Health and Environmental Impacts of Energy Systems

Ari Rabl, Ecole des Mines, 60 boul. St.-Michel, 75272 Paris CEDEX 06, FRANCE *

and

Mona. Dreicer
Environmental Assessments, 4501 Connecticut Ave NW, Washington DC 20008

* address for correspondence

International Journal of Global Energy Issues, vol.18(2/3/4), 113-150 (2002)

Abstract

The assessment of health and environmental impacts of energy production has undergone a major evolution in recent years, reflecting progress in the underlying scientific domains. This paper reviews these developments and draws conclusions. The paper begins with a discussion of the relation between purpose and scope of an assessment. The following sections describe the methodology, with particular attention to key issues such as dispersion modeling, epidemiology, discounting, and the valuation of mortality. In the light of this discussion the major fuel chain studies since 1990 are reviewed and compared, to lead up to the present authors' best estimate of the impacts and damage costs of the most important energy technologies. The generalizability of the results to other sites and variations in emissions is discussed.

Expressed in monetary terms as cost per kWh, the impacts of electricity from fossil fuels are not negligible: even for "best available technology" they are in the range of 10 to 100% of the market price of electricity, being about two to four times higher for coal than for gas. The damage costs of nuclear are much smaller, a few percent of the market price of electricity even at zero discount rate, assuming normal functioning in a stable mature society. Not surprisingly, the damage costs of renewable energies are, in most cases, very small. In view of the controversies surrounding far future impacts, we also present some comparisons of physical impacts, for example showing that the increase in radiation dose from an all nuclear scenario would be small relative to natural background.

Key words: solar energy, renewable energy, fossil fuels, nuclear energy, environmental impacts, health impacts, external costs, air pollution, dose-response functions, atmospheric dispersion

1. Introduction

The assessment of environmental and health impacts or risks is needed for more informed decision-making about:

- choices of energy systems (e.g. coal vs. nuclear), and
- environmental regulations (e.g. limits for emission of pollutants).

A large number of fuel chain studies and comparative risk assessments (CRA) have been carried out since the seventies, and the art and science of fuel chain analysis has been evolving (we use this term instead of the more common "fuel cycle" because the processes form a chain rather than a cycle). Fuel chain studies have been approached in the spirit of life cycle analysis, trying to account for all effects, direct and induced, from mining to waste disposal. The undertaking is so complex that full documentation is difficult. In designing each study a large number of choices need to be made, such as:

- specification of technologies involved in a fuel chain,
- impacts to be included (public and occupational health, visual amenity, etc.),
- assessment boundaries (time and space), and
- models and hypotheses for the analysis,
- key economic parameters (value of life, discount rate),
- underlying philosophy (average case vs. worst case conditions).

One needs to pay attention to the different information needs of different decision makers. This consideration determines the scope of the analysis, as well as the presentation of the results and their aggregation (over affected regions, over time, over sites, over impact categories or over stages of the fuel chain).

Table 1.1. Possible applications of fuel chain studies: decisions and information requirements.

Application	Information requirement
Public choice of technologies (e.g. coal vs. nuclear)	impacts and costs of fuel cycle (aggregation over all stages of the technologies under consideration)
Choice of a new power plant	impacts and costs of power plant (aggregation over the emissions for each of the technologies under consideration)
Optimal dispatching of existing plants	impacts and costs of each of the plants in electric grid (aggregation over all stages)
Optimization of regulations (emission limits, tradable permits, pollution taxes, ...)	impacts and costs, for each pollutant and each polluter (no aggregation)
Green accounting (correction of GNP for environmental damage)	costs, (aggregation over all emission sources in a country)

Therefore one should begin by asking what the results are to be used for. As highlighted in Table 1.1, different applications have very different information requirements. For example, for the optimization of a pollution tax it would be perverse to aggregate the impacts of different actors (fuel supplier and power plant) or of different pollutants, otherwise one would make the polluter pay for someone else's pollution or pay for one pollutant according to the emission of another. By contrast, aggregate numbers for an entire fuel chain are needed for general policy decisions such as the choice between fuel chains, a classic question being "nuclear or coal?"

Furthermore, the uncertainty is different for different impacts, and the role of the uncertainty depends on the application. For example, for a comparison of different coal-burning technologies among each other the uncertainty of the costs of global warming has little effect, except to the extent that the emission of greenhouse gases may be somewhat different. For the choice between technologies the accuracy only needs to be sufficient to permit the correct ranking.

The analysis of the impacts of a single pollutant is far more transparent than an entire fuel chain analysis. It is also far easier to update as new information becomes available, for instance a new study on health effects. By contrast, when there is a change in one of the many elements of a fuel chain analysis, the effect on the aggregated result is not obvious unless they are presented and documented in sufficient detail.

In fact, the very definition of a fuel chain is problematic in view of the large number of elements that need to be specified. The term "fuel chain" is misleading, because it implies a simple monolithic system while the reality is a complex chain whose elements can consist of a variety of different technologies. For example, the power generation stage of the oil fuel chain could consist of a boiler plus steam turbine, or a simple gas turbine, or a gas turbine plus steam turbine (= combined cycle); furthermore, there is a choice of several different pollution control technologies, including the sulfur content of the fuel itself. In recent years emissions have been greatly reduced due to improved technologies and tightened environmental regulations (e.g. flue gas desulfurization cuts SO_2 emissions about tenfold), and further progress can be expected. Clearly the emissions will be very different for each of these options.

When comparing fuel chains, one should also keep in mind at what time of day or year a kWh is to be provided. Because of the difficulties and costs of storing electricity, a technology that is good for meeting base load demand (e.g. a nuclear plant) may be prohibitively expensive for peak demand (where a gas turbine is usually the most cost effective).

The selection of priority impacts also depends on how the results are to be used. The troublesome and highly site dependent issue of the impacts of power lines (electromagnetic fields, visual intrusion), for example, need not be examined if one only seeks a comparison of power plants that can be built in the same locations. It is interesting to note that there has been an evolution in the selection of priority impacts: whereas in the past most studies focused on impacts on workers, recent studies have brought public health impacts to the fore.

A single number for "the" external cost of a fuel chain may most capture the attention, yet it is the most misleading and least useful result. One needs great care to present the results in sufficiently clear detail to meet the needs of different readers.

In this paper the methodologies of CRAs are described and key issues are highlighted (Sections 2 and 3). The results of the latest studies (since 1990) are reviewed (Section 4). In Section 5 we present our own best estimates, for nuclear, fossil fuels (coal, oil, gas) and several renewable energy systems (hydro-electricity, wind, PV, biomass), with special focus on the generalizability to other sites and to variations in the technologies. In Section 6 we draw some general conclusions about CRAs of fuel chains.

2. Methodologies for Assessment of Nuclear and Coal Fuel chains

2.1 Scope of the Analysis

The work begins by specifying the scope of the analysis according to the type of decision to be evaluated (see Table 1.1). The most comprehensive is a complete fuel chain analysis, as appropriate for public choice of energy systems. For other decisions a subset of such an analysis is sufficient.

It is helpful to present the scope in terms of a matrix of activities (or "stages") of the fuel chain and impacts of those activities to be included in the analysis. This is shown in Table 2.1 for coal and in Table 2.2 for nuclear. The scope for the other fossil fuels (oil and natural gas) is essentially a subset of that of coal. Each activity can impose a number of different burdens (e.g. emissions of SO_2 from the power generation stage for coal) and each of these burdens can cause a variety of impacts (e.g. health impacts and crop losses from SO_2).

The coal fuel chain entails a wide variety of different burdens and impacts, and Table 2.1 is a rather simplified presentation with just three general categories of impacts: public health, occupational health, and environment (the latter with subcategories natural environment, agricultural environment and man made environment). Global warming is more difficult to classify because it overlaps two of these three categories (public health and environment). For this reason, as well as the uncertainties and controversies surrounding global warming, it should be treated as a separate category.

For the nuclear fuel chain, CRA is more advanced than for other fuel chains, due to many more years of experience and data gathering. It is also simplified by the fact that although different radioactive materials are released from the facilities, methodologies have been developed for estimating their contribution to the total dose, which in turn can be converted to human health effects by means of universal dose-response functions. The nuclear fuel chain can also entail significant non-radiological occupational impacts. Non-radioactive emissions from the nuclear fuel chain also contribute some impacts but they are not significant. Environmental impacts arise mainly from land use; radiological impacts on the environment are entirely negligible, with the exception of a very large reactor accident.

Table 2.1 Overview in matrix form of the stages and burdens of the coal fuel chain and the major impact categories (oil and gas cycles are essentially subsets, except for upstream impacts).

