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Nuclear Electricity Generation: What Are the External Costs?

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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, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, 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.

FOREWORD

This report has been prepared by the OECD Nuclear Energy Agency (NEA) Secretariat, with the assistance of consultants and under the guidance of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC). It is the outcome of a desk study based upon a comprehensive survey of published literature, including reports from international organisations, national institutes and previous NEA work.

It is often claimed that there are major consequences arising from the deployment of nuclear power plants which are not paid for by the electricity consumers. The report covers direct and external costs of nuclear power and offers insights into external costs of other energy sources. It provides policy makers with background information and data on broad economic aspects of nuclear electricity generation.

The report was reviewed by the NDC and benefited from comments and suggestions from its members. However, its contents do not necessarily reflect the views of all member country governments or their representatives. The report is published under the responsibility of the OECD Secretary-General.

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EXECUTIVE SUMMARY

Like other energy sources, nuclear energy has risks and benefits that need to be fully recognised and assessed to evaluate its external costs. In the process, it is essential to analyse the direct economic costs of nuclear-generated electricity in order to delineate accurately the boundary between economic (internalised) costs and potential external costs, and to indicate the potential impact on total costs if the external costs were internalised. Indeed, an externality exists if, and only if, some negative or positive impact is generated by an economic activity and imposed on third parties, and that impact is not priced in the market place.

Aspects of nuclear energy that often are suggested to entail external costs include: future financial liabilities arising from decommissioning and dismantling of nuclear facilities, health and environmental impacts of radioactivity releases in routine operation, radioactive waste disposal and effects of severe accidents. It has to be acknowledged that those aspects could become external costs if adequate funds for discharging them would not be established on a timely basis, guaranteed through reliable and independent bodies, and included in the costs (and the market price) of nuclear-generated electricity. However, a number of mechanisms have been established to provide such funds, thereby largely internalising these potential externalities, as highlighted in the following paragraphs.

The nuclear energy industry operates under regulations that impose stringent limits to atmospheric emissions and liquid effluents from nuclear facilities as well as requiring the containment and confinement of solid radioactive waste to ensure its isolation from the biosphere as long as it may be harmful for human health and the environment. Therefore, the capital and operating costs of nuclear power plants and fuel cycle facilities already internalise a major portion of the above-mentioned potential external costs, and these are reflected in the prices paid by consumers of nuclear-generated electricity.

It has been estimated that decommissioning costs represent some 10 to 15% of overnight capital costs of nuclear power plants. Since decommissioning activities and expenses occur after the plant has stopped producing electricity, decommissioning funds are accumulated, as a part of the electricity price, while the plant is in operation, according to the "Polluter Pays Principle". In OECD countries a wide variety of mechanisms and schemes are in place for ensuring that decommissioning costs are comprehensively estimated and that the necessary funds are accumulated and securely reserved, to be made available when needed.

High-level waste disposal costs, for the period until final repositories are in operation, are treated in the same way as decommissioning costs. Disposal cost estimates prepared by nuclear facility operators are checked and audited by independent governmental bodies, and the appropriate funds are accumulated by the operators, usually as a surcharge per unit of production, to cover the expenses in due course, thereby internalising this potential externality.

With regard to effects of severe nuclear accidents, a special legal regime, the third-party liability system, has been implemented to provide limited third party liability coverage in the event of a nuclear accident. This insurance system, which has been established from the beginning of the civil nuclear power industry, is considered essential to nuclear power development for two reasons. First, it resolves the problem of open-ended liabilities for investors, and second it provides a high level of assurance to a public concerned about the possibility of damages from severe nuclear accidents, even though the probability is very small.

Typically, the nuclear plant owners are held liable for some specified first substantial part of damages to third parties, and must secure insurance coverage adequate to cover this part. An industry-funded "secondary financial protection" programme, or in some countries the government, provides coverage for some specified substantial second part of the damages, with any remaining damages to be considered by the national legislation.

For example, under the Price-Anderson Act in the USA, the nuclear plant operators are assessed up to USD 88 million (not to exceed USD 10 million per year per reactor) for the second part of the damages arising from an incident that exceeds the primary level of coverage. In addition, the Congress may establish additional assessments if the first two levels of coverage are not adequate to cover claims. It is important to note that, in return for a limit on liability, the Price-Anderson Act establishes a simplified claims process for the public to expedite recovery for losses, thereby eliminating the delay that plaintiffs in ordinary damage cases must incur before receiving compensation for injuries or damages. It also provides immediate reimbursement for costs associated with any evacuation that may be ordered near nuclear power plants. It is important to stress also that all costs for the Price-Anderson nuclear insurance scheme are borne by the nuclear plant owners, either through premiums for insurance to cover liability for the first part of the damages or through retroactive assessments to cover the second and third parts of the damages. Thus, the Price-Anderson scheme ensures that the costs of an incident or accident are fully internalised in the costs borne by the nuclear plant owners.

Remains the externality related to potential health and environmental impacts of radioactive releases during routine operations. These have been assessed in a large number of comprehensive studies, in particular the ExternE (Externalities of Energy) project that was created in the framework of the European Commission Joule research programme. Although the results, both for direct (internalised) costs and external costs, from different studies and for different energy sources vary over rather wide ranges, they do allow some generic findings to be drawn with regard to the relative magnitude of direct and external costs for each technology. For fossil fuels and biomass, external costs are of the same order of magnitude as direct costs. On the other hand, for nuclear electricity, solar photovoltaïc and wind power, external costs are at least one order of magnitude lower than direct costs.

Externalities of energy are of course not limited to environmental and health related impacts, but may result also from macro-economic, policy or strategic factors not reflected in market prices, such as security of supply, cost stability and broad economic impacts on employment and balance of trade. Although those externalities generally have not been subjected to quantitative evaluation, they have been analysed qualitatively in some studies and the results indicate that they are not a major cause of market price distortion. If such externalities would be internalised, the effect would be positive (i.e. a cost benefit) for nuclear energy.

1. INTRODUCTION

External costs, that is, costs that are borne by society as a whole rather than by consumers of a good, product or service, are detrimental to global economic, social and environmental optimisation since they prevent market mechanisms from operating efficiently through adequate price signals. Therefore, identifying and quantifying external costs of energy systems are essential in a sustainable development perspective (OECD, 2001; NEA, 2000).

Costs have always been a very important factor in decision making, in particular for choices between alternative energy sources and electricity generation technologies. However, it is only recently that external costs have started to receive the attention they merit. Furthermore, although those costs play a growing role in policy making, the process of their identification and quantification, and of finding appropriate ways to include them in the prices paid by consumers, is far from being completed. Thus, this is the subject of a large body of ongoing work.

This report focuses on the potential external costs of nuclear-generated electricity. The data and analyses presented herein, drawn from previous NEA studies and authoritative literature from national institutes and international organisations, have the objective of providing a sound and transparent basis for understanding what are the potential external costs of nuclear energy, how they are assessed and to what extent they have been internalised already in the prices paid by consumers.

Eventually, costs, risks and benefits of nuclear-generated electricity need to be analysed in comparison with those of other energy sources and options. Generally, national energy policies aim at implementing systems ensuring diversity and security of supply, including various primary energy sources and conversion technologies. The assessment of external costs in support of decision making should reflect this policy objective. Therefore, the data and analyses provided in this report are intended to support eventual comparative assessment studies.

Like other energy sources, nuclear energy has risks and benefits that need to be fully recognised and assessed to evaluate its external costs. In the process, it is essential to analyse the direct economic costs of nuclear-generated electricity in order to delineate accurately the boundary between economic (internalised) costs and potential external costs, and to indicate the potential impact on total costs if the external costs were internalised. Indeed, an externality exists if, and only if, some negative or positive impact is generated by an economic activity and imposed on third parties, and that impact is not priced in the market place (Pearce, 2001).

Nuclear reactors and fuel cycle facilities are complex and highly-technical systems with a large inventory of radioactive materials which, if they would not be securely isolated from the environment, have the potential to cause significant damages. However, the nuclear industry operates under a strictly regulated safety regime, which ensures that any effects on human health and the environment are kept to levels so low as to be judged essentially negligible.

Aspects of nuclear energy that often are suggested to entail external costs include: radioactive waste disposal, future financial liabilities arising from decommissioning and dismantling of nuclear facilities, health and environmental impacts of radioactivity releases in routine operation and effects of severe accidents. Those aspects are included in the scope of the report, since they indeed could become external costs if adequate funds for discharging them would not be established on a timely basis, guaranteed through reliable and independent bodies, and included in the market price of nuclear-generated electricity.

Issues related to non-priced benefits of nuclear energy are covered also insofar as they are relevant to assess externalities. Beyond the competitive generation costs of existing nuclear power plants in most markets, benefits of nuclear energy, that are not reflected currently in prices, include: security of supply, cost stability and the quasi absence of atmospheric emissions of greenhouse gases,[1] other pollutant gases and particulates. In particular, security of supply and cost stability rely on the availability of adequate fuel resources. Uranium resources are sufficient to support a significant increase in global nuclear power capacity, and the geographic distribution and stable governments

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[1] There are no emissions of greenhouse gases, other pollutant gases or particulates from the nuclear power plants themselves. However, the use of fossil fuels at other stages of the nuclear energy chain (e.g. for uranium mining, fuel preparation, transportation) would lead to very small emissions, which have to be accounted for in a “full energy chain” assessment.

of uranium producing countries offer an adequate guarantee of supply security in the future (IAEA and NEA, 2002).

Further to this introductory chapter, Chapter 2 provides an overview on the concept of externalities and methodologies to assess and quantify them, with emphasis on the application to nuclear-generated electricity. Positive externalities of nuclear energy – such as security of supply, environmental protection, R&D spin-off, and benefits to balance of payments and price stability – are addressed briefly in Annex 1.

Chapter 3 describes internalised and external costs of nuclear-generated electricity, and puts nuclear costs in perspective through comparisons with some alternative energy sources and electricity generation technologies. It includes quantitative cost data drawn from authoritative studies such as ExternE (EC, 1999 and 1995) and economic analyses published by OECD (e.g. IEA and NEA, 1998). Annex 2 presents a more comprehensive description of the health and environmental externalities of nuclear energy, and Annex 3 highlights the future financial liabilities borne by nuclear operators.

Chapter 4 addresses key issues raised by internalisation of external costs in policy making, including assessment of long-term global impacts, monetary valuation, risk perception, uncertainties and consistency of the overall economic approach to external and already internalised costs. Finally, some main findings and conclusions that may be drawn from the information presented in this report are summarised in Chapter 5.

Each chapter and annex is followed by a list of references providing more information on each topic, and a bibliography for further reading is given at the end of the document.

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2. EXTERNALITIES

Background and definitions

The concept of externalities has been referred to in the economic literature since early in the 20th century. In 1920, Pigou qualified detrimental consequences of economic activities as external costs (Pigou, 1920). Later on, Kapp anticipated the far reaching consequences of economic growth on the environment and introduced the concept of "social cost", defined as all direct and indirect burdens imposed on third parties or the general public by the participants in economic activity (Kapp, 1950). More recently, in 1974, the Council of OECD recommended the application by governments of the "Polluter Pays Principle", defined in the early 1970s as a means to allocate costs of pollution prevention and control measures to polluters, and thereby to consumers of their products, rather than to society as a whole.

External costs arise from the economic consequences of an activity that accrue to society but are not explicitly accounted for by the economic agents in their decision-making process. The relevance of recognising, assessing and internalising external costs is increasingly acknowledged by economists and policy makers in the context of sustainable development goals. However, more analytical work is needed to support a comprehensive internalisation of externalities in the decision-making process.

In purely competitive markets, in the absence of externalities, prices constitute the instrument for efficient resource allocation, both on the production and consumption sides of the economy. External costs resulting from the imperfections and/or non-existence of markets, as is the case for clean air and fresh water, prevent optimal resource allocation. Market prices cannot give the right signals to economic agents and policy makers as long as externalities exist. For example, in the absence of a "carbon value", e.g. through taxes on carbon emissions, market prices cannot signal producers and consumers of energy to switch to lower carbon energy sources.

In the energy sector, a wide range of external costs may arise in particular from health and environmental impacts of emissions and waste. Impacts on public and occupational human health (mortality and morbidity), on natural ecosystems, fauna and flora, agriculture, building and cultural objects as well as global environmental impacts, such as climate change induced by greenhouse gases, remain external costs of energy systems in so far as they are not paid for by energy producers and consumers.

External costs and externalities

An externality may be defined as "A cost or benefit that is not included in the market price of a good because it is not included in the supply price or demand price. An externality is produced when the economic activity of one actor (or group of actors) has a positive or negative impact on the welfare function of another actor (or group of actors) and when the former fails to be fully compensated, or to fully compensate the latter, for that impact. Externality is one type of failure that causes inefficiency."

This definition is most often used in the context of negative environmental externalities such as air pollution which damages human health, crops or materials and in which the polluter may not suffer from the direct or indirect damages. In principle, externalities may also be positive; e.g. the case of a bee-farmer whose bees help pollinate the fruit trees of a nearby orchard.

Essential to the definition are both the lack of participation in the decision concerning the economic activity by one or more of the parties affected, and the absence of full compensation of the costs or benefits accruing to the receiving party. It should be noted that, under this definition, environmental pollution will not be an externality if those who suffer from the negative impacts of that pollution are fully compensated. (from Virdis, 2002)

In this connection, it should be noted that the implementation of environmental protection or other damage prevention measures internalise *de facto* some externalities. In the nuclear energy sector, safety and radiation protection norms, standards and regulations, based upon the ALARA (As Low As Reasonably Achievable) principle, reduce external costs drastically. By imposing stringent limits on radioactive emissions and releases, the potential impacts on health and the environment of nuclear facility operation are kept to very low levels.

Since the early 1970s, there has been increased interest in the environmental impacts caused by electricity generation systems, including by nuclear power plants and fuel cycle facilities. This interest has given impetus to the assessment of external costs, which is essential for a fair comparison of alternative electricity generation options. Efforts to fully characterise those costs have been made by many experts, national institutes and international organisations.

Studies on external costs of electricity generation started in the 1980s with the work of Hohmeyer and Ottinger (Hohmeyer and Ottinger, 1994 and 1992). Their assessments covered nuclear-generated electricity but were based upon very specific assumptions that led to challenge of the relevance of their results in a broad generic context. The methodological issues raised by the assessment of external costs led the European Commission and the United States Department of Energy to launch in the early 1990s a joint research project ExternE (Externalities of Energy) to address those issues and identify a relevant methodology for estimating the external costs of energy.

