 1.0E-4 and 3.8E-3 USD/MWh.

5.1.3 Other external costs

Externalities not related to environmental and health impacts have not been investigated extensively and are seldom valued. However, some non-environmental externalities are potentially important, in particular for the nuclear chain. They include costs and benefits associated with security of supply, liability not covered by insurance, R&D expenses financed by governments, resource depletion and proliferation risk.

Valuing security of supply likely would benefit nuclear and renewable energy sources, but as noted above there is no consensus on the cost of insecurity or on the willingness to pay of civil society to ensure security of supply.

Another way to quantify the value of security of energy supply is to consider it as an externality and apply the methods used for valuing other externalities such as environmental impacts. Traditionally, environmental externalities are valued either through damage cost estimates or through the "willingness to pay" for avoiding those damages. Both approaches have proven difficult to apply to security/insecurity of supply and published literature on the subject matter remains scarce.

Considering energy system R&D costs covered by governments as external costs of energy chains is debatable. Taking into account the role of governments in education, training and infrastructure building, it is legitimate to expect them to pay for a significant part of basic R&D devoted to advanced systems. Moreover, in many cases, supporting R&D on advanced energy systems is integrated in national energy policy aiming at environmental protection and/or security of supply.

Resource depletion is a very important external cost closely linked with sustainable development and the concept of maintaining assets. However, there is no consensus on how to represent natural resource exhaustion as an externality. Quantifying the corresponding external costs may affect the ranking of options as fossil fuels likely would have much higher external costs in this regard than renewable sources and nuclear.

As shown above by results from published studies, per unit of electricity generated, the contribution of severe accidents to external costs is very small and smaller for nuclear than for the other major energy chains. Accident liability is partially internalised for nuclear energy in accordance with existing legislation, as opposed to large hydro, which lacks the corresponding insurance, and the non-internalised externality for nuclear accident is quite insignificant (Schneider and Zweifel, 2004). Nevertheless, it might be worthwhile to consider the feasibility of innovative insurance schemes that could take care also of this politically sensitive nuclear externality.

5.2 Internalisation of external costs

The internalisation of external costs is increasingly being recognised as one of the pillars of sustainable energy policies. Though wide-spread internalisation of external costs has not yet been implemented, decisions on specific energy projects and on energy policies are, in a number of countries, directly affected by considerations of external costs. In particular, monetary evaluation of externalities is used to carry out cost-benefit analyses encompassing ecological implications of the supply options considered.

Internalising external costs, i.e., adding external costs to the economic costs reflected in market prices, to compare alternative options would be the perfect approach to decision making in a sustainable development perspective if the evaluation of those costs would be exhaustive, reliable and non-controversial. Although it is far from being true, total costs of specific options, including the best possible evaluation of external costs, may serve as a proxy to an aggregated, relative measure of their sustainability (Voss, 2000).

The total costs of electricity generation, comprising current average internal and external costs, including estimated costs of greenhouse-gas emission damages, are shown in Figure 5.4 for different German-specific energy chains (Hirschberg *et al.*, 2004a). As mentioned before, external costs associated with global warming are highly uncertain and much less robust than the ones due to other air pollutants; therefore, they are shown as a wide range on the figure.

In the case considered, nuclear energy is the cheapest option, followed by natural gas, hard coal, lignite and oil; solar photovoltaic shows by far the highest total costs but not owing to its external costs which are rather low (less than 1% of the total). It should be noted that a major contributing reason for the very low nuclear internal cost is that capital costs of nuclear plants are to a large extent amortised under German conditions. Nevertheless, adding the full capital costs would still result in nuclear having the lowest total cost. Also, the cost of the natural gas system would be much higher in 2006 than when the study was carried out owing to drastic gas price escalation between 2004 and 2006.