		Impacts					
		Health		Environment			Extent
Stages	**Burdens**	Occu-pational	Public	Natural	Agri-cultural	Man-made	of Impacts
Mining	Accidents	Q					L; P
	Waste water		nq	nq	nq		L; P,F
	Solid waste		nq, S	nq, S	nq, S		L; P,F
	Particles	nq	nq				L; P
	Land use			nq, S	nq, S	nq, S	L; P,F
	CH_4		Q	Q	Q	Q	G; F
Fuel transport	Accidents	Q	Q				L; P
	CO_2		Q	Q	Q	Q	G; F
	NO_X, SO_2		Q	Q	Q	Q	R; P
Construction of power plant	Land use			nq, S	nq, S	Q, S	L; P
	Accidents	Q	Q				L; P
Operation of power plant	Accidents	Q					L; P
	CO_2		Q	Q	Q	Q	G; F
	Particles		Q			Q	R; P
Primary	SO_2		Q	Q	Q	Q	R; P
air	NO_X		Q	Q	Q	Q	R; P
pollutants	CO		nq				R; P
	toxic metals		Q				R; P
Secondary	O_3 (from NO, VOC)		Q	Q	Q	Q	R; P
air	acid rain (from NO_X, SO_X)			Q	Q	Q	R; P,F
pollutants	aerosols (from NO_X, SO_X)		Q	Q	Q		R; P
	Thermal			Q, S			L; P
	Noise		Q, S			Q, S	L; P
	Waste water		nq	nq			L; P,F
	Solid waste		nq, S	nq, S	nq, S		L; P,F
Power transmission	Land use			Q, S		Q, S	L; P,F
Decommissioning							L; F

Q = quantified in at least one study

nq = not quantified, possibly significant

blank = not considered important

S = highly site-dependent

For Extent of Impacts: L = local, R = regional, G = global; P = present generation, F = future generations

Table 2.2 Overview in matrix form of the stages of the nuclear fuel chain and the major impact categories. Most of the burdens are radionuclide emissions, causing impacts of cancers and hereditary effects. Environmental impacts arise from land use.

Stages	**Occupational health**	**Public health**	**Environment**
Mining and milling	Q; n, r	Q; r	nq, S
Conversion	Q; n, r	Q; r	
Enrichment	Q; n, r	Q; r	
Fuel fabrication	Q; n, r	Q; r	
Construction of reactor	Q; n	Q; n	nq, S
Electricity generation	Q; n, r	Q; r	
Decommissioning of reactor	Q; n, r	Q; n, r	
Reprocessing of spent fuel	Q; n, r	Q; r	nq, S
Low/intermediate level waste	Q; r	Q; r	nq, S
High level waste	Q; r	Q; r	nq, S
Transportation activities	Q; n, r	Q; n, r	
Reactor accident	Q; r	Q; r, S	Q, S

Q = quantified in at least one study
nq = not quantified, possibly significant
blank = not considered important
r = radiological, n = non-radiological
S = highly site-dependent

2.2. Time and Space Distribution of Impacts

A correct analysis requires extending geographic range and time horizon sufficiently far to capture essentially all of the significant impacts. For most air pollutants from coal the geographic range extends over thousands of km, and the time extent is short, or medium in the case of chronic health impacts (but in any case limited to the present generation, less than about 50 years). For greenhouse gases the effect is global and may be significant for the next century or two. Certain radionuclides disperse globally and may have an impact for millions of years. In most other cases, except for ground water pathways and occupational impacts, the impacts are of regional extent.

The types of impacts and associated uncertainty can be quite different in different time frames. This is important to keep in mind when trying to integrate the assessment results in to one bottom line for decision-makers. It is instructive to define approximate time and space categories as indicated in Table 2.3 where the major impact categories (occupational health, public health, environmental) are shown as a 3 × 3 × 3 matrix (space × time × impact). In this way decision makers can carry out comparisons for each element of the matrix.

Table 2.3. Possible categories for distribution of impacts in time and space. Boundaries between categories are approximate, and different choices could be made, for instance present (<50 yr) and future (>50 yr) generations.

a) Coal

Time → Space ↓	**Short** (immediate or <1 yr)	**Medium** (1 yr to 100 yr)	**Long** (> 100 yr)
Local (< 100 km)	occupational health public health environment	occupational health public health environment	
Regional (100 to 1000 km)	public health environment	public health environment	
Global		global warming (public health, environment)	global warming (public health, environment)

b) Nuclear

Time → Space ↓	**Short** (immediate or <1 yr)	**Medium** (1 yr to 100 yr)	**Long** (> 100 yr)
Local (< 100 km)	occupational health	occupational health public health	occupational health public health
Regional (100 to 1000 km)		pubic health	public health
Global		public health	public health

2.3. Analysis of Impact Pathways

To evaluate the impact of a pollutant, one needs to carry out an impact pathway analysis, tracing the passage of the pollutant from the place where it is emitted to the affected receptors (population, crops, forests, buildings, etc.). The principal steps of this analysis can be grouped as follows:

1. Emission: specification of the relevant technologies and the environmental burdens they impose (e. g. tons of NO_x per GWh_e emitted by power plant);
2. Dispersion: calculation of increased pollutant concentrations in all affected regions (e. g. incremental $1 g/m^3$ of O_3, using models of atmospheric dispersion and chemistry for O_3 formation due to NO_x);
3. Impact: calculation of the dose from the increased exposure and calculation of impacts (damage in physical units) from this dose, using a dose-response function (e. g. number of cases of asthma due to this increase in O_3);
4. Cost: the economic valuation of these impacts (e. g. multiplication by the cost of an incident of asthma).

The impacts and costs are summed over all receptors of concern. This approach requires intensive data and computation, and it can yield precise site-specific results. In Sections 3.2 and 5.2 we discuss the generalization of site-specific results to representative numbers that may be needed for decision making.

For burdens other than pollutants the steps of the analysis may be simpler. For example, for occupational accidents one only needs actuarial data (supplemented by scenarios if one wants to assess a fuel chain as it may be implemented in the future).

By contrast to a detailed impact pathway analysis, an approach sometimes called "bottom up", most fuel chain studies took the much simpler "top-down" approach of replacing the dispersion step by average values. Typically a "top-down" assessment would begin with an inventory of emissions in the country or region. The percentage of emissions due to the power plant in question is then assumed to be the contribution of the power plant to the ambient average concentration of the pollutant observed in the region. Such an approach would be exact in a world where the atmosphere is uniformly mixed in the space above each region, without any transfer to or from other regions. That is obviously not a very realistic assumption, except for the case of long lived globally dispersing pollutants such as the greenhouse gases for which the relevant region is the world.

Only the most recent studies [ORNL/RFF 1994, Rowe et al 1995, ExternE 1995 and 1998] have carried out a detailed impact pathway analysis ("bottom-up") to assess the impacts of pollutants.

3. Key Issues

3.1. Emission of a Pollutant

The analysis of impacts begins with the determination of the emission of pollutants (source term). This is straightforward for pollutants such as CO_2 from combustion whose emission rate follows from mass balance. For major pollutants such as particulate matter (PM), NO_x, SO_x, and CO, the emission rates are controlled by government regulations; barring accidents or lapses in enforcement the regulatory values are upper bounds, and the real performance may be better. Unregulated pollutants such as heavy metals from coal, on the other hand, are rarely measured and quite uncertain.

For the nuclear fuel chain, the releases from major facilities such as power plants are routinely monitored and one has a good indication of routine average releases. Emissions from uranium mines are less certain, because the effluent from a mine shaft or from a surface mine is not monitored; here the source term must be estimated from other data.

A change in the emission rate of a particular pollutant at a given site and stack height can readily be evaluated by scaling the corresponding impacts, because impacts from a single power plant (assuming reasonably clean technology) are sufficiently small to permit a linear approximation: the impact can be considered proportional to the emission. The validity of such linearization depends on the impacts, in particular on the linearity of the dispersion model and of the dose-response functions. Linearity is in fact exact for atmospheric dispersion of pollutants without chemical transformation. Linearity has also been assumed as ground rule for most of the health related dose-response functions. By contrast to changes in the quantity of emissions, a change in emission site or stack height requires redoing the entire analysis of impacts from this site.

3.2. Site Dependence

With the exception of long lived globally dispersing pollutants, most impacts are strongly dependent on emission site: a ton of fine combustion particles emitted in a metropolis entails serious health impacts, emitted over the ocean it is harmless. For air pollutants such as particles, NO_X and SO_X, the impacts can easily vary by an order of magnitude due largely to differences in the regional population that is affected. Site dependence is particularly strong for impacts of water pollution, solid wastes, and mining (including accidents).

Site dependence has been one of the major stumbling blocks to using past comparative risk data, because it is not clear how representative the results of a specific site are. The French implementation of the ExternE program is the first to have carried out a systematic analysis of site dependence [Rabl et al 1996, Curtiss and Rabl 1996]. A large number of additional sites have been evaluated during the latest phase of ExternE [1998].

3.3. Health Impacts

3.3.1. Health Impacts of Air Pollution

A consensus has been emerging among public health experts that air pollution, even at current ambient levels, causes a variety of significant health problems, especially respiratory diseases and mortality [Lipfert 1994, Dockery and Pope 1994, Wilson and Spengler 1996, Bascom et al 1996]. There is less certainty about specific causes, but most recent studies have identified fine particles as a prime culprit; ozone has also been implicated directly. There may also be significant direct health impacts of SO_2, but for direct impacts of NO_x the evidence is less convincing.

For the classical air pollutants (particles, NO_X, SO_X, CO) the dose-response functions are usually based directly on air concentrations, hence the names E-R function (exposure-response) or C-R function (concentration-response) seem more logical. Depending on the epidemiological approach used to determine an E-R function, one talks about acute and chronic E-R functions. The most common approach, and the easiest to implement, is to carry out a time series study of a population by identifying short term correlations (over a few days) between air pollution and a health end-point. One chooses a functional form (typically linear, logarithmic or exponential) with one adjustable parameter (more cannot be identified in practice), and determines the parameter by regression against the pollution data. Time series studies identify only short term effects and yield acute E-R functions. This approach has the great advantage of being easy to implement and insensitive to the confounders (such as smoking).