The ExternE project was created in the framework of the JOULE research programme and provided authoritative results on a wide range of electricity generation sources and technologies. In this framework a common methodology, based on scientific and economic information, has been developed continuously by the European Commission since 1994 (EC, 1999; EC, 1995). Today, a rather comprehensive set of data is available, and a rather large number of researchers from different disciplines continue to work on the project aiming at a better harmonisation of the results into a coherent framework.

Externalities of energy are of course not limited to environmental and health related impacts, but may result also from macro-economic, policy or strategic factors not reflected in market prices, such as security of supply, cost stability and broad economic impacts on employment and balance of trade (NEA, 1992). Although those externalities generally have not been subjected to quantitative evaluation, they have been analysed qualitatively in some studies and the results indicate that they are not a major cause of market price distortion. Annex 2 provides information on the main externalities of nuclear energy that may not be captured by health and environmental impact assessments.

Methodologies for evaluating externalities

The design of scientifically sound and internationally agreed evaluation methodologies is a necessary first step for estimating the external costs of electricity generation. Essential features of such methodologies are that they:

1. describe all stages (or process steps) in the fuel cycle (or energy chain);
2. provide information on material and energy flows and environmental burdens (e.g. emissions and wastes) associated with each stage;

3. allow the estimation of health and environmental impacts resulting from the burdens; and, finally,
4. provide a mechanism for estimating the costs of the impacts.

The methodology that was developed and used in the ExternE project provides a good example of the current state-of-the-art. In the ExternE methodological approach, a form of life-cycle analysis (LCA) was used to meet the needs of the first two essential features listed above, while the other two essential features are met by a subsequent impact pathway analysis (IPA). These two analytical features of the ExternE methodology are described briefly below.

Life-cycle analysis (LCA)

The life-cycle analysis (LCA) method, that has been developed since the beginning of the 1970s, offers a tool for developing a detailed quantitative inventory of material and energy flows associated with all stages in the life cycle of a product or activity, from raw material production and transformation to end use and waste disposal, that is, "from cradle to grave" (see IEA, 1993; IEA and NEA, 2002; Dones *et al.*, 1998; Vattenfall, 1996). For electricity generation systems, LCA encompasses all segments including processes before (up-stream) and after (down-stream) of the power plant. It identifies and places emphasis on the segments of the fuel cycle (or energy chain) that lead to the largest externalities. Factors related to the production and use of the construction materials and personnel are included in the analysis if they are estimated to be an important source of externalities (e.g. for some renewable energy systems). Generally, the analyses are done on a marginal basis; that is, per unit of electricity production.

The first step of the LCA is to identify the different stages of the energy chain to be studied. For the nuclear energy chain, eight stages usually are considered: mining and milling; conversion; enrichment; fuel fabrication; electricity generation; low and intermediate level waste disposal; and reprocessing and high level waste disposal or spent fuel disposal. The transportation of radioactive materials and waste between these stages, as well as plant and infrastructure construction, operation and dismantling, also are considered in the evaluation.

The next step prepares a list of environmental burdens (or "stressors"), defined as conditions that may lead to human health or ecological impacts, associated with each item in the inventory of material and energy flows. Stressors can be raw material and energy consumption, liquid effluents, atmospheric emissions, solid waste generation and treatment, thermal releases, land use, noise, etc. For these physical parameters, the inventory can be of good quality, but it is more difficult to describe “soft” parameters like visual intrusion, aesthetic disturbance, changes in migratory patterns of animals, etc. The stressor inventory generates a long list of substances that are generated by the system either as useful products or as waste discharged into the environment, or are consumed by the system in material or energy form. The identification of stressors can be done through expert knowledge or through references available in the literature on the particular segment of the system considered.

Impact pathway analysis (IPA)

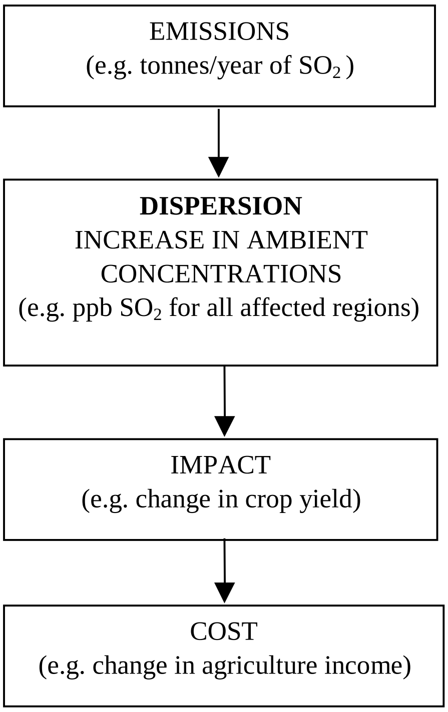
The third step, assessment of the different impacts associated with each stressor, is much more complex and difficult than performing the inventory. The impacts are sometimes assessed according to a geographical and time decomposition. Some of the contributions to local and regional impacts can be quantified easily, while others are difficult to treat numerically, and some can be handled only in a qualitative way. Methods that can be used to assess the potential health and ecological impacts of stressors range from simple approaches that examine loading (e.g. quantity released per unit of time) to more complex approaches that estimate environmental exposure and link that exposure to effects on populations, communities and ecosystems. Other methods include impact assessment by equivalency factors, eco-toxicity, persistence and bio-accumulation profile (see SETAC, 1994; SETAC, 1993, SETAC, 1992).

The impact pathway analysis (IPA) methodology has been developed in the framework of European Commission ExternE studies as a tool for assessing the different impacts associated with each stressor and valuation of those impacts.

A specific technology is assumed for each stage of the energy chain, and the different stages may be carried out at different locations. For high level radioactive waste disposal, generic assumptions have been adopted in the ExternE study since no repository currently is in operation in Europe. At each stage of the fuel cycle, the analysis takes into account the specific characteristics of the technology and of the site of the facility.

The analysis includes an inventory of releases to the environment at each stage, taking into account the construction, normal operation and dismantling of the facility, as well as accidental situations. The releases from each facility in the nuclear fuel cycle fall into the three major categories: atmospheric emissions, liquid effluents discharged in rivers or seas, and solid waste disposed of in the ground. Experts set a hierarchy in these releases in order to focus the study on the most important in terms of impacts. The next step consists in following the transfer and the transformation of the materials released, taking into account their routes through the environment or pathways as provided by transfer models. This evaluation must reflect specific local and regional characteristics of the sites where facilities are operated. After using dispersion models in the environment and doing concentration calculations, impacts are evaluated. The main steps of the IPA methodology are illustrated in Figure 2.1 (from EC, Vol. 2, 1995). Each step shown is analysed with detailed process models.

Figure 2.1 An illustration of the main steps of the IPA methodology applied to the consequences of pollutant emissions



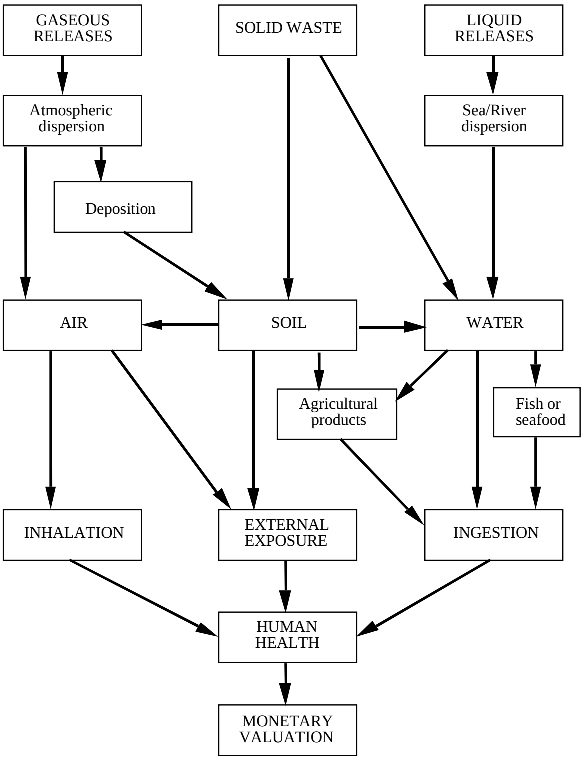
Although both radioactive and non-radioactive substances are released at the different stages of the nuclear fuel cycle, the most important impacts are those from the radioactive releases and the priority pathways are those concerned with the radiological impacts on human health. The total dose to population is calculated by summing the contributions of each radio-nuclide through each pathway. Doses are used to calculate impacts on human health assuming a conservative linear dose-effect relationship. The indicators used to assess human health impacts include deaths, injuries, working days lost and permanent disabilities, taking into account radiological impacts such as fatal cancers, non-fatal cancers and severe hereditary effects in future generations, estimated according to the recommendations of the ICRP (International Commission on Radiological Protection).

Occupational exposures and accidents are included in the assessment. For non-radiological occupational accidents, the assessment generally is based on site-specific information obtained from the facility. If the available data are insufficient to establish a representative value, the most recent national accident statistics reported by type of job are used, especially for occupational injuries and diseases. The assessment of the impacts of the transportation of radioactive material takes into account the external exposure to the public and the workers from the containers transported, as well as a probabilistic assessment for potential accidents. The impacts from a potential severe reactor accident are also evaluated using a risk-based methodology and an accident consequence assessment model, including health effects, social and economic disturbances and costs of countermeasures.

The temporal and geographic distribution of impacts is reflected in the IPA approach. Immediate or short-term, medium-term and long-term impacts are estimated separately and eventually aggregated. Impacts occurring within one year, such as injuries from occupational accidents, are considered immediate; medium-term impacts are those occurring within a lifetime, i.e. less than 100 years; and long-term impacts are those occurring beyond 100 years. For IPA studies of the nuclear fuel cycle, long-term impact assessment covers impacts resulting from the potential releases of radioactivity from high level waste repositories up to 100 000 years, or longer, although the relevance of assessments over such a long time period may be questionable. The geographic distribution includes local (less than 100 km), regional (100 to 1 000 km) and global (more than 1 000 km) scales.

The final step of the IPA methodology is the monetary valuation of the physical impacts that have been estimated (see EC, 1995). The ultimate objective of an IPA is to provide an estimate of the incremental impacts and costs of an additional power station that may be compared with the impacts and costs of alternative options. For this purpose the results are normalised (e.g. expressed per unit of electricity production). The valuation is based on economic models, often using willingness-to-pay methods for estimating the unit cost of health and environmental impacts. It raises a number of issues including the choice of a statistical value of life and of a discount rate for long-term impacts on future generations. Nevertheless, recent work shows progress towards consensus building on ranges of assumptions and results.

Figure 2.2 Schematic representation of the IPA methodology applied to radioactive releases from the nuclear energy chain



A schematic representation of the successive steps of an IPA applied to radioactive releases from the nuclear energy chain is given in Figure 2.2. The priority impacts of the nuclear fuel cycle to the general public are radiological and non-radiological impacts due to the routine and accidental releases to the environment. The sources of these impacts are the releases of materials through atmospheric, liquid and solid waste pathways.

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3. INTERNALISED AND EXTERNAL COSTS OF NUCLEAR-GENERATED ELECTRICITY

Internalised costs of nuclear-generated electricity

The nuclear energy industry operates under regulations that impose stringent limits to atmospheric emissions and liquid effluents from nuclear facilities as well as requiring the containment and confinement of solid radioactive waste to ensure its isolation from the biosphere as long as it may be harmful for human health and the environment. Therefore, the capital and operating costs of nuclear power plants and fuel cycle facilities already internalise a substantial number of potential external costs (NEA, 2000a), and these are reflected in the prices paid by consumers of nuclear-generated electricity.

The OECD has published a series of reports on projected costs of generating electricity which give a comprehensive overview on methodologies for estimating generation costs and a large number of cost data for various generation technologies in many countries. These publications provide a fairly detailed list of items included in nuclear-generated electricity costs, as well as some insights and qualitative information on external costs. The 1998 update (IEA and NEA, 1998) focuses on base load technologies and plant types that could be commissioned in participating countries by 2005-2010.

Generation costs (also referred to as "direct costs") include three main components: investment; operation and maintenance (O&M); and fuel. In the case of nuclear energy, investment costs represent some 60% of the total cost while O&M and fuel represent some 20% each. In order to assess external costs of nuclear-generated electricity, it is relevant to identify and quantify, as comprehensively and accurately as possible, the cost elements already included in the generation costs borne by electricity producers (i.e. already internalised).

Annex 3 provides an overview on the treatment of financial liabilities associated with nuclear power plants (e.g. for third-party liability insurance, plant decommissioning and waste disposal), and describes systems for ensuring the availability of funds to meet them.

Investment costs

Investment costs of nuclear power plants include a long list of items from land acquisition to construction, and cover indirect costs such as design and commissioning of the plant as well as contingencies and interest during construction (NEA, 2000b). It is difficult to isolate precisely the elements within those costs, which are related to health and environmental protection and, therefore, correspond to internalised externalities. For example, safety features serve several purposes, including health and environmental protection but also plant reliability and protection of physical assets. Although it has been suggested that up to 60% of a nuclear power plant overnight construction cost (i.e. not including interest during construction) can be related to protecting health, safety and the environment (see IEA and NEA, 1998 – Annex 6), the other functions of safety features (e.g. providing for reliability of operation and protection of assets) are not taken into account in such estimates. Nonetheless, the overall message is that the safety features built into nuclear power facilities reduce the probability of an accident to a very low level and thereby minimises the potential external costs associated with accident risks. Furthermore, a special legal regime, the third-party liability system, has been implemented to provide insurance coverage for any potential damage that might occur, and the cost of this insurance (usually included in O&M costs) also represents an internalisation of potential externalities.

The future costs of decommissioning of nuclear facilities are already internalised, by being included in the prices charged to customers during the operating lifetime of the facilities. In the case of nuclear power plants, it has been estimated that decommissioning costs represent some 10 to 15% of overnight capital costs of the plants. Since decommissioning activities and expenses occur after the plant has stopped producing electricity, decommissioning funds are accumulated during plant operation, as a surcharge on electricity prices, according to the “Polluter Pays Principle”. In OECD countries a wide variety of mechanisms and schemes are in place for ensuring that decommissioning costs are comprehensively estimated and that the necessary funds are accumulated and securely reserved, to be made available when needed (NEA, 1996).

Operation and maintenance costs

Operation and maintenance costs, representing around 20% of total nuclear-generated electricity costs (NEA, 1995) include all costs borne by producers that do not fall within capital investment and fuel costs. The internalisation of externalities in O&M costs includes a number of expenses arising from health and environmental protection, monitoring of emissions and effluents, and accumulation of the necessary funds for management and disposal of radioactive waste and for eventual decommissioning of the plant. Radiation protection equipment and staff, emergency planning measures and support/fees to regulatory bodies are examples of internalised costs of nuclear energy facilities. Also, operation costs associated with the implementation of the international safeguards regime are internalised in nuclear generated electricity prices (see IEA and NEA, 1998 – Annex 7).