Figure 5.4 Total costs of electricity generation in Germany

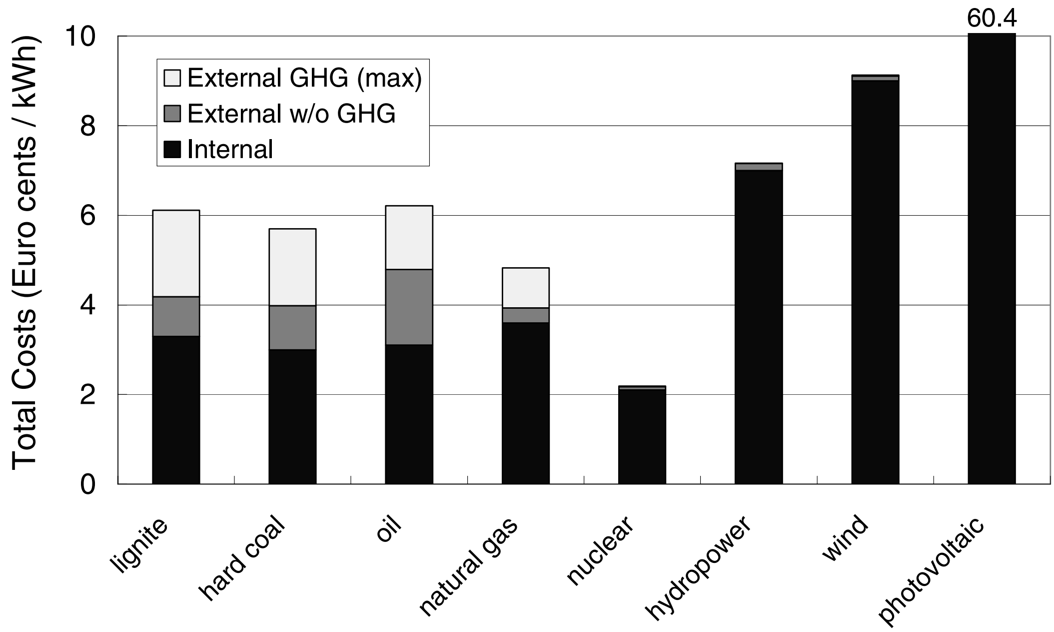


Figure 5.5 Total costs of electricity generation in the Shandong Province of China

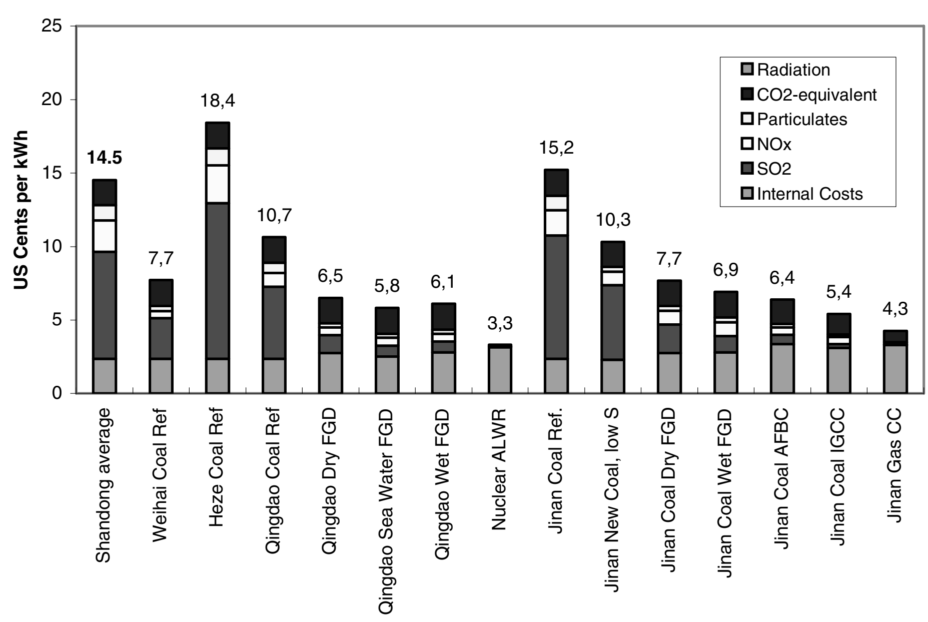


Figure 5.5 shows the total costs, including investment costs, of electricity generation for a variety of existing and considered power plants in the Shandong Province of China (Hirschberg *et al.*, 2003 and 2004b). All results provided in the figure include the contributions from the entire energy chains. For comparison, the average total cost of electricity generation in the Province is given also on the figure. As in the case of Germany, the nuclear chain has lowest total cost. It is interesting to note that conventional coal without scrubbers (FGD), which corresponds to the current situation, has a rather low internal cost but has the highest total cost.