End-points that show up only after a longer period require observations of individuals or populations that are exposed to different levels of pollution [Abbey et al 1991, Dockery et al 1993, Pope et al 1995]. Dose-response functions for chronic effects are notoriously difficult to establish with confidence, and there are only few studies that have determined chronic E-R functions. Of particular importance are the studies of Dockery et al [1993] and Pope et al

[1995] that find significant chronic effects of air pollution on mortality. The difference between chronic and acute E-R functions is not so much in the exposure (most people are chronically exposed) as in the effects that are measured: do they show up within a few days after a pollution peak or only after a longer period? By analogy the terms acute and chronic are also applied to E-R functions for mortality, even though the attributes appear strange in that context.

In ExternE [1995, 1998] the working hypothesis has been to use the E-R functions for particles and for O_3 as basis. Effects of NO_x and SO_2 are assumed to arise indirectly from the particulate nature of nitrate and sulfate aerosols, and they are calculated by applying the particle E-R functions to these aerosol concentrations. With this assumption the impacts of NO_2 and SO_2 become very large, but this is uncertain because there is insufficient evidence for the health impacts of the individual components of particulate air pollution. All dose-response functions for health impacts of air pollution have been assumed linear, in view of the lack of evidence for thresholds at current ambient concentrations (an E-R function in the form of a hockey stick has the same effect as a linear function of the same slope if the threshold is below background concentrations).

3.3.2. Health Impacts of Radiation

Incremental doses to the public from routine operations of the nuclear fuel chain are small compared to the typical background exposures (around 2 to 3 mSv/yr) from natural radiation, radon, medical x-rays, etc. The dose-response functions for this range are obtained by extrapolation from the much higher doses that were received by small case study populations. This entails great uncertainty. For the sake of conservative radiation protection purposes, it has been assumed that at low doses there is a linear dose-response function passing through zero, based on international recommendations [UNSCEAR 1993, ICRP 1990].

3.4. Other Impacts

3.4.1. Impacts on Crops

Dose-response functions are reasonably well established for certain economically important crops such as wheat and rye. Particles have no significant impact on crops, and NO_x is a fertilizer. SO_2 is beneficial at low, harmful at high doses; estimates of damage to crops from SO_2 have turned out small compared to health costs. On the other hand, ozone damage costs to crops appear to be quite significant [Rabl and Eyre 1998].

3.4.2. Impacts on Ecosystems

Estimations of ecosystem impacts, other than agricultural losses, have remained extremely uncertain, if they have been attempted at all. Some estimates have been made of the costs of forest decline due to acid rain, but more recently doubts have been raised about their validity. In general there is a lack of information on ecosystem impacts and their economic valuation.

Land use can certainly be very destructive to ecosystems. Local impacts may also be appreciable for air or water pollution from coal mines, from older power plants without flue gas treatment, and from waste sites. Accidents can cause large local disturbances, the Exxon Valdez oil spill being an egregious example. Near Chernobyl there have been some ecosystem impacts in areas where radiation doses have been very high, but on a gross somatic level there appear to be no long term ecosystem impacts [Dreicer et al 1996].

Air pollution from the normal operation of modern power plants does not seem to have significant direct (i.e. not acid rain) impacts on ecosystems. At first glance this claim may appear strange since human health impacts are significant and one might indeed expect similar impacts on animals as on humans. The explanation lies in what we value: we value ecosystem impacts at the level of a population, human impacts at the level of the individual. Concentrations of air pollutants are generally so small that the incremental mortality is at most a small percentage of the natural rate. Furthermore, most of the deaths from air pollution occur among individuals well beyond reproductive age. If a small percentage of animals die prematurely after having produced and raised offspring, the effect on the ecosystem is negligible. But if any human dies prematurely, we care a great deal.

The situation is different for aquatic impacts: acidification of rivers and lakes has been shown to be detrimental to aquatic life. A river can collect much of the air pollution from a large region, leading to relatively high concentrations in the water, quite apart from direct emission of pollutants to water.

3.4.3. Impacts on buildings and materials

Dose-response functions are fairly well established for the physical impacts of SO_x, and to some extent NO_x, PM, and O_3, on certain important materials (e.g. galvanized steel, stone, plaster, paints), but their application in damage cost estimates is problematic because of lack of information on inventories of exposed materials and on expenditures attributable to soiling or corrosion. One finds a wide range of damage cost estimates, from very small [Rabl 1999] to significant [ExternE 1995], but in any case they are far less than the health costs.

3.5. Upstream and Downstream impacts

3.5.1. Upstream Impacts

Upstream impacts arise from mining (accidents, land use, water pollution, etc.), transport (air pollution from ships, trucks or trains, accidents, etc.) and greenhouse gas emissions (e.g. some methane in coal is released to the atmosphere during mining). The latter is easy to take into account because it is site-independent, and it has been included in the studies of ORNL/RFF and ExternE.

Mining poses a problem because in most cases it takes place in a region different from where the electricity is generated. A typical example is France, where most of the coal is imported, from the USA, Australia, S. Africa and so on. Sizable quantities of air pollution are emitted by coal transport [Rabl et al 1996], but their impacts may be small because of low population density on the ocean. Accident rates per ton of coal differ by three orders of magnitude between different countries. ExternE [1995], Ball et al [1994] and ORNL/RFF [1994] consider only a limited source of coal (the country of the authors) and it is not clear how representative their results are of the total coal supply. For the nuclear fuel chain a very detailed analysis of upstream impacts (particularly fuel production) has been carried out, but here, too, only mines within the country have been considered until 1995. Only the latest phase of ExternE [1998] has assessed upstream impacts in the countries where the fuel is imported from.

Another type of upstream impact arises from the construction of the installations involved in a fuel chain, in particular from the pollution emitted during the production of the materials. For power plants using nuclear or fossil fuels the impacts from the production of the materials can be neglected because they are several orders of magnitude smaller than those from the operation. For most renewable energies, on the other hand, the emissions from operation are very small or negligible, and most the impacts arise upstream (but they tend to be small, see Section 5.4).

3.5.2. Wastes

Waste disposal has become an important consideration in technology choices, for both radioactive wastes and for wastes from coal. Impacts of solid hazardous wastes are difficult to predict to the extent that they depend on future waste management decisions. In principle such impacts can be kept negligible by storing wastes in well managed leak proof facilities. But will the integrity of the containers and liners be maintained forever? In case of a leak the most likely occurrence is leaching into the ground water, and the impacts tend to be limited to the local range and could be stopped or corrected, if appropriate measures are taken. Technologies for alternative methods of solid waste disposal are evolving; for example, coal ash is increasingly used as additive in building materials. Fly ash can be stabilized in concrete or glass. For coal none of the studies have succeeded in quantifying physical risks from solid wastes, which have the potential of being significant on the local level.

In attempts to solve radioactive waste management problems, numerous studies have been done over the years for both hypothetical and actual sites. Disposal sites for low- and intermediate-term waste have been operating for some time but to date no permanent long-term waste disposal of high-level radioactive waste has been implemented. Recent nuclear fuel chain estimates have been made based on scenarios of leaks from existing intermediate-level facilities. Generally worst cases scenarios are considered (e.g. total breach of containment at 300 years, or a facility with no oversight in the future) and may not be representative of what will evolve. The probability of a leak should be accounted for but it is very difficult to estimate.

3.6. Economic Valuation

3.6.1. Ground Rule

In earlier studies only direct costs were included. Today, the ground rule is to account for individual preferences rather than just direct costs. It turns out that the single most important parameter, for the nuclear and for the fossil fuel chains, is VSL ("value of statistical life"), the collective willingness-to-pay for reducing the risk of a premature death. In ExternE [1995], a

European-wide value of 2.6 MEuro (3.4 M$) was set; this is close to the values chosen for the other studies; for the latest phase the value has been increased to 3.1 MEuro [ExternE 1998].

3.6.2. Valuation of Life Span Reduction

A crucial question for the monetization of air pollution mortality is whether one should multiply the number of deaths N_{death} by VSL

$$cost_{VSL} = N_{deaths} \times VSL \qquad (1)$$

or whether one should base the valuation on the years of life lost (YOLL) per death

$$cost_{YOLL} = N_{deaths} \times (YOLL/death) \times v_{YOLL} \qquad ? \qquad (2)$$

The difference can be very important because most premature deaths from air pollution seem to involve only a slight shortening of life, unlike most deaths from accidents. The value v_{YOLL} of one YOLL is derived from VSL by imagining the latter as a discounted series

$$VSL = \frac{v_{YOLL}}{1+r} + \frac{v_{YOLL}}{(1+r)^2} + ... + \frac{v_{YOLL}}{(1+r)^{T_l}} \qquad (3)$$

where r = discount rate and T_l = number of years of life lost. For r = 0 one finds $v_{YOLL} = VSL/T_l$. In the $r \to \infty$ limit VSL approaches v_{YOLL} and the two valuation methods become equivalent. For example, suppose that a policy A can be implemented in two steps, the first, A', which increases life expectancy by 1 year, and the second, A", which adds 4 more years. For this latter the value according to $cost_{VSL}$ is zero. In effect any years beyond the initial extension are discounted so heavily as to have no benefit. In other words, a policy that increases (decreases) life expectancy, without changing the number of premature deaths, has zero benefit (cost).

Analysts of public policy lament the shortsightedness of the unreasonably high discount rates implicit in so many public or private decisions. The aim of this paper is to offer rational guidelines for public policy rather than trying reflect the irrationalities and inconsistencies of uninformed decisions; we therefore recommend a YOLL valuation.