Nuclear fuel cycle costs

Nuclear fuel cycle costs, which also represent some 20% of total nuclear-generated electricity costs, include all the costs related to the up-stream and down-stream steps of the fuel cycle, and the costs of transportation between steps. This includes the costs of uranium, conversion, enrichment, fuel fabrication, spent fuel conditioning or reprocessing, and management and disposal of conditioned spent fuel or radioactive waste from reprocessing. As is the case for nuclear power plants, uranium mining and milling plants and fuel cycle facilities operate under safety and radiation protection regimes that reduce to very low levels their potential health and environmental impacts.

A recent NEA study on the nuclear fuel cycle (NEA, 2002) provides a comprehensive overview of nuclear fuel cycle technologies and practices, covering ways and means to reduce atmospheric emissions, liquid effluents and solid waste, and some indications on residual external costs. High level waste disposal costs, until final repositories are in operation, constitute future financial liabilities and are treated in the same way as decommissioning costs (see Annex 3). Disposal costs are estimated by operators, checked/audited by responsible governmental bodies, and funds are accumulated by operators, usually as a surcharge per unit of production, to cover the corresponding expenses in due course (see NEA, 1996).

Nuclear generation costs

Table 3.1 shows levelised costs of nuclear-generated electricity drawn from (IEA and NEA, 1998) in some OECD member countries at 5% and 10% discount rates. The ranges of costs, from 2.5 to 4.1 US cents/kWh at 5% discount rate and from 4.0 to 6.4 US cents/kWh at 10% discount rate, illustrate the variability from country to country. The levelised costs given in Table 3.1 may serve as a reference to assess the relative importance of external costs described in the following section.

Table 3.1 Nuclear-generated electricity costs

Country	**Discount rate (%)**	**Investment (%)**	**O&M (%)**	**Fuel (%)**	**Total cost (US cent/kWh)**
Canada	5	67	24	9	2.5
	10	79	15	6	4.0
France	5	54	21	25	3.2
	10	70	14	16	4.9
Korea (Republic of)	5	55	31	14	3.1
	10	71	20	9	4.8
Spain	5	54	20	26	4.1
	10	70	13	17	6.4
Turkey	5	61	26	14	3.3
	10	75	17	9	5.2
United States	5	55	27	19	3.3
	10	68	19	13	4.6

Health and environmental externalities of nuclear-generated electricity

This section focuses on health and environmental externalities of nuclear energy which have been extensively studied and thoroughly assessed within a reasonable range of uncertainties. Other externalities, such as diversity and security of supply or macro-economic impacts, are addressed (see Annex 1) more briefly, in a qualitative manner, since their quantitative estimate and monetary valuation have not been carried out yet in a comprehensive, authoritative and reliable fashion (see Annex 2).

Results of ExternE for the French nuclear fuel cycle

Substantial progress has been made recently in estimating the monetary value of the impacts of electricity generation including by nuclear power plants. The following section provides illustrative estimates, essentially drawn from the ExternE project (EC, 1995) complemented whenever possible by results from other studies. The results presented below refer mainly to France, the country chosen as the reference within the ExternE study as far as nuclear energy is concerned because it was considered by the experts involved to be representative of generic values. However, some results available for other countries are given in order to broaden the scope of the review.

According to the ExternE approach and methodology (see Annex 2 for more details), this section starts by presenting the determination of reference source terms, then it deals with the evaluation of physical impacts and finally covers the monetary valuations of external costs expressed in value of impacts arising from a unit of energy, usually standardised as a kWh. The issue of global warming and the positive impact of nuclear energy in this regard is addressed briefly in Annex 1.

Source terms

At each stage of the nuclear fuel cycle, a list of main radio-nuclides released to the air and aquatic environment is established and the quantities released are estimated. When data reported by the facilities in compliance with safety and radiation protection regulations are available they are used to estimate the atmospheric and liquid source terms. When data specific to the facility are not available, the estimates are based on generic data from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 1993) that are considered representative within a reasonable uncertainty range. The source terms are calculated from release estimates normalised to electricity production. Regarding high-level waste disposal, the source term is derived from a dose assessment based upon a reference normal evolution long-term scenario in a deep geological repository for vitrified waste from reprocessing.

For the routine transportation operations, the source terms are calculated taking into account direct irradiation at the surface of transported packages. For accidental circumstances associated with transportation operations, only the releases of UF_6 (natural and enriched) are included in the evaluation because it is the most toxic of the potential releases (radioactive waste and spent fuel transportation are treated separately from “routine transportation” operations).

Results for physical impacts

The results obtained for the French nuclear fuel cycle are described in detail in (Dreicer *et al.*, 1995) and a summary of key outcomes may be found in (Schieber and Schneider, 2002). Table 3.2 illustrates the main results regarding radiological health impacts for routine operation of the nuclear fuel cycle, showing the spatial (i.e. local, regional, global) and temporal (i.e. short, medium and long term) distribution of impacts.

Table 3.2 Distribution of impacts from routine operation of the nuclear fuel cycle

	Local 0-100 km	**Regional** 100-1 000 km	**Global** >1 000 km
Short term (<1 year)	Non-radiological impacts on workers. Traffic accidents	–	–
Medium term (1-100 years)	Radiological impact on workers and the public	Radiological impact on the public	^{5}Kr, ^{3}H, ^{14}C, ^{129}I
Long term (100-100 000 years)	Radiological impact on the public	Radiological impact on the public	^{14}C, ^{129}I

In the French case, the total collective dose calculated for both the general public and workers, integrated over a constant global population of 10 billion people and a time period of 100 000 years, is 13.1 man.Sv/TWh taking into account all the stages of the nuclear fuel cycle. On a global scale, ^{14}C released from the electricity generation and reprocessing stages contributes the largest portion of the dose (more than 10 man.Sv/TWh). It must be stressed that even though this isotope is responsible for more than 77% of the total collective dose presented in the ExternE report, it is due to the addition of very small doses to a large population over a very long time period. The average individual dose from the annual atmospheric release of ^{14}C from the electricity generation and reprocessing stages (15% and 85% of total dose, respectively) has been estimated to be 2E-12 Sv/TWh. An individual dose of 1.1E-11 Sv/y can be estimated for the operation of one 900 MW PWR, assuming an electricity production of 5.7 TWh/y. It is apparent that this dose is insignificant when compared to the average individual dose of 1.2E-5 Sv/y due to natural ^{14}C or the 2.4E-3 Sv/y average individual dose due to the natural background.

Over 97% of the total collective dose of the French nuclear fuel cycle is due to public exposures. For the workers, the electricity generation and the mining and milling stages are the main contributors to the occupational collective dose. The ExternE results are quite similar to those published in a recent NEA study (NEA, 2000c) where the collective doses are summed only over 500 years and to the regional population.

The NEA study shows that the occupational and public doses are not significantly affected by the type of fuel cycle adopted (open with UO_2 fuel or closed with MOX fuel). Consequently, when considering a time frame of 500 years ahead, radiological impact is not a key factor favouring one option or the other and associated external costs do not differ significantly.

The evaluations made for the French fuel cycle show that most of the health impacts arising from the different stages of the nuclear fuel cycle concern short and medium terms, except for the electricity generation, reprocessing and waste disposal stages which create long-term health impacts. The occupational impacts, essentially due to non-radiological accidents, are in the short-term category although some radiological impacts occur in the medium- and long-terms. Over 93% of the public dose is due to the global dispersion of certain radio-nuclides (such as ^{14}C and ^{129}I).

The radiological health effects resulting from the routine operation of the nuclear fuel cycle are directly proportional to the total collective doses. The expected number of health effects are calculated assuming no lower threshold for radiological impacts (i.e. the linear no-threshold assumption for effects), and using internationally accepted risk coefficients from ICRP 60 (ICRP, 1991). Normalised to energy production, the total number of global expected health impacts are, in the French case: 0.65 fatal cancers/TWh; 1.57 non-fatal cancers/TWh; and 0.13 severe hereditary effects/TWh. These results include the global dose assessment estimates up to 100 000 years. Most of these impacts would be expected to occur in the public domain.

For workers in the nuclear industry, it is estimated that the production of 1 TWh would result in 0.02 deaths, 0.96 permanent disabilities and 296 working days lost. Occupational injuries occurring during construction and decommissioning of the reactor are the most important contributors to occupational impacts.

According to these estimates, the number of deaths by cancer in the European population due to the annual routine operation of one additional 1 300 MWe PWR, producing around 7 TWh per year, would be only 0.1 integrated over a period of 100 000 years. This may be compared to the approximate value of 800 000 fatal cancers from all causes that are reported in Europe each year.

The impacts from accidental situations related to transportation of radioactive waste materials are extremely low and mostly involve the general public. The number of non-radiological health impacts estimated in the French case are 0.0003 deaths and 0.0017 injuries per TWh. This represents around 0.1 death and 0.7 injury per year in France today, with an annual nuclear electricity generation of some 400 TWh, which is insignificant as compared with the current numbers of deaths and injuries by all types of traffic accidents.

Monetary valuation

The last step of the external cost calculation is the monetary valuation of the estimated damages. The external costs (as estimated within the ExternE study) obtained for the French nuclear fuel cycle in routine operation, calculated at three different discount rates 0%, 3% and 10%, are summarised in Table 3.3 (see Schieber and Schneider, 2002). The table provides the details of external costs for each fuel cycle step from mining to waste disposal, including electricity generation and transportation between successive steps. Electricity transmission and distribution impacts are not included, as they are not specific to nuclear generation.

Table 3.3 External costs of the French nuclear fuel cycle in routine operation (m€/kWh)

Fuel cycle stage	**Discount rate**		
	0%	3%	10%
Mining and milling	6.45E-02	1.84E-02	6.26E-03
Conversion	9.74E-04	4.78E-04	2.26E-04
Enrichment	1.19E-03	7.90E-04	4.13E-04
Fuel fabrication	1.89E-03	7.35E-04	3.10E-04
Electricity generation:			
Construction	3.94E-02	3.94E-02	3.94E-02
Operation	4.41E-01	1.68E-02	4.12E-03
Decommissioning	1.93E-02	6.91E-03	9.26E-04
Reprocessing	1.92E+00	1.45E-02	1.90E-03
LLW disposal	4.80E-03	8.52E-06	4.13E-07
HLW disposal	2.54E-02	6.41E-09	1.12E-10
Transportation	6.54E-04	2.66E-04	1.21E-04
Total	**2.52**	**0.10**	**0.054**

Source: ExternE, 1995.

The comparison of total external costs and their distribution between different fuel cycle steps at various discount rates shows the importance of the value adopted for discount rate, especially regarding the cost estimates for long-term damages. At 0% discount rate, the total external cost of nuclear-generated electricity is around 2.5 m€/kWh and the most important cost element is reprocessing, around 1.9 m€/kWh or 76% of the total. At 10% discount rate, the total external cost is around 0.05 m€/kWh and reprocessing represents only 4% while plant construction accounts for 0.039 m€/kWh or 73% of the total.

The range of external cost estimates resulting from varying the discount rate between 0% and 10% illustrates one of the key issues raised by the need to ensure economic consistency in the assessment of externality adders while reflecting sustainable development goals, i.e. protection of future generations. In the case of the French nuclear fuel cycle, as shown in Table 3.3, external costs vary from 0.05 m€/kWh to 2.5 m€/kWh, i.e. are multiplied by 50, when the discount rate drops from 10% – a relevant value for generation cost calculations – to 0% which is considered by some experts adequate to assess long-term impacts in a sustainable development perspective.

Another important issue is raised by the share of occupational effects in the estimated external costs of the nuclear fuel cycle. At 3% discount rate, according to ExternE, damages to workers account for more than 75% of the total. However, if it is assumed that these risks are internalised through higher wages, then they should not be counted again as externalities (Pearce, 2002). The issue of occupational effects is not unique to nuclear energy since the same remarks would apply to hazards affecting coal miners or workers on off-shore oil platforms who are, in principle, compensated at least partly for the risks of their jobs by higher wages and insurance coverage of professional illnesses and on-the-job accidents.

Nuclear accidents

Only radiological effects from accidents in reactors or fuel cycle facilities are addressed here since non-radiological health and environmental impacts are very small and their monetary valuation does not affect significantly the total external cost estimates. The calculations of economic consequences of a severe nuclear accident require a series of assumptions, including the choice of a reference scenario and associated probabilities. Furthermore, the calculated monetary value of an accident does not reflect a "risk-aversion premium", which is considered by some experts today as a key element (Eeckhoudt *et al.*, 2000).

The NEA study on methodologies for assessing the consequences of nuclear reactor accidents (NEA, 2000d) highlights the need for further work on methodologies and tools to evaluate the impacts of accidents and their monetary values. Although the imperfections and limitations of economic estimates carried out so far should be acknowledged, they provide some relevant insights on orders of magnitude and ranges of values.

The calculations carried out within the ExternE study in the case of France, based on a core melt probability of 10^{-5} per reactor.year and a release of about 1% of the core after meltdown, result in a direct cost of 0.0046 m€/kWh at 0% discount rate. The portion of this cost internalised by nuclear accident insurance has not been evaluated in the ExternE study. Beyond the direct costs of an accident, indirect impacts induce a multiplying factor that has been estimated at 1.25 based upon macroeconomic analyses. Furthermore, a multiplying coefficient approximately equal to 20 may be applied to reflect risk aversion. This would lead to an external cost of a nuclear accident equal to 0.12 m€/kWh instead of a direct cost of 0.0046 m€/kWh.

There are incremental costs, beyond those incurred for normal monitoring and planning arrangements, borne by all governments to prepare for the management of a severe nuclear accident but these are small in relation to the economic scale of a large power plant operation. These costs arise whether or not countries have chosen to deploy nuclear energy.

The estimated cost, including indirect effects and a multiplying factor due to risk aversion, represents less than 5% of the external cost of the nuclear fuel cycle (without accident) at 0% discount rate, or less than 1% of the total nuclear electricity generation cost without externalities. However, it has to be acknowledged that a severe nuclear accident in a small country, or a country with a small nuclear power programme, could have a relatively larger economic impact when expressed as a percentage of the nuclear generation cost in that country.

Results of ExternE for various countries

The ExternE methodology has been applied in national studies and the results published in 1999 (EC, 1999) include external cost estimates for the nuclear fuel cycle in Belgium, Germany, the Netherlands and the United Kingdom, in addition to the data already included in the 1995 publication for France. Those results, summarised in Table 3.4 at 0% discount rate, are indicative of the range of values resulting from differences in technologies, facility sites and socio-economic context prevailing in each country. Irrespective of those differences, the external cost estimates remain within the same order of magnitude with at most a threefold variation.