Earlier studies (e.g., Hirschberg *et al.,* 2000) showed that the ranking of technologies based on total costs remains robust also when future/advanced systems are considered in spite of expected internal cost reductions for "new" renewable sources

In ExternE-Pol, the recent EU study on externalities of energy (Rabl *et al.*, 2005), the macroeconomic implications of increases in oil prices are estimated to range between 0.05 and 0.8 m€/kWh. These estimates relate to energy sources which are very sensitive to price changes. The results are numerically low compared to estimates for health externalities. In the same report, a separate component of energy insecurity, i.e. the non-supply of energy that occurs in the case of electricity blackouts, or power cuts, is also covered. The literature estimates the costs of supply disruptions by multiplying the energy not served by a factor called the value of lost load (VOLL). VOLL can be estimated by different methods including econometric models and case studies of interruptions. However, customer surveys are the most prominent, e.g. willingness-to-pay to avoid a supply disruption. These estimates range between 1.8 and 4.6 m€/kWh.

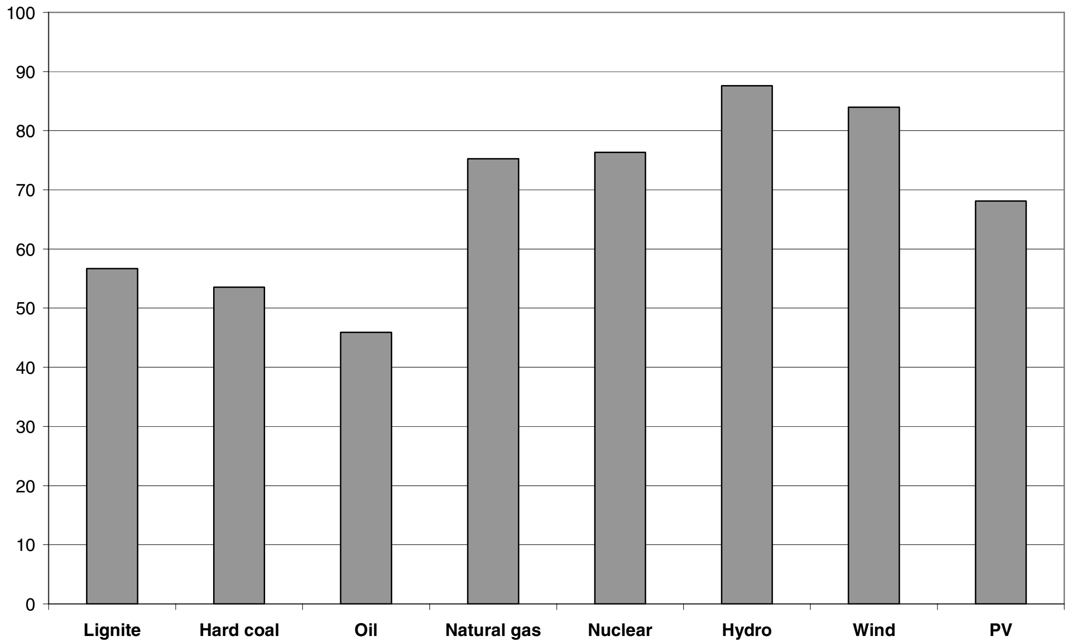
5.3 Multi-criteria decision analysis

Cost-benefit analysis based on (total) costs has great attractions for guiding public policy but the proposition that total cost may serve as an aggregated measure of sustainability is not universally accepted. Monetisation is not accepted by all stakeholders and social factors may be monetised only to a limited extent. Multi-criteria decision analysis (MCDA) can be used as a complementary evaluation approach enabling explicit accounting for social factors, allowing to facilitate controversial energy technology choices and improving the quality and transparency of the debate. The current trend is that MCDA is increasingly used, preferably along with total costs. Some experiences and recent results are addressed below.

As demonstrated in (Hirschberg *et al.*, 2000 and 2004d), MCDA for electricity supply options allows to aggregate the central results of the analyses performed for the economic, environmental and social attributes with preferences of the users. The technology-specific indicators constitute the analytical input to this evaluation. The approach used for the evaluation in the above references employs a simple-weighted, multiple-attribute function; more complex methods have been used by others (Haldi and Pictet, 2003). Individual weights reflect the relative importance of the various evaluation criteria, and are combined with the normalised indicator values (scores). A single overall value is obtained for each alternative by summing the weighted scores for all criteria. Ranking of the available options is then established on the basis of these values. The actual weights applied can be obtained from stakeholder considerations. Alternatively, various weighting schemes can be assigned to accommodate the range of perspectives expressed in the general energy debate. The sensitivity to these choices is investigated.