Valuing a year of life is of course a delicate matter, even more problematic than an average value of life VSL. Should the value of a YOLL be higher or lower for old age than for youth? There seem to be no firm data, and a priori one can think of arguments either way. For collective decision making it might be preferable to avoid such intergenerational questions altogether by using a single value per YOLL. That is also in the spirit of the general practice of using a single value of VSL for all individuals in a population, without distinction of wealth, health or will to live.

All the fuel chain studies before 1997 have used the VSL valuation; ExternE [1998] is the first to try a YOLL valuation. The chief difficulty and uncertainty lies in estimating the life span reduction ΔT for air pollution [Rabl 1998]. For the value of a YOLL ExternE [1998] assumes 0.083 MEuro for chronic mortality and 0.155 MEuro for acute mortality, the difference being due to discounting and the time delay between exposure and death. For the cost of a cancer ExternE [1998] assumes 1.5 MEuro for fatal and 0.45 MEuro for non-fatal cancers. It turns out that this implies only a small change in the overall cost per kWh of the nuclear fuel chain and so we simply cite the numbers from ExternE [1995].

3.6.3. Discounting

The discounting of future costs is straightforward in principle, but the choice of the appropriate discount rate is controversial, especially for intergenerational costs because they become negligible, unless the rate is very close to zero. For intergenerational costs one needs to distinguish the two main components of the discount rate: economic growth, and pure time preference (i.e. the premium people pay to be able to consume now rather than in the future).

If one chooses as criterion the preferences of future generations, the appropriate discount rate for intergenerational effects is significantly lower than the conventional social discount rate, because it should include only the growth of the economy (the pure time preference component of the discount rate involves only redistribution within the current generation and does not create wealth to compensate future generations) as shown by Rabl [1996]. The key question is an ethical one: should the generation that makes a decision compensate future generations for all the damages imposed on them? To see why such compensation is not possible with the conventional discount rate, imagine that a special fund is set up to cover all future damages and reinvested permanently at the conventional discount rate; that is in fact the implicit assumption of a cost-benefit analysis. Assuming rates to remain constant, the money will indeed be there to pay for all damages. However, most of this money will have been paid by intervening generations (thanks to their time preference); only the income generated by the growth component of the discount rate can be considered a contribution by the initial generation.

Just as important as the discount rate is the rate at which future costs will evolve; only the difference between this rate and the discount rate matters. This difference ("effective discount rate") is likely to be positive but small. Most studies have not addressed this point, and the rate they use is the effective discount rate.

To get a simple upper bound of costs and to facilitate the conversion to impacts the "effective discount rate" can be set equal to 0. The uncertainties and controversies about intergenerational discounting are one of the reasons why it is advisable to keep long term impacts in a category apart, thereby allowing decision makers to apply different weights. Work continues on trying to resolve this issue and at this time no general consensus has been reached.

3.6.4. Nonmonetary criteria

Most of the impacts are incommensurate, for instance mortality and soiling of buildings. For a comparison one needs either a multi-criteria analysis or else weighting or ranking by a common metric. In all but one of the recent studies, the economic valuation of the damages was the final step of the assessment, in order to present the results in a common unit of cost per kWh. One major problem with transforming the impacts to a common unit is a loss of transparency and of detail. A greater variety of impact indicators would therefore appear desirable, but it greatly complicates the presentation and comparison of the results. As a compromise between too many criteria and too few, it may be helpful to present the results in terms of a few categories such as suggested by Table 2.3. Comparison in terms of physical indicators may also be instructive, see for example the comparison of radiation dose from nuclear power with the cosmic ray background, in Section 5.3.

3.7. Global Warming

The assessment of global warming is difficult for reasons more complicated than the technical input. The technical work is intertwined with political issues, such as intergenerational equity and the value of life in developing countries. This is one of the reasons global warming should be treated as an independent impact category.

Damage cost estimates have been evolving. For ExternE [1995] global warming was addressed by reviewing the available literature. The major studies [Cline 1992, Fankhauser 1993, and Tol 1995] cluster around 14 Euro/t of CO_2, for discount rates of 0 to 1%. This corresponds to a reduction of 1 to 2% of gross world product for doubled CO_2.

For the latest phase of ExternE [1998] an independent assessment has been carried out, based on the reports of IPCC [1995]. The result has been presented in terms of intervals: a "conservative 95% confidence interval" from 3.8 to 139 Euro/t of CO_2, and an "illustrative restricted range" from 18 to 46 Euro/t of CO_2.

3.8. Accidents

3.8.1. Small Accidents

Most small accidents associated with fuel chains are fairly frequent and so there are good actuarial data. However, the application to fuel chain analysis is not straightforward because of the large variation with site. For example, the number of fatal accidents per ton of coal varies a thousandfold between different countries, and one can get very different results depending on the assumptions for the countries of origin of the coal.

Accidents in the coal mining sector have been surveyed recently by Holland [1996]. The rates depend on the type of mine, fatal accident rates being four to ten times lower in surface mines than in deep mines. For underground mines the lowest rate is 0.1 deaths/Mt of coal in the USA and in Australia. For most countries Holland has found only average data for all mines, mostly based on ILO [1995]; here we cite a few numbers to highlight the variability: Poland 0.59, India 0.75, China 6.1, Pakistan 29.9, and Turkey 119 deaths/Mt of coal. Not included is the number of premature deaths due to occupational disease, a number generally smaller but not negligible. Since a coal fired plant needs approximately 0.33 t of coal per MWh_e [ExternE 1995], a rate of 1 death/Mt implies 0.33 deaths/TWh_e.

There is also the question whether occupational accidents should be weighed on the same scale as impacts on public health. Impacts on workers are at least partially internalized because workers are aware of their risks, yet prefer the work to the available alternatives such as unemployment (as protests over mine closings amply demonstrate). Damage to public health, by contrast, clearly represents an external cost.

3.8.2. Severe Accidents

The assessment of the impact of severe accidents raises two general issues: the estimation of the probability of occurrence, and the methods of completing an assessment given the lack of data. The methods for estimating the potential impacts include complex probability safety assessments for nuclear reactor technologies, the use of complex accident consequence codes, and the compilation of statistical accident data, such as for the sea transport of oil.

Major accidents can happen with several fuel chains, in particular a dam failure, an oil spill or an explosion of a tanker of liquefied natural gas. But the nuclear accident assessment is unique in evoking extreme controversy. Many people believe that the assumed accident probabilities are too low, or that the consequences have not been adequately taken into account. Even a "worst case scenario" will not satisfy everybody, because one can always imagine something worse.

Some analysts base their assessment on Chernobyl type accidents. For new power plants in countries like the USA, the European Union or Japan that is clearly not appropriate because the technologies and the social context are totally different. However, nuclear power plants are also being planned or built in countries where coal mine accident rates are a two to three orders of magnitude higher than in the USA. While coal mines are not necessarily indicative of the way nuclear power would be managed, low safety standards in one sector offer no assurance that other sectors of the same country would fare better. This highlights again the need to account for the manner in which a technology might be implemented at a particular site, rather than passing global judgments.

Furthermore, there are considerations beyond damage and cost, as the following simple example can illustrate. Suppose someone invents an energy system that will supply the world's electricity (roughly 10^{13} kWh/yr) at the bargain price of \$0.01/kWh - with one little catch: there is a probability of an accident occurring once every 100 years that will kill 25000 (roughly the total toll for Chernobyl if one multiplies the UNSCEAR estimate of committed dose by the standard linear dose-response function). Even at \$4 million/life and zero discount rate, the levelized cost of such an accident has an expectation value of only

$$2.5 \times 10^4 \times 4 \times 10^6 \ \$/10^{15} \ \text{kWh} = 10^{-4} \ \$/\text{kWh}, \quad (4)$$

a mere 1% of this low electricity price. But would people accept such a deal? It would depend on the nature of the deaths. If all occurred at once, the deal would probably be considered unacceptable. The perception would be quite different if there were only delayed deaths occurring gradually over several decades. In fact, people accept much higher mortality costs if they are gradual. This can be demonstrated by the results reported below in Table 5.3 for coal fired power plants with "best available technology". Even if one takes only the mortality due to particulate emissions (the mortality component is 85% [ExternE 1998] of the 3.1 mEuro/kWh in Table 5.3), one finds a cost approximately 30 times higher than Eq.4. Note that this comparison is not unfair to coal because Table 5.3 is based on a YOLL valuation.

3.9. Uncertainties

The wide scatter of results of fuel chain studies is in part a reflection of large inherent uncertainties. It is appropriate to group the main contributions to the uncertainty in several qualitatively different categories

- technical/scientific (models, input parameters, data, dose-response functions, ...)
- policy/ethical choice (value of life in developing countries, intergenerational discount rate, ...)
- scenarios for the future (lifestyles, population size and distribution, medical advances, ...)

All is compounded by idiosynchrasies of the authors of the studies (interpretation of scientific evidence, choice of scenarios, and occasionally human error).

For the first category one can attempt to assign uncertainty distributions for each component of the analysis and calculate the uncertainty of the damage according to the rules of statistics. In practice this is problematic because of the wide variety of possibly large sources of error that are difficult to identify and even more difficult to quantify. Rabl and Spadaro [1999] have estimated the uncertainties of air pollution damages, based on a literature survey of component uncertainties for dispersion, dose response functions and economic valuation. They find that air pollution damages may have multiplicative confidence intervals of about 3 to 5 (= geometric standard deviation). For lognormal distributions, typical of this field, a geometric standard deviation of 4 means that the true value has a 68% probability of being in the interval of 1/4 to 4 times the estimated median.