Table 3.4 External costs of the nuclear fuel cycle in different countries

Country	External cost (m€/kWh)
Belgium	4.0-4.7
France	2.5
Germany	4.4-7.0
The Netherlands	7.4
United Kingdom	2.4-2.7

Source: ExternE, 1999.

Results of other studies

Comparing results from ExternE and other studies raises a number of issues associated with inconsistencies between methodologies, scope of the damages taken into account and boundaries of the energy systems considered. The range of results shown in Table 3.5 may be attributed to a number of factors such as: number of fuel cycle stages included in the assessment; methodology for the valuation of health impacts; discount rate applied; and methodology and assumptions used for the assessment of a severe nuclear accident. The relatively low values obtained by ORNL (ORNL, 1993), Pearce *et al.*, and Friedrich and Voss, compared with the ExternE results, can be attributed mainly to a narrower definition of the boundaries of the system. In the case of Friedrich and Voss, the low values result from the fact that the analysis covers routine operation only (the cost of severe accident is not included).

Table 3.5 External costs of the nuclear fuel cycle from different studies

Study	External cost (m€/kWh)
ORNL (1993)	0.2-0.3
Pearce et al. (1992)	0.8-1.8
Friedrich and Voss (1993)	0.1-0.7
PACE (1990)	29.1

In the case of the PACE study (Pace, 1990), the very high estimate of external costs can be explained by a number of factors (NEA, 1992). Firstly, the PACE externalities include a figure of five mills/kWh for decom-missioning nuclear plant, whereas decommissioning costs usually are included in direct generation costs (see, for example, International Energy Agency and Nuclear Energy Agency, 1998). Secondly, the PACE estimate for the external cost of nuclear accidents is based on a frequency of major core releases to the environment, on the scale of Chernobyl, of one in 3 300 years. This is much higher than that which experts consider appropriate for new nuclear plants in OECD.

Thus, the only component of external costs this leaves is that arising from routine operation. The PACE starting point value of 1 mill/kWh derives largely from occupational health impacts; in particular delayed occupational mortality (0.7 mills/kWh). To derive this cost the study employs the top end of a range of delayed deaths from nuclear operations of 0.15 to 1.95 per GW.year, which compares with the range of 0.25 to 0.9 per GW.year, inclusive of the whole nuclear fuel cycle used in the NEA study (Nuclear Energy Agency, 1998), which are based on the 1991 Helsinki Symposium[1] conclusions.

Nevertheless, both the PACE and NEA studies concur that the external costs associated with routine nuclear operations are at the most a few percent of total nuclear generation costs and that they are significantly smaller than those associated with coal and oil combustion, even with greenhouse gas effects of the latter excluded.

Nuclear and other electricity generation technologies

Tables 3.1 and 3.4 showed that nuclear electricity generation cost estimates, both for internalised (direct) costs and externalities, vary from country to country. Similar variations are observed for alternative technologies. Table 3.6 summarises external cost ranges for different technologies obtained within the ExternE study (EC, 1999), and presents, for comparison purposes, direct cost ranges that are an average in European Union countries drawn from the Green Paper of the European Commission (EC, 2000).

Although both direct and external costs vary within rather wide ranges, some generic findings may be drawn from the overall comparison of direct versus external costs for each technology. For fossil fuels and biomass, external costs may be of the same order of magnitude as direct costs. On the other hand, for nuclear electricity, solar photovoltaïc and wind power, external costs are at least one order of magnitude lower than direct costs.

A study on power generation in Germany (Voss, 2002) illustrates the type of findings that may be obtained from external cost analysis. If the external cost estimates from that study are combined with direct costs, nuclear, which is already nearly competitive with coal and cheaper than natural gas, becomes the lowest cost option for base load electricity generation in Germany. Large uncertainties in terms of data and choice of discount rate limit the applicability of external cost adders in national policy making, but the outcomes from in-depth studies do provide guidance to decision makers.

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2. Author's note: see International Atomic Energy Agency, 1991.

Table 3.6 External and direct costs of electricity generation in the EU (m€/kWh)

External costs	Coal & Lignite	Oil	Gas	Nuclear	Biomass	Solar PV	Wind
Austria			11-26		24-25		
Belgium	37-150		11-22	4-4.7			
Germany	30-55	51-78	12-23	4.4-7	28-29	1.4-3.3	0.5-0.6
Denmark	35-65		15-30		12-14		0.9-1.6
Spain	48-77		11-22		29-52		1.8-1.9
Finland	20-44				8-11		
France	69-99	84-109	24-35	2.5	6-7		
Greece	46-84	26-48	7-13		1-8		2.4-2.6
Ireland	59-84						
Italy		34-56	15-27				
Netherlands	28-42		5-19	7.4	4-5		
Norway			8-19		2.4		0.5-2.5
Portugal	42-67		8-21		14-18		
Sweden	18-42				2.7-3		
UK	42-67	29-47	11-22	2.4-2.7	5.3-5.7		1.3-1.5
Direct costs	**32-50**	**49-52**	**26-35**	**34-59**	**34-43**	**512-853**	**67-72**

Other externalities of nuclear-generated electricity

Externalities of nuclear energy, other than residual health and environmental impacts, include costs or negative externalities and benefits or positive externalities. On the negative side, governmental support to research, development and deployment of nuclear energy, and governmental contribution to the third party liability regime, are the most prominent elements. On the positive side (see Annex 2), security and diversity of energy supply and macro-economic impacts – including spin-off effects from R&D, contributions to balance of payments and stable energy prices, and environmental protection – are important items.

A key issue, for most of the items listed above is the difficulty to quantify them and assess their monetary value in an objective and non-controversial way. However, qualitative reviews that have been carried out from the early 1990s (NEA, 1992) provide a robust basis to support the view that externalities of nuclear energy other than residual health and environmental impacts, although worth mentioning, would not affect significantly nuclear electricity generation costs if they were internalised. Moreover, it is expected the internalisation of these “other external costs” (other than health and environmental impacts) for all alternatives would not affect the relative competitiveness of generation options.

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4. INTERNALISATION OF EXTERNALITIES AND POLICY MAKING

The internalisation of externalities raises a number of generic policy issues that are compounded, in the case of nuclear-generated electricity, with specific challenges resulting from the characteristics of external costs and benefits of nuclear energy.

The objective of internalising external costs is “to get the prices right” in order to provide economic actors, in particular consumers, with signals that point to optimised choices. The larger the uncertainties on external costs, the more unlikely it is that internalisation of externalities will lead to a global social, environmental and economic optimum. Therefore, improving the assessment of external costs is an essential step forward.

However, the present knowledge on externalities, including qualitative and quantitative results from models and analytical studies, already provides useful guidance for policy making. The outcomes from past and ongoing studies can be used to a certain extent in support of decision making in spite of uncertainties and imperfections of the methodology (Virdis, 2002).

Most of the issues addressed below are relevant for all energy sources, and even for other goods and products, but the analysis focuses on specific challenges regarding the internalisation of externalities in the case of nuclear-generated electricity.

Assessment of long-term global health impacts of radiation

Although especially important for assessing the nuclear fuel cycle, radioactive emissions are not unique to nuclear energy since coal-fired power plants, for example, also release radioactivity in the environment. A comprehensive assessment of the impacts from the nuclear fuel cycle requires the assessment of radiation effects in the long-term owing to the very long lifetime of some of the radio-nuclides released and/or their rapid migration into the environment. The main radio-nuclides raising issues in this regard are ^{3}H,

^{14}C, ^{129}I and ^{85}Kr. Their impacts were estimated within the ExternE project using models and hypotheses (migration into the environment, dose calculations, dose-response relationships, constant population, etc.) that were agreed upon by senior international experts but are still challenged by some scientists and analysts.

For example, long-term radiation exposures are estimated in the ExternE study assuming that current conditions will remain unchanged during 100 000 years regarding: level of internal and external background radiation exposure; dose-response function of humans to radiation exposure; and fraction of cancers that result in death. Obviously, over millennia, the size and lifestyles of population will change as well as health-care effectiveness. The assumptions adopted are thought to be conservative, although this cannot be demonstrated absolutely, in the light of the expected progress of human knowledge and skills, but they nonetheless result in uncertainties and inherent bias in the results.

The collective dose approach adopted in ExternE integrates the average individual doses over the total population to be considered. Although considered relevant, the method does have some recognised drawbacks. The aggregation on a large population of extremely low individual doses leads to significant collective doses, and masks the very low level of individual risk. Furthermore, the increase of uncertainties with time weakens the pertinence of impact estimates in the very long term. This approach, nevertheless, allows to express the impact on populations in space and time and provides additional information on individual exposures in the very long term.

The evaluation of long term and global impacts raises various theoretical issues related to the validity of the quantitative assessment of what could be the future risks, and also related to the ethical position with regard to future generations. From a practical point of view, however, a responsible attitude implies that we should use in a precautionary manner the available information about the possible consequences of our present actions, even though the information contains uncertainties and reflects limited knowledge owing to limitations of present approaches for assessing consequences in the distant future.

While criticisms against the approach are valid, a robust assessment of the nuclear fuel cycle impacts requires taking into account, as far as feasible, the effects of radio-nuclides released to the environment for as long as the radioactivity level remains above background. It means covering in the assessment the period during which these radio-nuclides remain a source of exposure and the geographic area over which they are dispersed. The individual dose and collective dose concepts allow to determine the order of magnitude of the long-term and global impacts and to assess whether these impacts might induce any problem in the future in terms of individual risk or public health.

Monetary valuation

Key issues raised by monetary valuation of impacts from energy systems are the estimation of health effect values, including valuing statistical lives, and the choice of relevant discount rates. Both issues are highly controversial and there is no consensus so far among experts on the right approach. These two issues are very important in assessing external costs of nuclear generated electricity since a significant share of the estimated nuclear fuel cycle impacts are on human health and occur in the long term (e.g. carcinogenic effect of radiation). It should be stressed, however, that these issues affect similarly the valuation of global climate change impacts and thereby the external cost estimates for fossil-fuelled technologies.

While economists have developed reasonably good estimates of social discount rates at the national level and applicable on periods of a few decades, the relevant discount rate for the world as a whole and adapted to very long-term effects is less easy to determine (Pearce, 2002). Discounting, to make an arbitrage between present and future, is a procedure coming from financial mathematics and interest theory, usually applied for determining the profitability of investments. An investment decision is made by comparing net benefits of the investment with those of the same financial fund placed on the financial markets. However, financial markets do not provide information beyond 40 years (which approximately corresponds to the maturity period of US Treasury Bonds). Thus, the normal use of discount rate is for short and medium-term decisions (up to a few decades).

For long-term decisions, discounting requires at least some adaptation. The impact of discount rate assumption on external costs of nuclear energy is illustrated by the range of estimates obtained for the French nuclear fuel cycle in ExternE (see Table 3.3). This results from the fact that discounted values of damages occurring beyond 100 years are reduced greatly when any discount rate higher than 0% is applied. Recent economic research indicates that the long-term discount rate almost certainly should decline with time (Pearce, 2002). However, there is no consensus today on the "correct" discount rate applicable in the very long term, and this leads to challenges of the validity of external cost estimates. Furthermore, there is no economic theory foundation to an approach that would include various discount rates, including 0%, applied to different cost items, to be eventually aggregated, which is a necessary step to assess the total cost resulting from short- and long-term impacts.

Regarding health effects and their valuation, more research is needed on epidemiology and economic valuation of life risks in order to enhance confidence in external cost estimates (Pearce, 2002). For example, there is limited evidence on how willingness to pay for lifetime extension relates to age, although it would seem logical to assume that a correlation exists between the age of the affected person and the appropriate economic value of days of life loss. The "value of statistical life" approach or the "valuation of the years of life lost" used in the latest ExternE studies (Rabl and Spadaro, 2002), although based upon average values, provide reasonable estimates of health impacts.

Further issues raised by monetary valuation of the nuclear fuel cycle impacts include the questionable relevance of using the same methodology to value very low and quite uncertain individual risks to a large population and also for valuing rather large and more certain individual risks to a small population, and eventually to aggregate the monetary values found for the two types of risks into a unique external cost value.

Risk and risk perception

There is a discrepancy between the social acceptability of a risk and the calculated monetary value of its consequences (see Chapter 3). There is extensive literature on risk perception, including how it applies to nuclear energy risks and accidents (NEA, 2002). However, the choice of a risk perception coefficient remains rather judgmental. It is difficult to find a method that can incorporate social perceptions of risks in terms of time and space, keeping in mind the eventual need to carry out comparative assessments between alternative options and their associated different types of risks.

The need to compare risks of different types may be illustrated within the nuclear fuel cycle itself by alternative options regarding ^{14}C emissions. If ^{14}C is released today, it is diluted and results in low immediate individual risks but no future need for disposal and associated impacts. On the other hand, if ^{14}C is captured for disposal, it may lead to increases in occupational risks (for workers in the capturing facilities) and waste repositories must be implemented that could entail risks to the local public in the far future (if there is leakage from the repositories).

Ultimately, a fair evaluation of external costs should rely on the willingness to pay of affected parties to avoid damages and impacts. In this context, risk perception is a driving factor. In the case of nuclear energy, the unknown and potentially catastrophic consequences are key elements in risk perception by the public that may affect the value of external costs (NEA, 2002). The catastrophic potential is relevant also for other energy sources such as gas, hydro power and, to a lesser extent, coal and oil.

Although it is generally thought that the public is more sensitive to a large number of deaths in one accident than to the same number of deaths in a large number of accidents each with one or few deaths, studies on disaster aversion show very little evidence for such a difference (Ball and Floyd, 1998). Indeed, little empirical work has been done to test whether people really are averse to disasters; such studies are needed to back-up the risk aversion functions used in studies such as ExternE.

From a policy-making view point, however, the use of a risk aversion factor in external cost assessment does not change dramatically the outcomes in relative terms (i.e. external versus internalised costs). Moreover, applying a hypothetical factor for the public aversion to catastrophic risks provides a conservative estimate, consistent with the precautionary principle.

Uncertainties in assumptions and assessments

The level of uncertainty associated with external cost estimates results from uncertainties on input data, lack of information on some pathways and simplifying approximations embedded in the models used. The combined uncertainty levels at each stage of the calculations limit the overall confidence in the final results.

In general, for the nuclear fuel cycle, each part of the impact assessment for routine operation provides results that can be considered to have an uncertainty well within one order of magnitude even when generic or average transfer coefficients and assumptions are adopted. However, a lower level of confidence exists for the results of global assessments for the impacts of ^{14}C, ^{3}H, ^{129}I and ^{85}Kr emissions, owing to the generic models used and the assumptions needed to simulate the propagation of very low doses over a large population for very long periods of time. The uncertainty in these estimates probably is greater than one order of magnitude, except in the case of ^{14}C (the global carbon cycle is quite well known). The estimates of doses for the waste disposal stages are also considered to have a greater level of uncertainty due the long period of time over which models must be run in order to assess the global impact.