In the base case, the weights are equally distributed between the three main components (economy, environment and social), thus postulating that sustainability ultimately calls for equal importance being given to each of them. In this case (see Figure 5.6, from Hirschberg *et al.*, 2004a, where high indicator values correspond to good performance and vice versa), top performance is attributed to hydro and wind, followed by nuclear and natural gas. Nuclear is at a lower rank than in the "total cost" case as a result of the inclusion of social criteria. A number of sensitivity cases demonstrate specific patterns in the ranking. Thus, nuclear energy exhibits a top performance when emphasis is put on economic and/or on environmental dimensions (this behaviour in MCDA analysis is consistent with "total cost" analysis).

Figure 5.6 Multi-criteria sensitivity mapping for Germany



It is evident that the MCDA approach enables a more extensive representation of social criteria. Thus, in the case of nuclear power, issues such as the disposal of high-level, long-lived radioactive waste, aversion towards hypothetical severe accidents and proliferation can be included. These issues remain controversial and, depending on the socio-political perspective of those involved, can be of paramount importance. As shown in (Hirschberg *et al.*, 2004d) developments towards a strong limitation of the consequences of hypothetical accidents, along with a radical reduction in waste confinement times may have a highly favourable impact on the MCDA-based ranking of the nuclear chain.

Other weight distributions may be considered to reflect preferences of various stakeholders and policy makers. For example economy-centred, environment-centred and social-centred weighting may be considered. The economy-centred case corresponds to the economic dimension being given a weighting of 80%, while the environmental and social dimensions each have a weighting of 10%; the other cases are defined in an analogous manner. The outcomes will differ depending of the weights adopted and results from various cases could enhance the transparency of the decision making process.

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Chapter 6

ADVANCED NUCLEAR SYSTEMS

6.1 Introduction

The main objective pursued by designers and developers of advanced nuclear systems is to obtain better performance than those of current nuclear and alternative energy systems. Designers, operators of nuclear power plants and facilities and researchers work to enhance the capabilities of new nuclear systems essentially in two frameworks: short- and medium-term improvements based on evolutionary approaches; and long-term improvements relying on innovative concepts.

The reactors being built at present such as the ABWR and the EPR are representative of the evolutionary approach. Their characteristics bring improvements mainly on safety and economic indicators but their enhanced safety features and fuel performance provide also advantages in terms of environmental and social indicators, e.g., reduction of fuel consumption and volumes of waste.

The next generation of systems, commonly called Generation IV (GEN IV) systems has more ambitious goals requiring innovative technologies and extensive research and development. Their development to commercial and industrial stages will take more than a decade but they could be available on the market by 2020-2030.

This chapter reviews the characteristics of evolutionary and innovative systems and provides insights on how they address challenges raised by economic competitiveness, enhanced safety and reliability, improved global efficiency, i.e., reduced fuel consumption and waste, and better proliferation resistance and physical protection.

6.2 Generation III/III+ systems

Based on the current generation of plants and operational experience, a new generation of reactors was developed in the 1990s. The concepts of the Generation III/III+ plants are based on existing technologies; they have mainly evolutionary features but take advantage of technology progress and innovation.

Passive safety designs[1] adopted in GEN III/III+ systems require no active control or human intervention to prevent severe accidents in the case of malfunction, with accident prevention based on gravity, natural convection, electrical or physical resistance or physical temperature limits. Inherently safe features[2] make criticality accidents practically impossible.

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1. *Passive Safety Systems* are designs that react on their own (i.e. without human intervention and without external energy sources) when there is any departure from normal operating conditions. They are initiated and driven only by physical properties like temperature, hydrostatic pressure, etc.
2. *Inherent Safety* means that certain dangerous situations, e.g. overheating of the reactor, are excluded under all circumstances, because any disturbance of the reactor will be returned to a safe condition on the basis of physical laws.

The probability of core melt and the probability of a related release of radioactivity into the environment are significantly reduced, 10^{-6}/Reactor*yr and 10^{-7}/Reactor*yr respectively in the new generation of reactors. Multiple containments and barriers ensure a minimal imposition on the environment. The reliability of GEN III/III+ systems is increased through redundancy, diversity and spatial separation of the safety systems.

Generation III/III+ systems achieve better economic performance through feedback from experience. Reduction of construction costs, the most important parameter for nuclear energy competitiveness, is pursued by standardisation and improved construction methods, including modularity and factory building. These measures contribute to shorter construction times which reduce interest during construction. Simpler designs reduce operation and maintenance costs. Higher fuel use efficiency improves economics and resource management.