For the second and third of the above categories it is more appropriate to indicate how the results depend on these choices and present numbers for different scenarios if the effect on the result is not obvious.

The uncertainties of the nuclear health impacts stem mostly from the calculation of the collective dose (person·Sv per Bq of activity from the radionuclide emissions) and from the dose-response functions (fatal cancers, non-fatal cancers, and hereditary effects per Sv). The uncertainty of the dose depends on the pathway; Bouville et al [1994] estimate that for many radionuclides the multiplicative confidence intervals of the dose are in the range of 2 to 20. However, for the dominant radionuclide of the French fuel cycle, C-14, the uncertainty of the dose calculation is relatively small, and the uncertainty of the dose-response function overwhelms the result. The data in NRPB [1995] suggest that the 90% confidence interval for the number of cancers per Sv might extend from 0 to 3.7 times the central estimate. The uncertainty of damage costs increases the further one looks into the future.

4. Comparative Risk Assessments Since 1990

4.1. General Remarks

In this section we review seven major fuel chain studies published since 1990 [Ottinger et al 1991, Pearce et al 1992 and 1995, Friedrich and Voss 1993, Ball et al 1994, ORNL/RFF 1994, Rowe et al 1995, ExternE 1995 and 1998]. Key characteristics are summarized in Table 4.1, and numerical results are compared in Tables 4.2 and 4.3 [see also review by Krupnick and Burtraw 1996]. The original values as reported by the authors are included in the text and converted to a common unit of mEuro/kWh by the following: 1 Euro = $1.24 = £0.87 = 1.96 DM (such conversions involve some ambiguity because of currency fluctuations, around 25% during this period, and differential inflation rates).

A review of the results gives an overall impression that :

- there is wide range of different damage estimates;
- large differences in assumptions and methodologies make direct comparisons difficult; and
- some important impacts (e.g. global warming) are not included in all the assessments.

In Section 5 we will present our own best assessment, based on these studies, especially the latest version of ExternE [1998].

Table 4.1. Fuel chain studies published since 1990.

Study	Methodology	Key attributes
Ottinger et al 1991	"top down"	USA. Nuclear, coal, oil, gas, hydro, solar, wind, energy from waste. Impacts: health, crops, forests, fisheries, materials, visibility, reactor accidents. Global warming by abatement cost, not damage cost.
Pearce et al 1992 and 1995	"top down"	UK and EU. Thirteen fuel chains/technologies. Impacts: health, crops, forests, biodiversity, materials, visibility, reactor accidents.
Friedrich&Voss 1993	"top down"	Germany. Nuclear, coal, wind, photovoltaics. Impacts: forests, agriculture, fauna, materials, health, reactor accidents.
Ball et al 1994	"top down"	UK. Nuclear, coal, oil, gas, wind, tidal. Focus on risks to human health. Transboundary air pollution and global warming are not taken into account. No monetary valuation.
ORNL/RFF 1994	"bottom up"	2 sites SE and SW of USA. Nuclear, coal, oil, gas, hydro, biomass incineration. Local and regional impacts.
Rowe et al. 1995	"bottom up"	2 sites in New York State, USA. Nuclear, coal, oil, gas, biomass incineration, wind. Local and regional impacts.
ExternE 1995	"bottom up"	EU, 3 sites (UK and Germany). Nuclear, coal, lignite, oil, gas, hydro, wind. Local, regional, and global impacts. Literature survey for global warming.
Rabl et al 1996	"bottom up"	Application of ExternE [1995] to France. Nuclear, coal, oil, gas. First systematic study of site dependence.

ExternE 1998	"bottom up"	15 countries of EU, most with several sites. Large number of technologies. Local, regional, and global impacts. New analysis for global warming. Chronic mortality according to Pope et al [1995], applied to primary and secondary particles. YOLL valuation of mortality.

4.2. "Top-Down" Studies

4.2.1. Ottinger et al [1991]

Ottinger and his colleagues at Pace University relied heavily on data from past studies to estimate emission-to-externality factors for different types of technology for coal, oil and natural gas-fired electricity generation; monetary valuation was used with VSL at US$ 4 million. The ranges of externality costs per kWh were estimated as follows:

Coal-fired	$0.025 - $0.058
Oil-fired	$0.025 - $0.067
Natural gas-fired	$0.007 - $0.010.

Where less information was available, the authors set out what they considered to be a lower bound (which they call “starting point”) rather than leaving a gap in the analysis. The “starting points” for the estimation of the external costs from renewable energy technologies were:

Solar	$0.00 - $0.004
Wind	$0.00 - $0.001
Biomass	$0.00 - $0.007.

For nuclear power plants, the estimates of environmental externalities were considered to be a “starting point” of: $0.0011/kWh for routine operations, $0.023/kWh for accidents and $0.005/kWh for decommissioning; totaling $0.0291/kWh.

Table 4.2. Summary of impacts and damage costs for **coal** fuel chain. Numbers have been rounded.

Study	Occupational Fatalities	Total Costs	Public Health	Occupational Health	Environment	Global Warming
	deaths/TWh	mEuro/kWh	mEuro/kWh	mEuro/kWh	mEuro/kWh	mEuro/kWh
Ottinger et al 1991		22-55				
Pearce et al 1992		0.14	0.05		0.005	0.04
Pearce et al 1995		0.11				
Friedrich & Voss 1993		0.02-0.09	0.01-0.07		0.013-0.015	
Ball 1994	0.04-0.14					
ORNL/RFF 1994		0.7-1.4	0.01-0.64	0.08	0-0.1	nq
Rowe et al. 1996		3 to 5	3 to 5		0.1	nq
ExternE 1995		6 to 16 without glob.warm.	4 to 13	1 to 2	0.2 to 0.8	10 to 18 at 0% discount rate
Rabl et al 1996	nq	20 to 29	5 to 14	nq	0.02	15

ExternE 1998	see Section 3.8.1	20 to 100	10 to 50		0.5 to 2	10 to 50

nq = not quantified

The cost from normal operations of the nuclear fuel chain reported by Ottinger et al [1991] is much higher than those from later studies (when global effects are excluded in order to compare within similar assessment boundaries). This is mostly due to higher occupational health estimates (6 times higher) which is most likely based on data from aging nuclear power plants.

The severe accident assessment by Ottinger et al is based on Chernobyl and assumed that the probability of an accidental release is 8 times greater than the largest probability assumed for France [ExternE 1995] where Chernobyl is not considered representative of new technology. In addition, the population dose assumed in the calculation is about 4 times greater than the world-wide dose estimated by UNSCEAR in its 1988 report.

Table 4.3. Summary of impacts and damage costs for **nuclear** fuel chain. Numbers have been rounded.

Study	Public Fatalities	Occup. Fatalities	Total Costs	Public Health	Occup. Health	Environ-ment	Global Warming	Major Accident
	deaths/TWh	deaths/TWh	mEuro/kWh	mEuro/kWh	mEuro/kWh	mEuro/kWh	mEuro/kWh	mEuro/kWh
Ottinger et al 1991			23	4.9				18.5
Pearce et al 1992			0.007-0.017	0.003 - 0.009			0.0012	0.002-0.006
Pearce et al 1995			0.006 - 0.044				0.0012	
Friedrich & Voss 1993			0.002 - 0.01	0.001 - 0.005		0 - 0.002		0.0005-0.004
Ball 1994	0.01 - 1.23	0.02 - 0.09						
ORNL/RFF 1994			0.09 -0.1	0.012	0.08 - 0.09			
Rowe et al. 1996			0.09					
ExternE 1995	0.65	0.04	2.6	2.4	0.15			
Dreicer et al. 1995	0.62	0.02	2.5	2.4	0.14			0.0005 -0.023

4.2.2. Pearce et al. [1992 and 1995]

At the same time, the UK Department of Trade and Industry sponsored a literature survey in an effort to derive preliminary estimates of social cost "adders" (= social cost surcharges) for

UK fuel chains [Pearce *et al.* 1992]. Thirteen fuel chains/technologies were considered. The impact categories were human health, crops, forests, biological diversity, buildings and materials, noise, global warming damage, land, water, and visibility. In general, cost per unit pollutant concentration or statistical life was used and no discount rate was applied. This study took an approach similar to Ottinger et al [1991].

Pearce et al [1992] includes mortality, morbidity, health effects due to severe accidents and greenhouse gases emissions for the nuclear fuel chain. A range of economic values were presented for morbidity and severe accidents. Radiological morbidity values are presented as a function of the cost per unit collective dose. The recommended range of VSL is 1.4 to 2.4 MEuro. The report concluded that the health effects due to a severe nuclear accident would be negligible after assuming a probability of one in a million chance (10^{-6}) of an accident per reactor year for the technology that would be built in the UK today. However, different attempts at adding a risk aversion factor, to take into account the social reaction of the public, produced estimates that ranged from 0.02 to 0.05 pence/kWh but possibly as high as 0.27 pence/kWh.

A revised version [Pearce 1995] takes into account new information, in particular the ExternE project, new work on dose response functions, and revised forest damage estimates for the fossil fuel assessments. The nuclear fuel chain “adders” remain the same.