The estimates of uncertainty ranges generally are based upon expert judgements, taking into account uncertainties on input data, sensitivity of model results to assumptions, and empirical rules regarding the combined effects of uncertainties due to modelling and input data. As a general rule, the longer the period and/or the larger the region considered, the larger the uncertainty in the model and the input data. This is especially important for energy systems since long-term global impacts, such as climate change and damages resulting from low doses of long-lived radioactive waste on large populations over a long period, constitute a major share of estimated external costs.

The difficulty in making relevant assumptions for long-term and/or global impacts is important not only for nuclear energy but also for fossil fuel sources in connection with global climate change. According to the ExternE and other study results, at 0% discount rate the long-term, global impacts represent the largest share of external costs of nuclear-generated electricity and global warming accounts for more than half of the external costs of fossil-fuelled electricity. Clearly, if the boundaries of the system are limited to local environment and the impact assessment covers only a century, or if a discount rate higher than zero is used for long-term assessments, the results, as well as eventual policy measures to internalise externalities, may be quite different.

Consistency of the global economic framework

The methodologies used to assess external costs of energy are based on an inventory of energy system impacts on health, the environment and society, followed by a valuation of impacts. The issue at this stage is to ensure that only the costs of impacts that are not supported by producers, and therefore not paid by consumers, are accounted for as external costs.

Occupational health effects are an example of impacts that, in most industrial sectors of OECD countries are internalised through wages and social security insurance. Usually, wages in risky occupations, such as mining, are higher because of the risk involved and therefore the costs that result from occupational risks are internalised. Nevertheless, most studies on external costs include risks to workers in the scope of their analyses and in the resulting costs (EC, 1995), which may lead to “double counting” of costs.

Other impacts and damages that easily may be a source of double counting, i.e. that are already internalised but nonetheless accounted as external costs, include transportation accidents, severe nuclear accidents and environmental impacts already penalised by taxes. Damages from accidents, including severe nuclear accidents, are largely compensated for by insurance, with the insurance premium being supported by the producer and reflected in the price paid by consumers. Therefore, the remaining externality is much lower than estimated on the basis of damage cost. Similarly, when environmental regulations include a tax on pollutant emission, the producer already supports at least a part of the damage cost through this tax, which is passed on through prices to the consumer.

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5. SUMMARY OF MAIN FINDINGS

Aspects of nuclear energy that often are suggested to entail external costs include: radioactive waste disposal, future financial liabilities arising from decommissioning and dismantling of nuclear facilities, health and environmental impacts of radioactivity releases in routine operation and effects of severe accidents. Indeed, these could become external costs if adequate funds for discharging them would not be established on a timely basis, guaranteed through reliable and independent bodies, and included in the market price of nuclear-generated electricity. Information presented in this report shows, however, that costs for all of these items already are internalised in the cost of nuclear-generated electricity.

The nuclear energy industry operates under regulations that impose stringent limits to atmospheric emissions and liquid effluents from nuclear facilities as well as requiring the containment and confinement of solid radioactive waste to ensure its isolation from the biosphere as long as it may be harmful for human health and the environment. Therefore, the capital and operating costs of nuclear power plants and fuel cycle facilities already internalise a major portion of the above-mentioned potential external costs, and these are reflected in the prices paid by consumers of nuclear-generated electricity. With regard to effects of severe nuclear accidents, a special legal regime, the third-party liability system, has been implemented to provide insurance coverage for any potential damage that might occur, and the cost of this insurance also represents an internalisation of potential externalities.

The future costs of decommissioning of nuclear facilities are already internalised, by being included in the prices charged to customers during the operating lifetime of the facilities. In the case of nuclear power plants, it has been estimated that decommissioning costs represent some 10 to 15% of overnight capital costs of nuclear power plants. Since decommissioning activities and expenses occur after the plant has stopped producing electricity, decommissioning funds are accumulated while the plant is in operation, according to the “Polluter Pays Principle”. In OECD countries a wide variety of mechanisms and schemes are in place for ensuring that decommissioning costs are comprehensively estimated and that the necessary funds are accumulated and securely reserved, to be made available when needed.

High level waste disposal costs, until final repositories are in operation, also constitute future financial liabilities and are treated in the same way as decommissioning costs. Disposal costs are estimated by operators, checked/ audited by responsible governmental bodies, and funds are accumulated by operators, usually as a surcharge per unit of production, to cover the corresponding expenses in due course, thereby internalising this potential externality.

As shown in the report, nuclear electricity generation cost estimates, both for internalised costs and externalities, vary from country to country. Similar variations are observed for alternative technologies. Nonetheless, some generic findings may be drawn from the overall comparison of direct versus external costs for each technology. For fossil fuels and biomass, external costs may be of the same order of magnitude as direct costs. On the other hand, for nuclear electricity, solar photovoltaïc and wind power, external costs are at least one order of magnitude lower than direct costs.

Externalities of energy are of course not limited to environmental and health related impacts, but may result also from macro-economic, policy or strategic factors not reflected in market prices, such as security of supply, cost stability and broad economic impacts on employment and balance of trade. Although those externalities generally have not been subjected to quantitative evaluation, they have been analysed qualitatively in some studies and the results indicate that they are not a major cause of market price distortion. Indeed, information presented in Annex 2 shows that, if such externalities would be internalised, the effect would be positive (i.e. a cost benefit) for nuclear energy.

Annex 1

POSITIVE EXTERNALITIES OF NUCLEAR ELECTRICITY

Energy security

As presented in Chapter 1 (Introduction), externalities are costs or benefits, related to the production and use of goods or services, that are not borne by the producer or consumer. Environmental externalities are the best known, but the concept of externalities can be applied to energy security as well.

An "energy security externality" can be defined as a cost to the economy as a whole, arising from the use of specific fuels, which is not borne directly by the fuel user. By using a particular fuel, an energy consumer might reduce the probability that others be supplied with the energy services they demand at prevailing market prices in the event of a supply disruption. Those others then might have to pay higher prices without compensation (Nuclear Energy Agency and International Energy Agency, 1998, Annex 9). In the electricity sector, two obvious means for reducing the probability of interruption of electricity generation exist: diversity of generation technologies and input fuels; and stockpiling of fuels.

Diversity acts as an insurance against various kinds of problems. Diversity of plant technology, for example, reduces the risk that basic design flaws in a certain technology might cause a large share of the total generation capacity to be shut down for repair or retrofitting. Similarly, diversity of fuel types or sources of supply can minimise the impact in case the supply of one fuel or from one source is interrupted.

In the case of power plant investment decisions, a trade-off is made between low expected prices, but with a high level of uncertainty, and higher expected prices, but with a lower level of uncertainty. Adding some higher-cost generating options then acts as an "insurance policy" against large price increases in fuels consumed in lower-cost plants. It has been argued that higher discount rates, as might be expected in liberalised, more competitive power markets, reduce the incentive for society to insure itself against these risks, since the higher discount rates reduce the present value of future electricity cost increases stemming from rising fossil fuel prices (Nuclear Energy Agency and International Energy Agency, 1998, Annex 9). A study carried out for Scottish Nuclear in 1994 (Scottish Nuclear, 1994) does indeed implicitly predict that competitive power markets provide less diversity. The study argues that it is advantageous for society to insure itself against the risk of fossil fuel price increases by opting for diversity, and notably by using non-fossil energies, especial nuclear. As a central result, it states that nuclear power reduces risk significantly, and at little extra cost.

The nuclear fuel (uranium) resources and reserves are distributed among many countries in different regions of the world, providing diversity and security of fuel supply (International Atomic Energy Agency and Nuclear Energy Agency, 2002). The high energy content of the nuclear fuel, the stability of the ceramic form and the low share of fuel in total nuclear electricity generation cost make it feasible and cost-effective to maintain strategic inventories at reactor sites, allowing ample time for any interruptions in supply to be resolved.

Furthermore, nuclear fuel supply may continue to be sought from various sources other than newly mined uranium, including recycled materials and thorium. The capacity for recycling of nuclear fuel is a unique feature that distinguishes it from fossil fuels which, once burned, are largely dispersed into the environment in gaseous or particulate forms. The spent fuel from the once-through nuclear fuel cycle contains fertile material that can be converted to fissile plutonium in adequately designed reactors. The resource base can be extended by a factor of about 30% by reprocessing the fuel and recycling the fissile material as mixed oxide fuel (MOX) in light water reactors. Moreover, by converting the bulk of uranium resource to fissile material in fast neutron breeders or other types of advanced reactors, it is possible to multiply the energy produced from a given amount of uranium by 60 times or more. A decision to move to those types of reactors and fuel cycles could transform the spent fuel repositories or storage facilities into a mine of nuclear fuel. That is part of the interest in maintaining a capacity for retrieving the spent fuel, seeing it as a potential resource rather than waste.

Environmental protection

In the electricity sector, the environmental dimension of sustainable development is especially relevant since all forms of electricity generation have some impacts on the environment. Nuclear power is no exception, but it has specific characteristics that enable it to make a contribution to environmental protection. For example, a 1 000 MWe reactor uses around 25 tons of fuel per year as compared with 4 million tons of coal burnt by a coal-fired power plant of the same size. Nuclear power plants provide more than 10 000 times more energy per unit mass from uranium than other energy technologies (fossil or renewable fuels). A much smaller amount of material is extracted, processed, stored, and transported for each kWh of electricity produced than for other sources, and the waste volumes are also proportionately smaller.

Moreover, environmental impacts of mining activities are lower for nuclear power than in the case of fossil fuels. The nuclear energy chain does not release gases or particles that acidify rains, contribute to urban smog or deplete of the ozone layer. Nuclear energy is essentially carbon-free[1] and contributes to reduce greenhouse gases emissions that induce global warming, as well as to reduce other gas or particulate emissions that cause local atmospheric pollution. In 1995, nuclear energy avoided the emission of nearly 2 billion tons of carbon dioxide that would have been produced if fossil-fuel power plants had been used instead of nuclear units. Between 1973 and 1995, the use of nuclear energy avoided a cumulative emission of around 22 billion tons of carbon dioxide. In the long-term, stabilising the emissions of greenhouse gases world-wide could be facilitated through expanded use of nuclear power since it is one of the few existing technologies that could currently supply a large share of non-carbon energy demand.

These environmental advantages constitute a positive externality (benefit) for nuclear power, which usually is not explicitly recognised in economic analyses.

Research and development spin-off

Research and development (R&D) costs are a specific example of infrastructure costs when they are funded by the government. The total national and international investment in nuclear energy R&D has been high, but it has to be noted that many countries engage in R&D to improve their technology

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[1] There are no emissions of greenhouse gases, other pollutant gases or particulates from the nuclear power plants themselves. However, the use of fossil fuels at other stages of the nuclear energy chain (e.g. for uranium mining, fuel preparation, transportation) would lead to very small emissions, which have to be accounted for in a “full energy chain” assessment.

knowledge, whether or not they plan (initially or subsequently) to deploy the technologies.

Today, there is a well-established international co-operation framework in the nuclear energy field, especially for R&D to enhance the overall efficiency of national efforts and facilitate technology development. Governments and industries benefit from pooling resources and carrying out studies jointly instead of separately. As national nuclear R&D budgets are shrinking, they tend to concentrate on co-ordinated strategies aiming towards technology progress and safety enhancement. Government-funded R&D does not substitute to industry-supported R&D, but complements it in the fields that are under the main responsibility of the government, such as basic sciences, safety and environmental protection, innovative concepts requiring long-term development. Technology transfer, technical assistance and co-operation with non-member countries are also important in the light of the growing demand for energy. Governments from OECD countries have an important role in providing those countries with information and resources to address key issues in the fields of nuclear power electricity generation.

Past R&D expenditure is sunk and has no direct financial bearing on future investment decisions, whereas much ongoing R&D is likely to be related to future systems development. Utility funded R&D or technical support related to a specific future plant should and does have its costs reflected in the generation costs. Some public funded R&D costs are recovered from utilities via licensing or royalty payments. On the contrary, publicly funded generic R&D should not appear in investment analysis costs.

All advanced technologies call for new materials, instrumentation, techniques and skills, many of which can find application in other sectors of the economy. This use of products or skills developed as part of one technical programme in other spheres of economic activity is commonly called “spin-off”. The term may suggest that the process is wholly accidental or incidental to the main thrust of an R&D programme. In the case of nuclear power, however, while some technology transfer is fortuitous, a far larger part arises from the conscious recognition of the need for, and benefits from, the wider application of the capabilities that are developed. Indeed, nuclear power has had spin-off that has contributed to technical progress in many fields. Most countries involved in nuclear development can point to past and continuing economic benefits which would not have been expected to arise had attention been focused on less demanding technologies. Four main avenues of spin-off benefits can be recognised:

- application of special materials;

- application of new techniques;
- application of intellectual capital;
- creation of new companies or entirely new industries.

Nuclear science and technology have contributed to substantial progress in fields as diverse as medicine and health (diagnosis and treatment); industrial processes and their control (new products, improved processes and greater manufacturing efficiency); environmental science, monitoring and control (detecting pollution, monitoring transport and plant uptake mechanisms, effluent control); agriculture and farming (pest control, monitoring fertiliser efficiency, nuclear techniques for plant development); mineral exploration and extraction, etc.

These spin-off effects constitute a positive externality (benefit) on nuclear R&D, but the magnitude of the benefits is not readily susceptible to a rigorous quantitative analysis, except in instances where, for example, a new material or an improved process efficiency substitutes directly for earlier techniques.

Balance of payments

The effect of policy choices on balance of payments is used frequently as an argument to favour one option over another, on the basis that anything that reduces imports or increases exports is beneficial to the economy.

The nuclear industry can affect trade balances through the import or export of technology and/or fuels. Its potential for technology export has been advanced as an argument in many countries in support of its development, while its ability to substitute low-cost uranium imports for high-cost coal, gas or oil has been presented in support of its deployment domestically. Even countries with indigenous fossil-fuel supplies can argue that their substitution by lower-cost uranium will free the more expensive fuels for export.

Where trade imbalances occur, countries with chronic deficits will be likely to find greater difficulty in borrowing and to see their currencies depreciating in real terms relative to those of others with more balanced economies. In such countries, some additional economic value might be attached to technologies or products offering import substitution or export growth, in the sense that they offer the prospect of relieving one constraint on domestic economic growth.