The goals in terms of reduction of fuel consumption and waste volume and radiotoxicity are pursued through higher thermal efficiency of the plant, higher burn-up and modifications of the fuel cycle characteristics. Technological progress and improvement of industrial processes in fuel cycle facilities contribute to reducing the amounts of waste generated at each step of the cycle.

Some Generation III plants incorporating evolutionary features are already in operation (in East Asia) while others are under construction (also in Europe). The latest representative of this generation of LWR reactors is the European pressurised reactor (EPR) that is currently being built in Finland. The EPR is a further development of the proven, standardised French and German reactors. The probability of large radioactivity release from EPR is reduced to such extremely low levels that emergency measures in the surrounding area would no longer be necessary.

6.3 Generation IV systems

Many countries have programmes for the development of the next generation of reactors, mostly in the framework of bilateral or multilateral cooperation and international endeavours. Projects such as the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) and Generation IV International Forum (GIF) are examples of international cooperation in the field of advanced nuclear systems.

The points of focus for the development of advanced systems to be available in the medium- to long-term are resource sustainability, economics, safety and reliability, resistance to proliferation, and physical protection. The Generation IV systems should meet clean-air objectives, and promote effective fuel utilisation. The issues of minimisation of nuclear waste, and reduction of the long-term burden for future generations associated with their monitoring, are also being addressed. The systems target clear life-cycle cost advantages over other energy sources, at a comparable level of financial risk. In addition, they prescribe excellence in terms of safety and reliability, including, in the event of core damage, a very low likelihood of significant radioactivity releases to the environment, thus eliminating the need for off-site emergency response. Finally, the Generation IV reactors aim at enhancing proliferation resistance and physical protection.

Documents published by the IAEA in the framework of the INPRO project (IAEA, 2003 and 2004) provide an overview of the detailed objectives pursued by participants. The goals of the Generation IV International Forum (see Box 1, extracted from GIF, 2003), jointly defined and adopted by the countries participating in the endeavour,[3] offer a good illustration of the objectives adopted for nuclear systems of the 4th generation.

Box 1. Goals for Generation IV nuclear energy systems

Sustainability-1	*Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and provides long-term availability of systems and effective fuel utilization for worldwide energy.*
Sustainability-2	*Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden in the future, thereby improving protection for the public health and the environment.*
Economics-1	*Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.*
Economics-2	*Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.*
Safety and Reliability-1	*Generation IV nuclear energy systems operations will excel in safety and reliability.*
Safety and Reliability-2	*Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.*
Safety and Reliability-3	*Generation IV nuclear energy systems will eliminate the need for offsite emergency response.*
Proliferation Resistance and Physical Protection	*Generation IV nuclear energy systems will increase the assurance that they are very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.*

The set of goals agreed upon within GIF respond to objectives and priorities of participating countries for energy systems of the 21st century. They served as a basis to identify promising concepts deserving further joint R&D efforts and will be used for assessing progress towards designing and implementing innovative systems responding to the requirements of society for sustainable energy supply.

Though recognised as long-term options, Generation IV nuclear energy systems, at least some of them, could be available by 2020-2030, the time at which many of the currently operating nuclear power plants in the world will be at, or near to, the end of their operating lifetimes.

Table 6.1 provides a summary overview of the six Generation IV systems selected at the end of the roadmap process for further joint R&D efforts, taking into account the comparative evaluation of some hundred systems and a range of national priorities and interests of the individual GIF countries.

3. At the beginning of 2007, 12 countries (Argentina, Brazil, Canada, China, France, Japan, the Republic of Korea, Russia, the Republic of South Africa, Switzerland, the United Kingdom and the United States) and Euratom are members of GIF. The Goals of GENIV nuclear systems were defined initially by representatives from the 10 countries which participated in the preparation of the Technology Roadmap for Generation IV nuclear energy systems.