4.2.3. Friedrich and Voss [1993]

Friedrich and Voss [1993] published estimates of the external costs of coal, nuclear, wind and photovoltaic energy systems for Germany. The main categories of the impact assessment were forest damage, agriculture and fauna, material damage, effects on human health, and major reactor accidents. The discount rate was 4%.

The external costs of health effects presented by Friedrich and Voss [1993] are for normal operation of the nuclear fuel chain and assume a VSL of US $2.9 million. The "rough estimate" of the costs of a hypothetical accident assessment, based on the results of a US Nuclear Regulatory Commission report that were adjusted to conditions in Germany, ranged from 0.01 to 0.07 pf/kWh. Friedrich and Voss [1993] include a term for resource depletion: 0.013 to 0.015 mEuro/kWh for coal and 0 to 0.002 mEuro/kWh for nuclear.

4.2.4. Ball et al [1994]

Ball et al. [1994] present a literature review to compare the risks posed by seven cycles for the large-scale generation of electricity that would be available in the United Kingdom during the next two or three decades. A fuel chain approach was taken and the focus of the study was on the public and occupational health risks. Although the importance of impacts such as acid rain and greenhouse gas accumulation is acknowledged, they have not been quantified. The risks presented in this study are based on actuarial data, or from materials and man-power requirements and associated risk factors. The estimated risks are reported in acute and delayed occupational fatalities and delayed public fatalities. No monetary valuation is attempted.

4.3. "Bottom-Up" Studies

4.3.1. ORNL/RFF [1994]

This study was undertaken by teams at Oak Ridge National Laboratory and Resources for the Future ORNL/RFF [1994] as part of the joint EU-US Project on the External Costs of Fuel chains, to correct the past problems in comparative risk assessments by establishing a documented uniform framework. Detailed assessments were carried out for each of the stages of the fuel chains. Two hypothetical sites, in the Southeast and in the Southwest United States, were considered for the power plants. This study is fairly unique in having attempted an assessment of nonenvironmental externalities (road damage and employment). Health impacts have been calculated for primary air pollutants (particles, SO_2, NO_x) as well as O_3, but not for nitrate and sulfate aerosols; the geographic range for the atmospheric dispersion calculations was 1000 miles.

The results for the nuclear fuel chain are 0.1038 mills/kWh at the Southeast site and 0.0545 mills/kWh at the Southwest site. These results integrate two possible types of accidents into one risk figure and include the additional cost estimates of waste disposal, loss of utility assets, utility site clean-up, replacement power, and decommissioning. These additional costs contribute about 40% and 75% of the total costs reported for the Southeast and Southwest accident assessments, respectively.

ORNL/RFF assessed the costs of severe nuclear reactor accidents using the accident consequence computer code (MACCS). Two types of accidents at two sites were studied. The results presented in the draft report are 0.06 mills/kWh for the Southeast site (SE) and 0.006 mills/kWh for the Southwest site (SW). The additional costs for waste disposal, loss of utility assets, utility site clean-up, replacement power, and decommissioning after the accident contribute about 0.04 mills/kWh, which would about double the SE site accident costs and dominate the SW site accident costs.

At first glance the nuclear results of ORNL/RFF [1994] and ExternE [1995] appear to be an order of magnitude apart. The methodology used by both assessments is essentially the same and further investigation shows that these differences are due to the boundaries of the two assessments (local impacts versus regional (1000 km) and global boundaries). The ORNL/RFF assessment does not include reprocessing, conversion, enrichment, fuel fabrication and low level waste disposal stages. Reprocessing is not used in the US and the other stages were not considered as a priority for the project. An evaluation of the physical impacts of the high-level waste disposal was done but the valuation of this stage is not included in the final values reported. When comparable boundaries for the relevant stages (public local, public regional and occupational costs, including accidents) with a 3% discount rate are considered in France, the results range from 0.08 to 0.22 mEuro/kWh (0.1 to 0.27 mills/kWh), and are essentially within the same order of magnitude.

4.3.2. Rowe et al [1995]

RCG/Hagler Bailly and Tellus Institute worked together on the New York Environmental Externalities Cost Study [Rowe et al. 1995] to address the external costs from the production of electricity. Two sites are considered, Upstate New York and New York City, and two stack heights. They used the impact pathway methodology, with assumptions very similar to the studies of Oak Ridge and ExternE. Ozone damages due to NO_x emissions were estimated with a simplified model, and aerosol damages (nitrates and sulfates) were calculated by assuming that nitrate and sulfate aerosols have the same health impacts as PM_{10}. The analysis included an assessment of sensitivities and uncertainties. The atmospheric dispersion calculations cover the local and the regional range.

4.3.3. ExternE [1995 and 1998]

The ExternE Program ("External Costs of Energy") of the European Commission began as a collaborative project with the US Department of Energy, the US partners being Oak Ridge National Laboratory and Resources for the Future [ORNL/RFF 1994]. Whereas the US part was terminated after completion of the first phase, ExternE has been continuing with expanded scope (including transport and waste incineration). In the initial phase of ExternE [1995] the methodology was developed by carrying out relatively complete assessments of seven fuel chains, for installations at specific sites. An effort was made to present the results within the context of time and space to aid in the comparison process. The methodology developed in the ExternE project was then applied in a national implementation exercise, initially for France [Rabl et al 1996] and recently for all countries of the European Union [ExternE 1998].

Compared to the other studies, one of the hallmarks of ExternE is the thoroughness of the atmospheric dispersion modeling. For the fossil fuel chains the ISC model [Wackter and Foster 1987] has been used, a Gaussian plume recommended by the US EPA. For the regional dispersion two models, the Harwell Trajectory Model [Derwent and Nodop 1986] and EMEP [Sandnes 1993, Simpson 1993], have been used independently, with good agreement [Rabl and Spadaro 1999]. ISC and Harwell Trajectory Model have been integrated into the EcoSense software [Krewitt et al 1995] which has been used for most of the calculations of ExternE.

The nuclear fuel chain was assessed to a time limit of 100,000 years for the global population. Actual sites were used in all cases except for high level waste disposal (where an existing study was cited [EC 1988]). For the severe reactor accident assessment the risk was calculated for four possible scenarios.

The three "bottom up" studies published in 1994 and 1995 use essentially the same methodology and draw on the same literature of epidemiology and economic valuation. The main difference in the results comes from differences in local conditions (especially population density) and from differences in the atmospheric dispersion models. However, two major changes occurred between 1995 and 1997:

- the decision was made to take into account the results of Pope et al [1995] for chronic mortality due to air pollution, and
- the valuation of mortality was changed from VSL to YOLL (see Section 3.6.2).

As a consequence the calculations and the results are changed so much that comparisons of health damage costs between ExternE [1998] and the earlier bottom-up studies are not very meaningful.

5. Current Assessment of Fuel Chains

5.1. General Remarks

This section attempts to present typical values of damages for average European conditions and "best available technology". These values are a synthesis of the most recent calculations of ExternE [1998] and they build, of course, on the experience gained by all the previous studies. Table 5.1 shows the key assumptions. We focus on global warming and public health impacts because they appear to dominate the external costs. Note that mortality impacts are not at all comparable to those of previous studies because of two major changes: the inclusion of chronic mortality and the shift from VSL to YOLL valuation (although it turns out that the nuclear costs of ExternE [1995] are hardly affected by this change). The older studies do, however, remain relevant for accidents.

Table 5.1. Key assumptions for the results in this section.

Atmospheric dispersion and chemistry	
Local range:	ISC gaussian plume model
Regional range (Europe):	Harwell Trajectory Model as implemented in ECOSENSE
Global warming	Physical impacts according to **IPCC** [1995]
Impacts on health	
Form of dose-response functions (CR functions)	**Linearity** of incremental impact due an incremental dose for **all health** impacts
Chronic mortality	Dose-response function of Pope et al [1995] for PM, nitrates and sulfates
Acute mortality	For SO_2 and O_3, with 0.75 YOLL/death
Nitrate and sulfate aerosols	nitrates = PM_{10} sulfates = $PM_{2.5}$ (slope 1.7 times PM_{10})
Radionuclides	0.05 fatal cancers/man·Sv 0.12 nonfatal cancers/man·Sv 0.01 severe effects hereditary /man·Sv
Micropollutants	Dose-response functions of EPA [HEAST 1995]; Only cancers have been quantified (As, Cd, Cr, Ni and dioxins); Effects of Hg and Pb have not been quantified
Impacts on plants	Dose-response functions for crop loss due to SO_2 and O_3
Impacts on buildings and materials	Corrosion and erosion due to SO2 and soiling due to particles
Impacts **not quantified** but potentially significant	Reduced visibility due to air pollution Disposal of residues from fossil fuels
Economic valuation	
Valuation of a **premature death**	Proportional to reduction of life expectancy, with value of a YOLL (year of life lost)

	v_{YOLL} = 0.083 MEuro for chronic mortality, v_{YOLL} = 0.155 MEuro for acute mortality
Valuation of **cancers**	0.45 MEuro nonfatal cancers 2.0 MEuro fatal cancers 1.5 MEuro average for cancers from chemical carcinogens
Discount rate	3% unless otherwise stated; results for nuclear are shown for 0% "effective rate" (=discount rate – escalation rate of cost);

We do not address energy security, resource depletion, or public expenditures for R&D (the latter are clearly not relevant for future decisions to the extent that they are a sunk cost). We also omit another set of risks that defies quantification, namely those associated with proliferation (interpreting the term in the widest sense, including the temptation to expand market and profit by selling technology to countries where quality control or safeguards are inadequate).