The magnitude of this economic value is, however, very dependent on the economy concerned and the scenario adopted. Thus, for a technology which is cheaper and reduces import dependence, as nuclear power does for some OECD countries, the direct economic saving of the cheaper technology will be enhanced by the trade balance effect. On the other hand, where an expensive indigenous resource such as coal is displaced by cheaper import fuel, the impact of lower costs will help to offset, or even exceed, the negative trade balance effect of the imports.

For a country using light water cooled reactors and importing its nuclear fuel, including nuclear fuel services, the economic benefit can be substantial in comparison with importing coal, gas or oil. It has been estimated (Nuclear Energy Agency, 1992) that a 1 000 MWe light water reactor (LWR) operating at a load factor of 75% can save some USD 60 million to USD 100 million per year in imported coal fuel costs, or more for oil or gas, depending on how much of the nuclear fuel cycle services are imported. It has to be emphasised that these savings apply only to those OECD countries with out access to indigenous fossil-fuel supplies.

In summary, nuclear power development and deployment can have a positive effect on a country's balance of payment, but the magnitude of the effect will be dependent on the national situation vis-à-vis domestic fossil-fuel supplies and on the relative costs of nuclear and alternative technologies.

Price stability

The introduction of an additional large-scale energy source, like nuclear power, into the world's energy supply mix helps to provide price stability in three distinct ways.

Firstly, the availability and use of the additional source reduces demand pressures on the fuels it displaces, and leads to their future prices being lower that they otherwise would have been. This benefits all users of the other fuels, even though they themselves may not have adopted the new source. Thus, adoption of nuclear power by the industrial countries will have helped to restrain the world market price of oil and coal, to the benefit of developing countries amongst others.

A Japanese study (Yajima, 1990) has attempted to quantify the effect on fossil-fuel prices of nuclear power's contribution to world energy supplies. The analysis examined the cost implications of suspending nuclear power production globally, either immediately or over a ten-year period. In both cases, oil and coal prices were projected to rise to nearly their 1990 levels by 2005, resulting in a decline in the Japanese GDP by 1% in real terms by 2005. The effect of similar fuel price changes on the economies of other countries would differ depending on their use of imported fuels.

Secondly, one characteristic of nuclear power, and also of renewables, is its small post-construction operational costs (including fuel) in most OECD countries, compared with the fossil-fuelled options. Economic analyses for decisions on generation options take account of projected increases in the real price of fuels but, should the projections prove wrong, the cost of fossil-fuelled power is far more sensitive to error than nuclear power (or renewables).

Thirdly, the adoption of a significant amount of a non-fossil energy source can reduce significantly the economic impact of disruptions in the supply of fossil fuels, as was discussed above in the section on security of supply. An additional benefit is that the decreased dependence on imported fossil fuels reduces the leverage, and hence the likelihood of occurrence, of politically or economically driven artificial constraints of fossil fuel supplies.

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Annex 2[1]

HEALTH AND ENVIRONMENTAL EXTERNALITIES OF NUCLEAR ELECTRICITY

Routine operation

In normal operation under independent and effective regulation, nuclear power plants and fuel cycle facilities have relatively small health and environmental impacts. Radiation protection regimes based upon the "As Low As Reasonably Achievable" (ALARA) principle are effective in limiting the impacts of ionising radiation to workers in nuclear facilities and to the public to levels largely below regulatory limits. For the evaluation of external costs, the technologies taken as reference at each stage of the nuclear fuel cycle are assumed to be the best available technologies. In some cases, the different processes may be carried out at different locations, including a hypothetical facility for the high-level waste disposal, as shown in Table A.2.1 for the French nuclear fuel cycle.

Table A.2.1 Stages considered in the evaluation of the French nuclear fuel cycle external costs

Stage of the French nuclear fuel cycle	Site	Technology used
Mining and Milling	Lodève	Underground and open pit mines
Conversion	Malvesi and Pierrelatte	Yellowcake conversion to UF_6
Enrichment	Pierrelatte	Gaseous diffusion
Fuel Fabrication	Pierrelatte	Conversion of UF_6 to UO_2 pellets
Electricity Generation	Belleville, Flamanville, Nogent, Paluel, Saint-Alban	1 300 MWe PWR
Reprocessing	La Hague	PUREX process
Waste Disposal	Aube	Surface disposal
	Auriat	Underground disposal (hypothetical facility)
Transportation	–	Road and rail

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[1] This Annex is based mainly upon the assessment of the French nuclear fuel cycle carried out within the ExternE project (EC, 1995; Dreicer *et al.*, 1995).

Mining and Milling: a large mine located at the Lodève site in Hérault was chosen as the reference site. It was operated by COGEMA from 1975 to 1997 and included open pit and underground mines. It is representative of modern uranium mining techniques in France.

Conversion: the conversion of yellow-cake to uranium hexafluoride is carried out at Malvesi near the city of Narbonne (10 km from the Mediterranean Sea), and at Pierrelatte, in the Rhône River Valley between the Alps and the Massif Central. These plants are operated by COMURHEX.

Enrichment: the enrichment plant, operated by EURODIF, is situated on the Pierrelatte site and has been in operation since 1979. It supplies over one-third of the enriched uranium consumption in the world.

Fuel fabrication: there are two fuel fabrication facilities, operated by FBFC (Franco-Belge de Fabrication du Combustible), at Romans and Pierrelatte in the south-eastern part of France, which are equally representative. The Pierrelatte site was used as reference within the ExternE project.

Electricity generation: in France, more than 75% of the electricity is produced by nuclear power plants. This electricity is almost totally generated by the 58 PWRs (Pressurised Water Reactor) currently operated by EDF (Électricité de France). Although the 900 MWe PWR technology represents more than 50% of the reactors in operation in France, the 1 300 MWe PWR is considered to be representative of modern technology employed today. The evaluation of the external costs from routine operation comes from an average of five 1 300 MWe reactors (Belleville, Flamanville, Nogent, Paluel and Saint-Alban). These five sites are located in different areas of France and can be considered to represent the various types of sites currently in use. The average yearly production per reactor is about 7 TWh. For the electricity generation stage, in addition to the routine operation of a PWR, the construction and decommissioning are included in the assessment. The results for these phases of a 1300 MWe PWR are normalised to an average of 30 years of production.

Decommissioning: the dose estimates for the decommissioning stage were based upon a 1978 US study published by NUREG, because there is no concrete experience in France on the decommissioning of a large PWR. The public dose estimates associated with the decommissioning of a PWR are 1.45E-04 man.Sv/TWh in the case of deferred dismantling after 50 years. The corresponding health effects expected to result from the public collective doses are 7.25E-06 fatal cancers/TWh, 1.74E-06 non-fatal cancers/TWh, and 1.45E-06 severe hereditary effects/TWh.

The non-radiological public impacts resulting from the decommissioning of a nuclear power station are principally due to the transport of the resulting waste. In a first approximation, the non-radiological public impacts associated with the transportation of materials away from the site are assumed to be similar to those associated with transportation in the construction phase of the PWR. The expected public impacts of decommissioning, due to normal traffic accidents during the transportation of materials, are 8.5E-05 deaths/TWh and 5.4E-04 injuries/TWh.

For workers, external exposure is considered to be the dominant pathway. The occupational doses are based on task-by-task analyses of the number of hours needed and the expected dose rates associated with each task. The occupational exposure is dominated by the ^{60}Co contamination of piping systems, tanks and pools. The amount of time spent in the radiation zones directly influences the external exposure received by the workers. Annual collective occupational exposures during decommissioning are estimated to be very small due to the long period of time over which decommissioning is conducted.

The total dose associated with the decommissioning of a PWR is estimated at 2.16E-02 man.Sv/TWh. The corresponding health effects expected to result from the occupational collective doses are 8.64E-04 fatal cancers/TWh, 2.53E-03 non-fatal cancers/TWh, and 1.30E-04 severe hereditary effects/TWh. For occupational accidents, the accident statistics from the French workers compensation system for the building industry is applied. Normalised to the energy produced during the lifetime of the plant, the results are 2.9E-03 deaths/TWh, 59 working-days-lost/TWh and 0.18 permanent disabilities/TWh.

Reprocessing: the French commercial reprocessing plant is located at La Hague in Normandy on the north-western coast of France near the Flamanville power plant. The plant has two main units: UP2 (usine plutonium 2), which was brought into service in 1966, and UP3, which started up in 1990. Data presented in this section are based on the UP3 unit, which was built with a design capacity for reprocessing 800 tonnes of spent fuel per year. Emissions data used in ExternE were based on the year 1991, when the plant was not in full operation. The 351.4 t of spent fuel reprocessed in 1991 are considered to be equivalent to 81.4 TWh of nuclear electricity generation, and this value was used to calculate the emissions per TWh. For the assessment, it was assumed that the UP3 plant will operate for 30 years with the annual emissions per TWh remaining constant at the value calculated for 1991.

The global collective dose to the public from these emissions was estimated at 10.3 man.Sv/TWh, and the corresponding public health effects expected to result from this dose are 0.52 fatal cancers per TWh of nuclear electricity generation, 1.24 non-fatal cancers/TWh and 0.10 severe hereditary effects/TWh. It has to be stressed that these are effects that might occur over a time period of 100 000 years, and that the estimated effects would be distributed over a global population of 10 billion people, i.e. over 10 thousand billion deaths.

In the occupational domain, UP3 was designed to limit individual doses to workers to less than 5 mSv per year. Based on the measured collective dose for workers (1.76E-03 man.Sv/TWh), the estimated occupational health effects are 7.04E-05 fatal cancers/TWh, 2.11E-04 non-fatal cancers/TWh and 1.05E-05 severe hereditary effects/TWh. The non-radiological occupational impacts cannot be estimated directly from UP3 data on annual accidents, because the data are not statistically representative. Therefore, the assessment used data reported by the French chemical industry for the average number of accidents from 1980 to 1981. Based on these data, the non-radiological effects on UP3 workers are estimated to be 6.1E-04 deaths/TWh, 9.87 working days lost/TWh and 3.76E-02 permanent disabilities/TWh.

Waste disposal: for low and intermediate level radioactive waste the repository of the Centre de l'Aube, located 180 km east of Paris, was used for the assessment. It covers about 1 km^2 and is designed to contain the waste equivalent to about 10 000 TWh of electricity production. Since there is no high-level radioactive waste disposal site in operation in France, the ExternE study used the results reported in the European PAGIS (Performance Assessment on Geological Isolation Systems) study, for a hypothetical deep geologic disposal site on the Massif Central in France (CEC, 1998). This hypothetical site is assumed to hold vitrified waste from 1 800 GWy of nuclear electricity generation.

Transportation: the transportation of material between sites is considered as a separate fuel cycle stage in the assessment. In France, the transport of radioactive material by road or rail follows the International Atomic Energy Agency approved safety practices. The distances vary between 5 km and 900 km. Transport of material for the production of fuel, the actual fuel, and the waste generated during the cycle are considered for both routine conditions and potential accidents.

The distribution of public and occupational collective doses from the different stages of the French nuclear fuel cycle in routine operation is given in Table A.2.2.

Table A.2.2 Distribution of collective doses from the French nuclear fuel cycle

Fuel cycle stage	Collective dose (man.Sv/TWh)		
	Public	**Occupational**	**Total**
Mining and milling	1.77E-01 (1%)	1.12E-01 (32%)	2.89E-01 (2%)
Conversion	3.50E-05 (0%)	2.29E-03 (1%)	2.32E-03 (0%)
Enrichment	2.68E-05 (0%)	8.33E-06 (0%)	3.52E-05 (0%)
Fuel fabrication	9.21E-06 (0%)	7.14E-03 (2%)	7.15E-03 (0%)
Electricity generation	2.16 (17%)	2.02E-01(58%)	2.36 (18%)
Decommissioning	1.45E-04 (0%)	2.16E-02 (6%)	2.17E-02 (0%)
Reprocessing	1.03E+01 (80%)	1.76E-03 (1%)	1.03E+1 (79%)
LLW disposal	2.57E-02 (0%)	1.00E-04(0%)	2.58E-02 (0%)
HLW disposal	1.36E-01 (1%)	6.00E-07 (0%)	1.36E-01 (1%)
Transportation	9.50E-04 (0%)	1.14E-03 (0%)	2.09E-03 (0%)
Total	**1.28E+01 (100%)**	**3.48E-01 (100%)**	**1.31E+01 (100%)**

The total global collective dose calculated for both the general public and workers, integrated for a time period of 100 000 years, is 13.1 man.Sv/TWh taking into account all the stages of the nuclear fuel cycle. The reprocessing stage, including global impact and the occupational doses, is the largest contributor to the total collective dose with 79% of the total (10.3 man.Sv/TWh). The second largest contributor is the electricity generation stage with 18% of the total collective dose (2.36 man.Sv/TWh). Mining and milling and high-level waste disposal, with respectively 2% and 1% of the total collective dose, are minor contributors and the other stages have nearly negligible contributions.

Public exposure represents over 97% of the total collective dose of the French nuclear fuel cycle, while the total collective dose for the workers, about 0.35 man.Sv/TWh, represents some 3% of the total. The reason that the public exposure accounts for the major share of the total is due to the much larger number of persons in the public domain (10 billion people). The reprocessing and the electricity generation stages are the main contributors to public collective dose, representing respectively 80% and 17% of the total. For workers, the electricity generation and the mining and milling stages are the main contributors to the occupational collective dose, with 58% and 32%, respectively.

The evaluations carried out in other countries (EC, 1999) and with generic assumptions (NEA, 2000) illustrate the sensitivity of the results to the nuclear fuel cycle option adopted and to local conditions. Nevertheless, results from various studies for total health impacts are in agreement within a rather narrow range. The NEA study concludes that there is very little difference in total collective doses to the public and to workers between the open and closed fuel cycle, although the main contributors to the total are different in each case.

The ExternE estimates for the French nuclear fuel cycle highlight the weight of long-term effects in the total health impacts accounted for in routine operation, as shown in Table A.2.3 (Le Dars *et al.*, 2002). Short and medium-term impacts taken together represent less than 20% of the total while long-term impacts account for more than 80%. However, most health impacts arising from the different stages of the nuclear fuel cycle occur in the short and medium-terms, except for electricity generation, reprocessing and waste disposal stages, which create long-term health impacts. The occupational impacts, essentially due to non-radiological accident injuries, are mainly in the short-term category.