Table 6.1 Overview of Generation IV nuclear energy systems

System	Neutron spectrum	Coolant	Temp.	Fuel	Fuel cycle	Size (MWe)	Main uses
GFR (gas-cooled fast reactor)	fast	helium	850°C	^{238}U & MOX	closed, in-situ	288	electricity & hydrogen
LFR (lead-cooled fast reactor)	fast	PB or Pb-Bi	550-800°C	^{238}U & MOX	closed, regional	50-150, 300-400, 1 200	electricity & hydrogen
MSR (molten salt reactor)	epithermal	fluoride salts	700-800°C	UF_4 in salt	closed, in-situ	1 000	electricity & hydrogen
SFR (sodium-cooled fast reactor)	fast	sodium	550°C	^{238}U & MOX	closed	300-1 500	electricity
SCWR (supercritical water-cooled reactor)	thermal/ fast	water	510-550°C	UO_2	Open/ closed	1 500	electricity
VHTR (very high temperature gas reactor)	thermal	helium	1 000°C	UO_2	open	250	hydrogen & electricity

All GEN IV systems have features aiming at performance improvement. Two main means are relied upon to enhance sustainability through better use of natural resources: closed-fuel cycle with reprocessing, recycling and transmutation of actinides using fast neutron spectra; and high operating temperatures of the reactor coolant, ensuring high thermal efficiency and the possibility of efficient process-heat applications. The production of hydrogen, which is included in the objectives of several systems, could be a major drive for broader contribution of nuclear energy to global primary energy supply.

All the systems under consideration in the GIF framework present major technical challenges to be addressed for reaching a higher level of technology preparedness which is a prerequisite for industrial and commercial deployment. However, participant countries are confident that significant progress can be achieved in the coming decades that would lead to demonstrating fully the technical and economic viability of some of those systems.

6.4 Concluding remarks

Continuing technology progress is achieved in nuclear energy systems through evolutionary approaches. They have led to the design and implementation of GEN III/III+ systems responding better to society and market requirements.

Additional performance improvements are required to meet fully the goals of sustainable development and respond to social and environmental expectations in the 21st century. For this purpose, comprehensive R&D programmes are ongoing in the world. International cooperation and joint efforts from governments and the industry should facilitate the design and ultimately market deployment of advanced nuclear systems adapted to the needs of society.

It is essential to evaluate continuously alternative innovative concepts using a comprehensive assessment framework and relevant indicators to ensure effective allocation of R&D resources for the development of optimised nuclear systems.

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Chapter 7

MAIN FINDINGS

7.1 Role of nuclear energy

Nuclear energy plays a significant role in world electricity supply at the beginning of the 21^{st} century with a share of some 16% in total generation and its role will remain noticeable for decades. However, the contribution of nuclear to total primary energy supply worldwide remains modest with some 6%.

The fleet of nuclear power plants and fuel cycle facilities in operation today will continue to be part of the electricity generation landscape for some ten to fifty or more years as the most recently built units have a technical lifetime of more than 50 years. In the countries where those facilities are in operation, the assessment of existing nuclear energy chains is highly relevant to monitor that their performance remains at adequate level and improves over time.

According to most published projections, nuclear energy would not increase its share in total primary energy supply beyond some 10% by the end of the century in any scenario. Depending on the scenario considered, nuclear electricity generation is projected to be multiplied by 4 to 30 during the 21^{st} century, reaching some 12 to 93 000 TWh/year in 2100. It should be noted that those scenarios are "conventional" in many ways and in particular do not consider large-scale industrial production of hydrogen by nuclear power plants as an option. On the other hand, many technology breakthroughs may occur over a period of hundred years that would change dramatically the energy supply and/or demand side.

7.2 Assessment framework and indicators

Analysts have developed comprehensive frameworks to assess alternative options for energy and electricity supply in the context of sustainable development goals. The challenge for policy makers when they rely on such approaches is to address the three dimensions of sustainable development – economy, environment and society – in a balanced way, and to make the relevant trade-offs taking into account their specific conditions and priorities.

Extensive literature has been published on indicators of sustainable development in general and on those dedicated to energy systems in particular. Although comprehensive sets of indicators exist, experts acknowledge that some issues remain to be addressed for reaching a consensus among stakeholders on the adequacy, robustness and completeness of those sets.

Furthermore, key findings from previous studies include the recognition that the selection of indicators should be guided by the scope and objectives of the analysis to be conducted, taking into account the boundaries of the system to be assessed. Therefore, the first step of a comparative assessment study should be a review of existing indicators, followed by the selection of the set relevant for the specific context of the study.

7.3 Results of comparative assessments

Many studies have been carried out on comparative assessment of nuclear and alternative options for electricity generation and results from those studies are available in published literature. Each set of results, however, was obtained for specific technologies in a specific environment and generalisation of outcomes should be treated with caution. Results are essentially illustrative and should not be interpreted as generic ranking of alternatives.