5.2. Fossil Fuels

For the fossil fuel chains the lion's share of the external costs comes from air pollutants emitted by the power plant, the main impact categories being global warming and public health. Air pollutants from upstream and downstream activities contribute less than a percent of the total, with the possible exception of wastes (impacts not yet quantified) and of greenhouse gas emissions. Some greenhouse gases, especially CO_2 and CH_4, are emitted during production and transport of the fuel. Even though the mass of CH_4 per kWh is small, the impact can be appreciable because its GWP (global warming potential) is 21 for a time horizon of 100 years [IPCC 1995]. Of particular importance is the leakage of natural gas between well head and point of use: it appears to be around 1% or less for new systems, but can attain much higher rates in old systems especially those of the former Soviet Union for which loss rates are difficult to determine [Suter et al 1995].

Table 5.2 presents the typical values for damages for average European conditions for the major air pollutants emitted during combustion. Apart from CO_2, the damage cost is mostly due to health impacts, especially mortality. Since health damage is obviously proportional to the population density of the region where the pollutant is emitted, the numbers should be scaled accordingly if they are to be used elsewhere. Of course, such simple correction does not take into account the detailed distribution of the population, and the real damage for a particular site can be quite different as the column "Multiplier for site" tries to indicate. For primary pollutants the damage can also vary strongly with stack conditions, unlike secondary pollutants (nitrate and sulfate aerosols) which are formed mostly after the precursor has had the time to spread. The geographic extent of the impacts is global for CO_2 and CH_4, regional for the other air pollutants. With the exception of CO_2, the impacts are borne almost entirely by the present generation.

Table 5.2. Typical values of damage costs per t of air pollutant emitted in Europe.

Multipliers indicate how much the Euro/t numbers can change with site and stack conditions (stack height h, temperature T, exhaust velocity v). SO_2 damage is mostly via sulfates. (1 Euro = $ 1.00 to 1.25).

	Cost Euro/t	**%** due to health	**Multiplier for site** (rural ↔ urban)	**Multiplier for stack conditions** (height 250↔0m, T, v)
CO_2	29 [a]		1.0	1.0
PM_{10}	15400	100%	≈ 0.3 ↔ 3	≈ 0.6 ↔ 2.0
SO_2	10200	97%	≈ 0.7 ↔ 1.5	≈ 1.0
NO_2, via nitrates	14500	100%	≈ 0.7 ↔ 1.5	≈ 1.0
NO_2, via O_3	1500	77%	?	?
VOC (via O_3)	930	77%	?	?
CO	2	100%	?	?
As	170000	100%	≈ 0.3 ↔ 3	≈ 0.6 ↔ 2.0
Cd	20900	100%	≈ 0.3 ↔ 3	≈ 0.6 ↔ 2.0
Cr	140000	100%	≈ 0.3 ↔ 3	≈ 0.6 ↔ 2.0
Ni	2900	100%	≈ 0.3 ↔ 3	≈ 0.6 ↔ 2.0

[a] geometric mean of high and low estimates in ExternE [1998]

In Table 5.3 we show what the costs per ton of pollutant imply for the cost per kWh of electricity for new power plants. They generally involve "best available technology", but since there is no precise definition for this term, the emissions per kWh that have been assumed are indicated; they do not necessarily correspond to a particular installation but are readily achievable with off-the shelf equipment. The sulfur emissions depend not only on the technology but also on the sulfur content of the fuel, which is quite variable from one source to another; the sulfur content can be greatly reduced by appropriate treatment of the fuel. As an illustration of the difficulty of defining "best available technology" we mention that the among the Frame 7 and Frame 9 gas turbine combined cycle plants currently offered by GE, the rated NO_x emissions amount to 0.08 g/kWh for one model and to 0.24 g/kWh for another [R. H. Williams, personal communication 1998]. The emission of toxic metals is highly uncertain and variable from one source of coal to another; the numbers shown are not necessarily typical. However, the emission rates of toxic metals from fossil fuel power plants are in any case so small that their contribution to the total damage cost is negligible. The results are plotted in Fig.5.1. For occupational fatalities, see Section 3.8.1.

Table 5.3. Typical damage costs for the **fossil** fuel chains,
assuming average European conditions and new baseload power plants.

		Coal pulverized coal boiler + steam turbine, ESP, FGD, low NOx		**Oil** gas turbine combined cycle, oil with 1% S, ESP, FGD, low NOx		**Gas** gas turbine combined cycle, low NOx burner	
Pollutant	**Cost** **Euro/kg**	**Emission** g/kWh	**Cost** mEuro/kWh	**Emission** g/kWh	**Cost** mEuro/kWh	**Emission** g/kWh	**Cost** mEuro/kWh
CO_2		30 + 850 [a]		10 + 610 [a]		10 + 390 [a]	
CH_4		3		0.04		1.5	
Greenhouse gases, total, CO_{2equiv} [b]	0.029	940	27.3	621	18.0	430	12.5
Particles	15.4	0.2	3.1	0.02	0.3	ng	0.0

SO_2 [c]	10.2	1.0	10.2	1.0	10.2	ng	0.0
NO_x (NO_{2equiv}) [d]	16.0	2.0	32.1	1.0	16.0	0.7	11.2
Toxic metals arsenic	170	$\approx 2\times10^{-5}$	$\approx 3.4\times10^{-3}$		ng		ng
cadmium	20.9	$\approx 1\times10^{-6}$	$\approx 2.1\times10^{-5}$		ng		ng
Solid and liquid wastes	?	?	?	?	?	?	?
Land use, especially for mining	highly site specific		?		?		?
Total of quantified costs		72.7		44.5		23.7	

[a] the smaller of the two numbers is from upstream activities, the larger from the power plant

[b] assuming GWP of 20

[c] can be as much as ten times higher without FGD, depends on S content of fuel

[d] can be reduced by about factor of 3 with selective catalytic reduction, but with conventional burners NOx would be about 1.5 to 2 times higher than values in table

FGD = flue gas desulfurization, ESP = electrostatic precipitator

ng = negligible

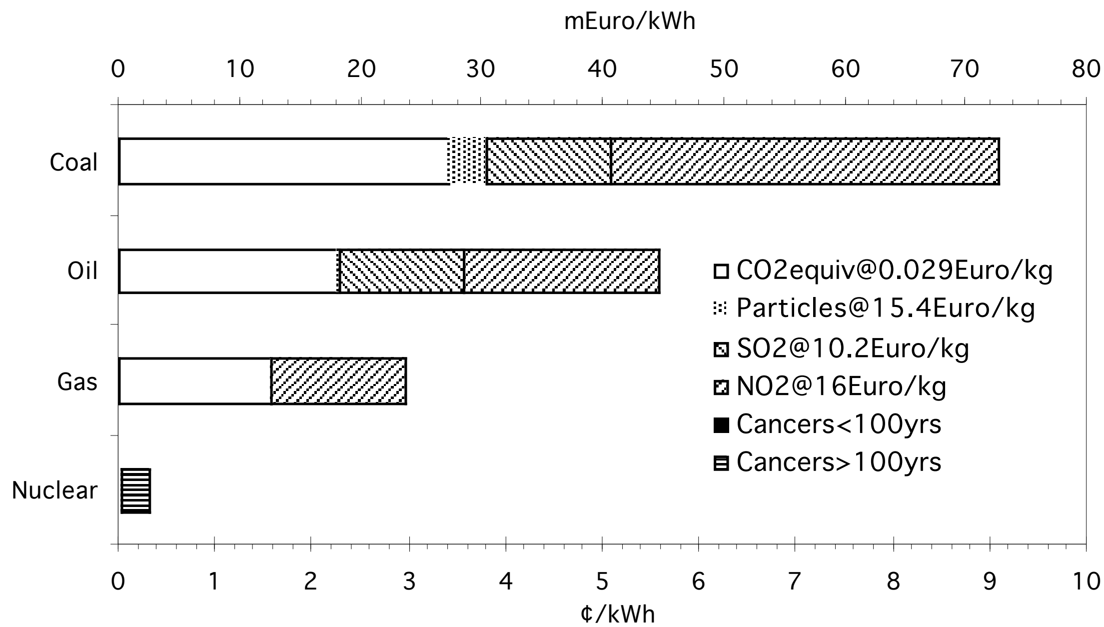

Fig.5.1. Damage cost of fuel chains for baseload power, "best available technology" with emissions of Table 5.3. Range of typical retail prices of electricity = 40 to 80 mEuro/kWh.

5.3. The Nuclear Fuel Chain

The emissions (source terms) assumed for the routine operation of the nuclear fuel chain are shown in Table 5.4 [Dreicer et al 1995]. Unlike the numbers in ExternE [1995] which were for a single 900 MW_e PWR (pressurized water reactor), these numbers represent the range over five 1300 MW_e PWRs in France; they are representative of a modern reactor, with fuel reprocessing.

The results of the analysis are shown in Fig.5.2, by stage of the fuel chain, for three discount rates (0%, 3% and 10%). The discount rates reflect the time horizon of the impacts. Although the results are based on facility specific releases at specific sites, they can be considered representative for the nuclear fuel chain in France. For the power plant, in particular, five sites have been analyzed in detail. The impacts due to water emissions can vary by several orders of magnitude (one of the plants is upstream of Paris, others are far from population centers); however, since they are much smaller than the impacts of the air emissions, the total damage cost does not vary much from one site to another.