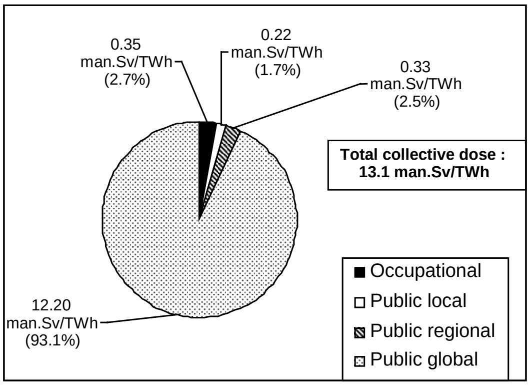
Table A.2.3 Time distribution of the health impacts from the French nuclear fuel cycle

Health impacts	**Short + medium term % (0-100 years)**	**Long term % (>100 years)**
Mining and milling	99	1
Conversion	99	1
Enrichment	99	1
Fuel fabrication	99	1
Electricity generation	1.7	98.3
Decommissioning	100	0
Reprocessing	10	90
LLW disposal	3	97
HLW disposal	0	100
Transportation	100	0
Total	**17.5**	**82.5**

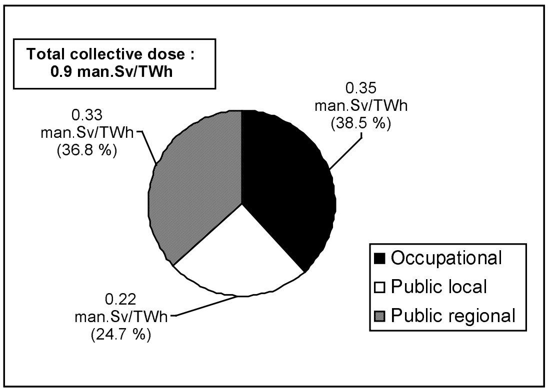
The importance of global impacts versus local and regional impacts is illustrated in Figure A.2.1. The total collective dose for all the stages of the fuel cycle integrated over a period of 100 000 years is 13.1 man.Sv/TWh of which 12.2 man.Sv/TWh are due to global public dose (owing to the global population being so much larger than local and regional population). Without global assessment, i.e. limiting the range of the dose integration to 1 000 km, total collective dose is reduced to 0.9 man.Sv/TWh, nearly equally distributed between occupational, public regional and public local.

It should be stressed that the estimated global collective dose results mainly from ^{14}C emissions, causing minute doses each year but remaining radioactive over millennia. Although the assumptions and model adopted are relevant in the light of the precautionary principle they may be overly conservative since the release of ^{14}C from one additional 1 300 MWe PWR adds only around 1.4E-08 mSv/y to a background radiation of some 2.4 mSv/y.

Figure A.2.1 Distribution of the total collective dose from all stages of the French nuclear fuel cycle



Local, regional and global impacts



Local and regional impacts

The outcomes of the ExternE estimates for the French nuclear fuel cycle are summarised in Tables A.2.4 and A.2.5 (Le Dars *et al.*, 2002) which provide total external costs and their distribution in time (short, medium and long term) and geographic range (local, regional and global). The totals include external costs associated with decommissioning, which account for 1.70E-02 m€/kWh at 0% discount rate, 5.96E-03 m€/kWh at 3% discount rate and 7.93E-04 m€/kWh at 10% discount rate.

Table A.2.4 Distribution of external costs of nuclear energy by time period (m€/kWh)

	Discount rate		
	0%	3%	10%
Short term	6.83E-02	5.87E-02	4.95E-02
Medium term	3.34E-01	3.90E-02	4.07E-03
Long term	2.11E+00	6.63E-04	7.47E-05
Total	2.51E+00	9.84E-02	5.36E-02

Table A.2.5 Distribution of external costs of nuclear energy by geographic range (m€/kWh)

	Discount rate		
	0%	3%	10%
Local	1.78E-01	7.69E-02	5.18E-02
Regional	6.19E-02	8.18E-03	9.24E-04
Global	2.27E+00	1.33E-02	8.81E-04
Total	2.51E+00	9.84E-02	5.36E-02

Nuclear reactor accident

The evaluation of the consequences of a severe nuclear accident plays an important role in the reliability and credibility of the overall external costs of nuclear-generated electricity. The following section describes the methodology used in the ExternE study and presents the results obtained in that study in the French case as well results from other studies. The assessments carried out refer to a severe accident at a nuclear power reactor. Although some fuel cycle facilities handle large inventories of radioactive material, their operation entails lower risks than reactors and it is generally agreed that their accident risks do not contribute significantly to the total external cost of nuclear-generated electricity.

Methodology

The methodology generally used to evaluate the impacts of accidental releases is based on expected damages (Markandya *et al.*, 1998). Risk is defined as the summation of the probability of the occurrence of a scenario leading to an accident multiplied by the consequences resulting from that accident over all possible scenarios. The results are very dependent on the values for the probability of occurrence of accidental releases, the magnitude of the release, and the exposure scenarios evaluated.

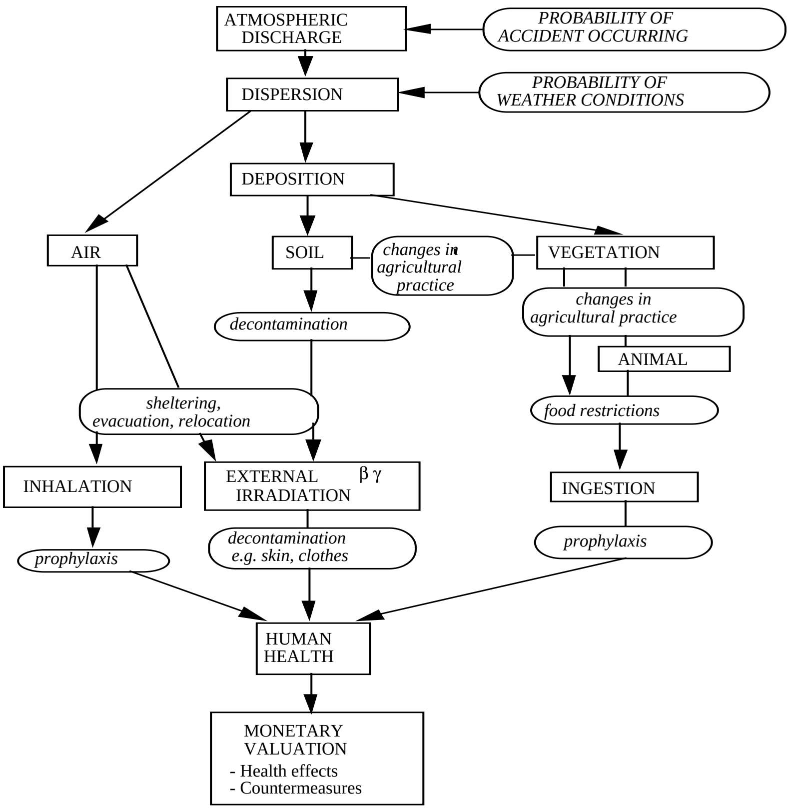
In the case of a severe nuclear reactor accident, probabilistic safety assessment (PSA) can serve as a basis to evaluate the potential causes of the accident, the possible probabilities of occurrence, and the corresponding expected environmental releases. A large number of PSA studies have been carried out for different types of reactors in various countries that give values of core melting probability. For example, the study of the USNRC (NRC, 1990) and other studies on European reactors provide estimated probabilities of a core melting for PWRs ranging from 3.7E-06 per reactor.year for Biblis in Germany to 3.4E-04 per reactor.year for Zion in the United States. The ExternE estimates for the French fuel cycle are based on a core melting probability of 1xE-05 per reactor.year.

The second step of the assessment requires identifying and estimating the source terms potentially released in the environment and conditional probabilities associated with these release scenarios. The magnitude and characteristics of radioactive material that can be released following a core melting would depend, inter alia, on the performance of the containment and its related safety systems. If the containment suffers massive failure or is bypassed, a substantial fraction of the volatile content of the core could be released to the environment, whereas if the containment remains intact the release would be very small. Figure A.2.2 illustrates the pathway for the assessment of a nuclear reactor accident, from the releases after the core melting to the monetary valuation of health damages.

The source term adopted in the ExternE estimate corresponds to a release of about 1% of the core (ST21), which is of the same order of magnitude as the reference accident scenario used by the French national safety authorities. To illustrate the sensitivity of the results, the impacts of the three other source term scenarios are presented also. The largest can be considered as release that would occur after a core melt accident with a total containment breach. The fraction of the core released, based on a source term used in an international intercomparison study, is about 10% of the core inventory. The smallest release can be considered to represent the situation after a core melt accident where all the safety measures have operated as planned and there is only leakage from the intact containment (0.01% of the core inventory).

The probability of a core melt accident, based on a French assessment of a major core melt accident at a 1 300 MWe PWR, is taken to be 1xE-05 per reactor.year. This is broadly consistent with other similar assessments based on engineering fault tree analysis, although a wide range of estimates have been proposed. The conditional probabilities of the large and small releases that would occur after a core melt accident are taken from a US Nuclear Regulatory Commission report, and are 0.19 for the three largest source terms and 0.81 for the lowest.

Figure A.2.2 Pathways for the assessment of a nuclear reactor accident



Radiological health and environmental impacts

There are many models to estimate the evolution of the accidental radioactive releases in the environment and their health impacts in space and time. The main difference between these models come from the degree of precision in transfer models and their capacity to take into account the efficiency of the countermeasures to limit the expected effects on health and the environment. The ExternE study used the COSYMA software developed under the umbrella of the European Commission in the early 1990s (EC, 1991).

The data concerning the source terms for releases after a core melting are drawn from a joint inter-comparison study conducted by NEA and the European Commission (NEA and EC, 1994), based on the worst case release characteristics reported by the US Nuclear Regulatory Commission in NUREG-1150 (NRC, 1990). A 1 250 MWe PWR reactor is considered as the reference technology and four contrasted scenarios are evaluated:

- Source term ST2 assumes a containment failure that results in the total release of noble gases from the core and a release of 10% of the more volatile elements, such as caesium and iodine.
- Source term ST21 assumes a containment failure that results in the release of 10% of noble gases from the core and 1% of the more volatile elements.
- Source term ST22 assumes a containment failure that results in the release of 1% of noble gases from the core and 0.1% of the more volatile elements.
- Source term ST23 assumes a containment failure that results in the release of 0.1% of noble gases from the core and 0.01% of the more volatile elements.

An indicative total collective dose for the population in a radius of 3 000 km has been estimated using COSYMA for the four accident scenarios. The impact of the reference scenario ST21 (core melt with 1% of the core released) is a collective dose of about 58 000 man.Sv and a risk of 0.016 man.Sv/TWh. For the other scenarios considered, the expected risk (consequences x probability of occurrence) varies between 0.001 and 0.078, as shown in Table A.2.6.

Table A.2.6 Expected collective doses for a major reactor accident (ST21: reference scenario for France)

Source term *(% of core released)*	**Core melt probability (per reactor.year)**	**Conditional probability**	**Collective dose (man.Sv)**	**Collective dose x probability (man.Sv/reactor .year)**	**Risk* (man.Sv/ TWh)**
ST2 *(10%)*	1E-05	0.19	291 200	0.55	0.078
ST21 ***(1%)***	**1E-05**	**0.19**	**58 300**	**0.11**	**0.016**
ST22 *(0.1%)*	1E-05	0.19	12 180	0.02	0.003
ST23 *(0.01%)*	1E-05	0.81	1 840	0.01	0.001

* 7 TWh/reactor.year.

In the event of a severe accident, where large amounts of radioactive material could be released into the environment, there would be environmental impacts such as the loss of land use and effects on the ecosystems. Ecological damages such as long-term effects of contamination on wildlife and vegetation, beyond impacts on agriculture and forestry, are difficult to value in monetary terms. Other effects to be considered include loss of recreational use of land and decrease in value of regional land and properties, even when not directly affected by contamination. Although those impacts would need to be covered in a fully comprehensive approach, qualitative estimates and analyses indicate that environmental impacts not accounted for in the direct and indirect costs described below are not significant adders to external costs.

Monetary valuation

The direct costs of a severe reactor accident, calculated with a risk-based methodology for the ExternE reference scenario (ST21, core melt followed by a release of 1% of the core) for France, are summarised in Table A.2.7.

Direct costs taken into account in the assessment include the costs of implementing countermeasures, such as transporting the population away from the area, temporary accommodation and food, costs related to loss of income and capital, agricultural restrictions, decontamination, and costs of radiation-induced health effects. The result per unit of energy produced, 0.0046 m€/kWh, assumes a 0% discount rate for health impacts. The portion of these costs that may already be internalised by nuclear accident insurance has not been evaluated.

Indirect economic consequences of a severe nuclear accident would result from the decrease or interruption in most economic activity (essentially agricultural and industrial production) in the affected territories for a significant period of time. The importance of this interruption would depend on the size of the accident. In terms of monetary indicators, this disturbance of the economic activity would mainly induce a loss of added value corresponding to the different direct and indirect incomes of the various economic agents.

Table A.2.7 Direct external costs of a severe nuclear reactor accident

Core melting probability (per reactor.year)	1E-05
Conditional probability for release	0.19
Total cost of accident damages (M€), including:	17 093
Cost of health impacts	
Local	1 525.2
Regional	9 318.6
Cost of agricultural restrictions	
Local	3 30.7
Regional	5 820.0
Cost of evacuation and relocation	98.1
Direct external cost (m€/kWh)	0.0046

An economic evaluation of indirect effects of a severe nuclear reactor accident can be based on the use of input-output methods. Such methods allow an analysis of amplified impacts on the regional and national economic system through interrelationships in terms of demand and supply of goods and services with the areas affected by the accident. The decrease or interruption in the economic activity of the affected areas would induce a loss of demand and supply in the local and regional economies as well as some economic disturbances in the regions where evacuated or relocated populations would live following the accident. Introducing these modifications into the relationships described by the input-output matrix allows to derive the indirect economic consequences associated with the occurrence of a nuclear accident, reflecting the cost related to the adaptation of economic activities not included in the direct costs.

In order to derive the order of magnitude of these indirect economic consequences, calculations have been performed notably using the NEA-EC exercise (NEA and EC, 1994), the COSYMA code and the monetary value of life adopted in the EC ExternE project. The reference accident (scenario ST21) is assumed to induce an indirect cost which represents about 10% of the regional gross domestic product during the first two years after the accident and about 0.2% of the national gross domestic product. The indirect costs lead to an increase of 25% of the direct external costs of the nuclear accident as far as local consequences are concerned. Based on this calculation, a multiplying factor of 1.25 has to be applied to the local external cost calculations in order to derive the total external cost of the reactor accident. Assuming accident scenarios leading to significant radioactive releases into the environment, the ExternE calculations taking account the indirect costs lead to an external cost associated with a nuclear reactor accident of 0.0048 m€/kWh for a reference source term of 1%, instead of 0.0046 m€/kWh when indirect costs are not included (Schneider, 1997).