Bearing in mind the limitation of each study, their main findings show that nuclear energy systems in operation which were analysed and assessed have very good performance for a wide range of indicators covering economic, environmental and social aspects.

A spin-off benefit of in depth analyses of current nuclear energy systems is the identification of specific points, steps of the chain, processes or aspects, deserving improvements. The findings from past assessments have been used to set the goals of innovative nuclear energy systems.

7.4 Decision-aiding tools

Comparative assessment studies are complex and their results often not straightforward to interpret for policy makers. Decision-aiding tools are designed to assist and support policy makers in their choices among alternative options. Their objective is to assist in the decision-making process not to substitute to decision makers who remain responsible for setting priorities and making relevant trade-offs.

External cost valuation is theoretically a perfect method for incorporating all dimensions and aspects of any system into its evaluation prior to decision making. Unfortunately, it is perfect only if the inventory of externalities is exhaustive and if their value is estimated in an accurate and reliable manner endorsed by all stakeholders. Although those conditions are seldom, if ever, fully met, the internalisation of external costs is an important tool to assist policy makers.

Multi-criteria decision analysis (MCDA) is a powerful tool to enable explicit accounting of social and environmental factors which are very difficult to value in a non-controversial way. The MDCA approach facilitates a more holistic representation of social criteria and improves the quality and transparency of the debate between policy makers and other stakeholders.

7.5 Technology progress

Designers and developers of advanced nuclear energy systems aim at achieving better performance than those of current nuclear and alternative systems. Evolutionary reactors, already under construction or in operation in some countries, have enhanced economic and safety performance and higher global efficiency, leading to reduced fuel consumption and waste volumes. Generation IV systems expected to reach commercial deployment stage by 2020-2030 have more ambitious goals that should be achieved through innovative technology and processes.

Large RD&D programmes are pursued by many countries, mostly in the framework or bilateral of multilateral cooperation, for the development of innovative nuclear systems, reactors and fuel cycles. International cooperation and private/public partnerships are essential to ensure the success of these ambitious endeavours. The effective management of RD&D programmes requires constant monitoring of the interim results to ensure that the concepts and designs under development respond to the pursued goals. In this context, the approaches and tools described in the report provide a relevant support to decision making on the most promising options.

Appendix 1

GLOSSARY

ALWR	Advanced light water reactor
CCGT	Combined cycle gas turbine
CSD	Commission on Sustainable Development
EC	European Commission
EEA	European Environment Agency
ENSAD	Energy-related severe accident database
EPR	European pressurised reactor
EU	European Union
Eurostat	Statistical Office of the European Communities
FGD	Flue-gas desulphurisation
GDP	Gross domestic product
GEN III/III+	Generation III/III+
GEN IV	Generation IV
GFR	Gas-cooled fast reactor
GHG	Greenhouse gas
GIF	Generation IV International Forum
HDI	Human development index
HLW	High-level radioactive waste
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles

IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LFR	Lead-cooled fast reactor
MCDA	Multi-criteria decision analysis
MIT	Massachusetts Institute of Technology
MSR	Molten salt reactor
NEEDS	New Energy Externalities Development for Sustainability
NIMBY	Not In My Back Yard
NPT	Nuclear Non-Proliferation Treaty
LWR	Light water reactor
PSA	Probabilistic safety assessment
PV	Photovoltaic
SCWR	Supercritical water-cooled reactor
SDC	Swiss Agency for Development and Cooperation
SFR	Sodium-cooled fast reactor
UCTE	Union for the Coordination of Transmission of Electricity
UNDP	United Nations Development Programme
UNCED	United Nations Conference on Environment and Development
VHTR	Very-high-temperature reactor
VOLL	Value of lost load

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In the context of sustainable development policies, decision making in the energy sector should be based on carefully designed trade-offs which take into account, insofar as feasible, all of the alternative options' advantages and drawbacks from the economic, environmental and social viewpoints. This report examines various aspects of nuclear and other energy chains for generating electricity, and provides illustrative examples of quantitative and qualitative indicators for those chains with regard to economic competitiveness, environmental burdens (such as air emissions and solid waste streams) and social aspects (including employment and health impacts).

This report will be of interest to policy makers and analysts in the energy and electricity sectors. It offers authoritative data and references to published literature on energy chain analysis which can be used in support of decision making.

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