The results of a comprehensive economic assessment as presented above may be challenged by civil society in the light of their inability to reflect risk perception. It is generally recognised that there is a discrepancy between the social acceptability of the risk and the average monetary value which corresponds in principle to the compensation of the consequences for each individual of the population affected by the accident (NEA, 2002). Several recent studies have tried to integrate the risk perception in the external costs of severe nuclear reactor accidents and several methods have been tested for this purpose (Markandya, 1998).

Economic developments based on the expected utility approach in order to integrate risk aversion within the evaluation of the external cost of the nuclear accident (Eeckoudt et al., 2000) offer the advantage of relying on available experimental data concerning the risk aversion coefficient. Although a large range of values has been published for this coefficient, mainly based on the analysis of financial risks, it seems reasonable to adopt a risk coefficient around 2 for the specific case of nuclear accident. This leads to an estimated multiplying coefficient approximately equal to 20 to be applied to the external cost of a nuclear accident corresponding to a release of about 1% of the core. Applying this factor leads to an external cost of a nuclear reactor accident of around 0.1 m€/kWh, i.e. about 3.6% of the total external cost of the nuclear fuel cycle with no discount rate and without accident.

A major difficulty that has to be noted when examining risk-aversion approaches is that the theory of external costs is based on the preferences and willingness-to-pay of individuals. In the case of a severe nuclear accident, a large number of individuals is affected. The transposition of economic models using an individual view to a reflection of collective damage appears questionable. Some theoretical developments deal with the integration, in the economic theories of behaviour under risk, of a new concept that could distinguish between a component “anxiety about one’s own life” and another component described as “concern, anxiety or attention about large accidents where a lot of people are affected even if happening at a great distance”. Further research is needed to develop and implement enhanced methodologies in this field.

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Annex 3

FINANCIAL LIABILITIES OF NUCLEAR OPERATORS

Nuclear insurance

Nuclear power companies, like operators of any other plants, are liable for any damage to third parties that their operations may cause, as well as for the welfare of their employees and their own commercial interests. Following normal business practices, nuclear power plant operators cover such liabilities through insurance coverage to provide protection against risks of economic loss, financial consequences of plant shutdown or closure, occupational health and safety claims, construction delays, costs of outage, etc.

A particularly important issue is that of the small, but non-zero, probability of a severe nuclear reactor accident. Although the high safety standards of the nuclear industry ensure that the risk of a severe reactor accident is low, the magnitude of damage that could result to third parties from such an accident is potentially considerable. The economic consequences of a nuclear accident may be broadly summarised as resulting from the cost of the following impacts: countermeasures to reduce radiation doses from possible releases of radioactive materials, radiation-induced health effects in the exposed population, psychological effects, evacuation and relocation of the population in the affected area, impact on economic factors (employment, revenues, losses of capital, tourism, agricultural restrictions…), long-term social and political impact, environmental and ecological impact, and decontamination/rehabilitation of the affected area.

Traditionally, insurance deals with events that are expected to occur with relatively high frequency, but which would have fairly low consequences, and for which both the probability of occurrence and their consequences are generally well established through the statistics of past events. The unique third party liability regime established for severe nuclear accidents, on the other hand, deals with events that have a very low probability of occurrence, but for which the consequences could be very large and extend beyond national boundaries. Furthermore, the fortunately low number of severe nuclear accidents means that the statistics of past events do not provide a meaningful guide to the probability of such accidents. Thus, it is necessary to utilise mathematical tools such as Probabilistic Risk Assessment (PRA) to estimate such probabilities.

Because of the high potential costs that could arise in the unlikely event of a severe nuclear reactor accident, two international conventions constitute the nuclear energy insurance regime: the 29 July 1960 Paris Convention on Third Party Liability in the Field of Nuclear Energy established under the auspices of the OECD and to which 14 OECD countries are Contracting Parties, and the 21 May 1963 Vienna Convention on Civil Liability for Nuclear Damage established under the auspices of the IAEA. These two Conventions are linked by the 1988 Joint Protocol. In particular, the Paris Convention establishes a system in which, on the one hand, governments set a limit on the liability of their operators for nuclear damage, and on the other hand, the operator of the installation concerned is strictly and exclusively liable. Operators are required to obtain insurance coverage up to the liability limit but not beyond it.

More precisely, insurance for nuclear accidents has been structured to provide limited third party liability, with nuclear plant owners being liable for some specified first substantial part of damages to third parties. An industry-funded “secondary financial protection” programme, or in some countries the government, provides coverage for some specified substantial second part of the damages, with any remaining damages to be considered by the national legislation.

For example, under the Price-Anderson Act in the USA, the nuclear plant operators are assessed up to USD 88 million (not to exceed USD 10 million per year per reactor) for the second part of the damages arising from an incident that exceeds the primary level of coverage. In addition, the Congress may establish additional assessments if the first two levels of coverage are not adequate to cover claims. It is important to note that all costs for the Price-Anderson scheme are borne by the nuclear plant owners, either through premiums for insurance to cover liability the first part of the damages or through retroactive assessments to cover the second and third parts of the damages. Thus, the costs are fully internalised in the costs borne by the nuclear plant owners. It is important to stress also that, in return for a limit on liability, the Price-Anderson Act establishes a simplified claims process for the public to expedite recovery for losses, thereby eliminating the delay that plaintiffs in ordinary damage cases must incur before receiving compensation for injuries or damages. It also provides immediate reimbursement for costs associated with any evacuation that may be ordered near nuclear power plants.

Such insurance schemes have been established from the beginning of the civil nuclear power industry and have been considered essential to nuclear power development for two reasons. First, the insurance schemes resolve the problem of open-ended liabilities for investors, and second they provide a high level of assurance and speedy compensation to a public concerned about the possibility of damages from severe nuclear accidents, even though the probability is very small.

However, since the Chernobyl accident, the international nuclear community has recognised the need for extensive revision of the international regime to enhance their provisions for protecting victims and to promote a global regime attractive to all countries. Those efforts resulted in a Diplomatic Conference in September 1997 that led to the Convention on Supplementary Compensation for Nuclear Damage (called the "Compensation Convention"). Today the amount of liability of an operator is not less than 300 million SDRs.[1] Under the Compensation Convention, a two-tier system of compensation for nuclear damage is established. The first tier comprises 300 million SDRs which must be made available by the State in whose territory the liable operator's nuclear installation is situated, while the second tier is comprised of a fund made up of contributions from the Contracting Parties determined in accordance with a formula that is set out in the convention. The exact size of the fund would depend on the installed capacity of the Contracting Parties at the time of the nuclear incident that triggers the operation of the fund.

Special nuclear insurance, which is provided in most countries through a nuclear insurance pool, covers for example health risks of operations that are conducted in radiation zones. This type of insurance carries high fees because it is usually provided by captive insurance companies. Experience to date shows that neither the ability to obtain insurance nor the cost of premiums has been adversely affected for nuclear power plants.

Plant-specific insurance premiums are paid by generators to cover the different nuclear risks. The costs of premiums are incorporated in the costs (and prices) of nuclear-generated electricity, and thereby are internalised.

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1. A Special Drawing Right is a unit of account defined by the International Monetary Fund. It is calculated on the basis of a basket of currencies of five of the most important trading nations. In May 1997, 1 SDR was worth approximately USD 1.39.

Funds for liabilities concerning decommissioning, radioactive waste and spent fuel management

Decommissioning

Permanently closing a nuclear power station is complicated by the presence of radioactivity, therefore two processes are involved: decontamination of surfaces to remove radioactive deposits, and dismantlement of the structure. Three internationally accepted stages of the decommissioning process have been defined by the International Atomic Energy Agency (IAEA). These are:

Storage with surveillance: mechanical openings are permanently sealed, and the contamination barrier remains intact as it was during operation. The containment building is closed. Surveillance, monitoring and inspection of the plant are an ongoing process.

Restricted site release: easily dismantled parts are removed to reduce the contamination barrier to minimum size. This barrier is physically reinforced and a biological shield is ensured. After decontamination, the containment building may be modified or removed if it is no longer required for radiological safety. Access to the building can be permitted, and non-radioactive buildings on site can be used for other purposes.

Unrestricted site use: all parts of the plant containing significant levels of radioactivity are removed, no further inspection or monitoring is required. The site may be used for any purpose.

Two main options are currently under discussion for the decommissioning of nuclear power stations: immediate or deferred decommissioning. The advantage of deferring decommissioning, from several years up to a few decades, is that the radioactivity levels will decrease due to natural decay. This in turn reduces the occupational doses and the protection measures needed.

In the final analysis, the cost of immediate dismantling including conditioning and storage of waste products should be compared with deferred dismantling costs including upkeep and surveillance of the site. There will, of course, be an economic optimum for the time period of the delay, although relatively accurate economic forecasting is needed. In France, for example, the current thinking for the decommissioning of 900 MWe pressurised water reactors envisions a three stage process:

- one year for shutdown, including cooling and evacuation of the fuel;

- four years to achieve a stage 2 situation, leaving only the reactor building;
- fifty years before removing the reactor building and its contents (i.e. stage 3).

The role of governments is essential in formulating regulatory frameworks and policies that allow a coherent step-by-step approach towards decommissioning of nuclear facilities. Governments are responsible for decisions on measures to ensure that adequate funds, collected from users, are set aside and guaranteed to cover, in due course, expenses associated with decommissioning.

Decommissioning of nuclear power plants is recognised to be a costly process, but how costly will largely depend on the extent and timing of the site restoration process. Cost estimates are based mainly on experience acquired with research facilities or small reactors and, with increasing feedback from experience, the uncertainties of those estimates are being reduced progressively. Based on estimates provided by Member countries, the undiscounted costs for nuclear power plant decommissioning range between 15% and 20% of the initial construction costs. However, when discounted and amortised over the electricity production, the contribution of decommissioning to nuclear generated electricity costs is less than 3%.

Nuclear plant owners accumulate funds over the lifetime of the plant to meet the estimated costs of decommissioning. Contributions to decommissioning funds for existing power plants have been predicated on assumed electricity sales volumes, and are collected through a surcharge per kWh of sales over the operating lifetime of the plant. To the extent that the cost estimates are correct and the expected level of electricity sales is achieved, the cost of plant decommissioning may be considered to be fully internalised. In the case of Finland, for example, the estimated cost of decommissioning the nuclear power plants is 1 281 million euros, and the decommissioning fund already had accumulated 1 260 million euros up to the end of 2002.

However, a problem for funding decommissioning is the prospect of early closures (i.e. before the end of their planned operating lifetime) of some nuclear power plants. Indeed, assessing and allocating financial responsibility in the event a shortfall due to early closure is a growing concern in some countries. Since the charge per kWh is based on accumulation of decommissioning funds over the total planned operating life of the plant, early closures will result in insufficient funds to cover decommissioning costs, thereby creating an “externality”. Pressure to resolve this matter arises in countries where there is political debate about whether to close down nuclear power plants before the end of the operating period authorised by license or before the end of their viable economic life. An essential issue is who, among the beneficiaries of the plant operation (i.e. plant owners, electricity consumers, governments who made the political decision for early closure) should absorb the additional costs. One possibility is for the power company that owns the nuclear power plant to continue charging its customers the decommissioning cost levy, in which case no residual externality would be caused by the early closure of the plant.

On the other hand, many nuclear power plants are expected to continue operating beyond their originally planned operating lifetimes, and this will generate excess decommissioning funds, since the value charged per kWh is based on funds being accumulated during the originally planned lifetime.

Radioactive waste and spent fuel management and disposal

Funding for spent fuel and high-level waste management is similar to that for decommissioning. In many cases, a levy for the cost of nuclear spent fuel and waste disposal is taken into account in nuclear fuel costs, creating a fund available to plant operators who are responsible for financing the disposal. Although the absolute value of cost of cost for radioactive waste and spent fuel management and disposal is high, it represents only a few per cent of the full cost of nuclear-generated electricity. This cost is accounted for by nuclear electricity generators and internalised in the prices paid by consumers.

For example, cost estimates for high level waste or spent fuel disposal in geologic repositories of high-level waste have been reviewed and analysed in the 1993 NEA study. Undiscounted estimates provided by Member countries for encapsulation and disposal of spent fuel or reprocessing waste vary between USD 25 000 and 410 000 ($ of 1st July 1991) per tonne of uranium contained in the spent fuel before reprocessing. When discounted, however, the levelised costs are shown to be between about 15% and 30% of the total fuel cycle costs, that is 3% to 6% of overall electricity generating cost. For low level radioactive waste disposal as well, the cost is a very small part of the total cost of nuclear electricity generation, representing only about 0.016 US mills/kWh (July 1995 currency value, with a 3% discount rate).

Nonetheless there are two important uncertainties regarding costs of radioactive waste management. The first is whether or not the funds accumulated will be sufficient to manage/dispose spent fuel and waste according to regulatory requirements. The second is the nature of the disposal or management plan and obtaining its approval. Many countries have already implemented a policy for waste and spent fuel management, but no final decision is taken yet. A critical consequence of not having reached a political consensus on waste and spent fuel management is that a range of uncertainties remains on the management cost. The large potential liability stands as a strong deterrent to future private capital investment in nuclear power, and financial institutions are reluctant to invest in operations that have undefined and unsecured liabilities of such magnitude. How these liabilities are defined and secured will depend for the most part on the government and the standards and requirements established for the spent fuel and waste management.

A variety of funding schemes is currently used in NEA countries. The schemes adopted to guarantee the availability of funds differ in OECD countries depending on a number of factors. These range from dependence on normal accounting practise in large diversified companies (e.g. Canada, France, Germany, Japan, Switzerland) to the establishment of a fund administered and centrally controlled by a State organisation (e.g. Belgium – for the radioactive waste disposal fund; Finland, Italy, Korea, Spain, Sweden, United States). Among intermediate financial schemes already in place, funds may be accrued at a rate determined by a government body, administered by a non-government body separated from the generator of the liability, and spent by the generator when necessary.

In countries where the State owns industrial groups operating a large number of power plants (France, UK), it has not generally been considered necessary to impose a requirement for such funds. On the other hand, some OECD countries (e.g. Belgium, Finland, Spain, Sweden, United States) have established a decommissioning and waste management funding system by law. The main advantages of this funding system are that:

- the liabilities of nuclear power plants are covered directly by electricity consumers (i.e. internalised);
- the funds are assured to be available when they will be needed, irrespective of the financial health of the electricity producer. Even bankruptcy of an electricity producer would not affect the system seriously (e.g. see following box).

USA Yucca Mountain Funding

It was reported recently that an average of USD 1.3 billion per year from the Nuclear Waste Fund and the Defense Nuclear Waste appropriations will be needed between 2005 and 2010 for funding Yucca Mountain.

There currently is more than USD 14 billion in the Nuclear Waste Fund, and the program will continue to collect more than USD 1.5 billion annually through fees and interest.

Source: Nuclear News, March 2003, p. 84.

Suggested Additional Reading

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