For another presentation Table 5.5 shows a breakdown by impact category, in part a), and by time and space, in part b). All of the damage cost of low level radiation is due to human health effects (cancers and hereditary effects), whereas of environmental costs are negligible. It is interesting to note that the death rate among workers is about the same for cancers from radiation as for conventional accidents (e.g. a worker falling from a scaffold during construction of the reactor). The breakdown by space and time highlights the role of C-14 from reprocessing: without discounting most of the damage cost comes from global impacts over the long term.

Table 5..4. Emissions (source terms) for the nuclear fuel chain in routine operation, in MBq/TWh, and Total public dose, person·Sv/TWh.

Radio-nuclide	**Half life**	**Mining and milling**	**Conversion +Enrichment +Fuel fabrication**	**Power Plant**	**Reprocessing**
H-3	12.3 y			1.47 to 3.23E+6	2.89E+7
C-14	5710 y			1.40E+4	1.17E+5
Mn-54	310 d			2.40 to 9.50E+1	
Co-58	71 d			3.80E+2 to 1.40E+3	
Co-60	5.3 y			1.20 to 7.31E+2	9.10E+3
Kr-85	10.7 y			3.50E+4 to 1.70E+5	7.13E+8
Sr-90	28.1 y				1.46E+5
Ru-106	367 d				8.77E+4
Ag-110m	253 d			3.90E+1 to 3.50E+2	
Sb-124	60 d			8.00E+1 to 4.20E+2	
Sb-125	2 y				6.17E+4
I-129	1.6E7 y				7.35E+2
I-131	8.1 d			6.70E+0 to 1.96E+1	7.08E-1
I-133	21 h			3.00E+0 to 1.10E+1	3.13E-1
Xe-133	5.2 d			4.80E+5 to 2.30E+6	
Cs-134	2.1 y			8.01E+0 to 1.31E+2	1.50E+3
Cs-137	30 y			1.03E+1 to 2.31E+2	1.38E+4
Rn-222	3.8 d	5.10E+8			
U-234	2.5E5 y	2.10E+3	1.78E+1		
U-235	7.1E8 y	8.90E+1	8.64E-1		

U-238	4.5E9 y	2.10E+3	1.37E+1		1.47E+1
Pu-238	86.4 y				9.04E+1
Pu-239	2.4E4 y				5.43E+1
Am-241	458 y				9.21E+1
Cm-244	17 y				4.42E+1
Total public dose, person·Sv/TWh		**1.77E-1**	**7.09E-5**	**2.16E+0**	**1.03E+1**

At zero discount rate, reprocessing is the most significant contributor because of the long-lived globally dispersing C-14 and I-129 releases; but this cost drops by two orders of magnitude if one discounts instead at 3%. Discounting shrinks far future costs to insignificance. The reprocessing result highlights the crucial role of the time and space boundaries of the analysis as well as the choice of technologies: other technologies capture much of the C-14 (as it is done at Sellafield, UK) or do not recycle (USA, with entirely different impacts).

As for accidents, two types have been analyzed by Dreicer et al [1995]: accidents during transport of radioactive materials between sites, and accidents of the reactor. The costs due to accidents during transport have been found to be relatively small. For a severe reactor accident with core melt the probability is taken to be 1.0E-5 per reactor·year [EdF 1990], broadly consistent with other assessments based on engineering fault tree analysis. Several scenarios for the source term have been evaluated. For the result reported in Fig.5.2 the source term corresponds to a release of about 1% of the core, the same order of magnitude as the reference accident scenario used by the French national safety authorities. The COSYMA accident consequence assessment code [Ehrhardt and Jones 1991] was used to estimate the doses, costs of countermeasures and economic losses that would be expected after an accident. The collective dose for this accident is 58,000 Person·Sv (compared to about 560,000 for Chernobyl) which amounts to 0.016 Person·Sv/TWh; the corresponding cost is 0.0046 mEuro/kWh at zero discount rate for health costs; these numbers are expectation values.

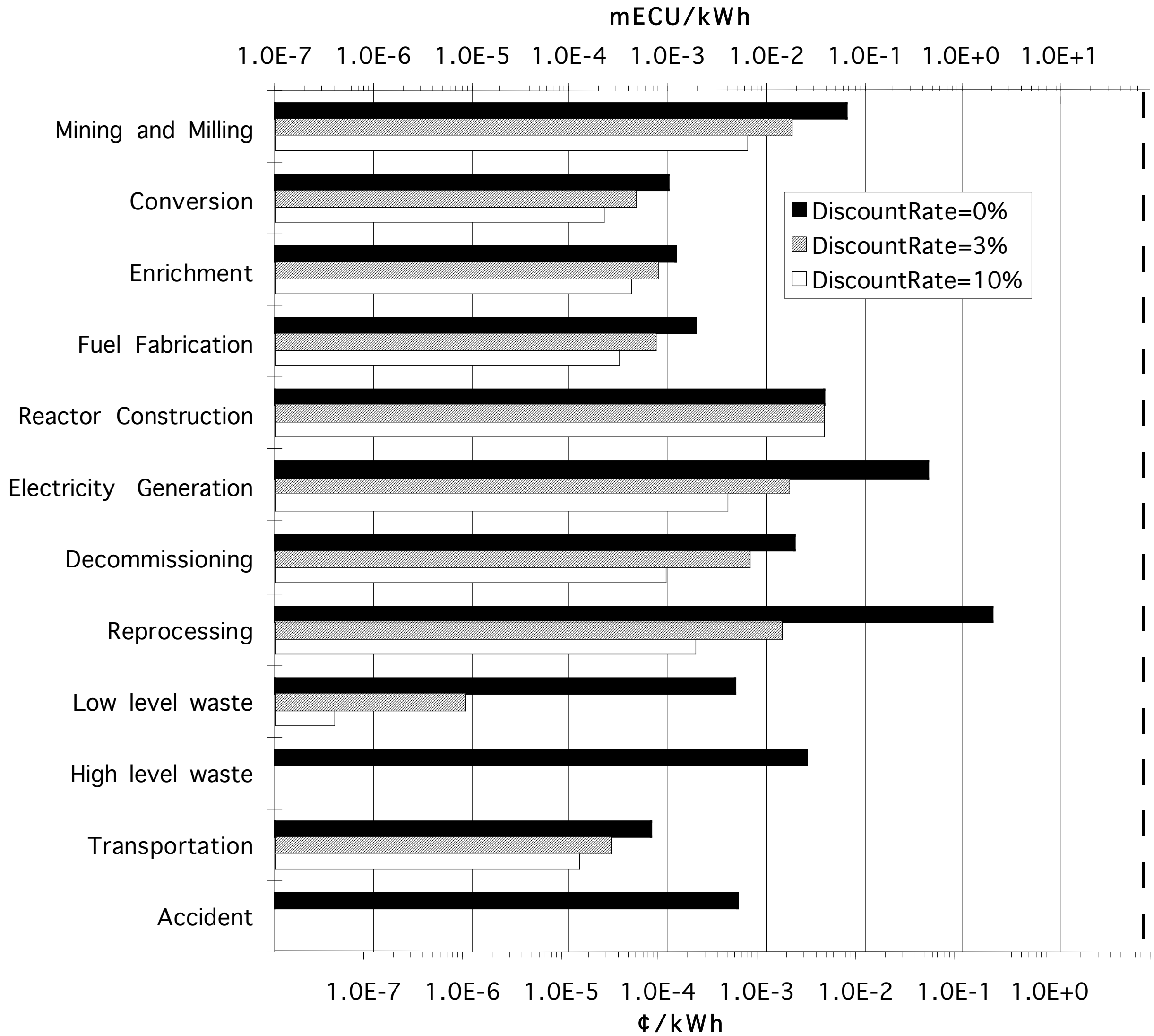

Fig.5.2. Logarithmic plot of damage cost for the **nuclear** fuel chain, by stage of cycle, for three discount rates: 0% (black), 3% (gray), and 10% (white).
Costs are based on VSL valuation; for YOLL valuation the radiological costs (i.e. most of the costs other than reactor construction) would be about half as large.
Dashed line = average retail price in France 65 mEuro/kWh = 0.081 US$/kWh [EdF 1994]. ECU = Euro.

Table 5.5 Nuclear Fuel chain impacts by time, space and impact category at 0% discount rate.
Costs are based on VSL valuation; for YOLL valuation the radiological costs would be about half as large.
a) breakdown by impact category, b) breakdown by time and space.

a)

	deaths/TWh	**mEuro/kWh**
worker, non-radiological	0.019	0.07
worker, radiological	0.02	0.07
public, total	0.65	2.38
environment	na	considered negligible
	Total	**2.52**

b)

		mEuro/kWh
short term (< 1yr)	local	0.068
	regional	0
	global	0
medium term (1-100yr)	local	0.084
	regional	0.06
	global	0.19
long term (100-100000yr)	local	0.026
	regional	0.002
	global	2.1
	Total	**2.52**

For nuclear the dominant impacts from normal operation are cancers and hereditary effects. For the public the individual risks are extremely small, but summed over the world population and over very long times, they appear significant - if the dose-response function is linear without threshold (as all studies of the nuclear fuel chain have assumed in the name of the precautionary principle).

Since most of the impact is imposed on people living in the far future, a cost as calculated above is not very satisfactory. For another perspective let us look at the implications of using nuclear power on a large scale. According to data of OECD [1995] the population of the world is about 5.5 billion and the electricity consumption 12000 TWh/yr. Both will increase, especially the latter, although saturation can be expected eventually. Technologies will certainly evolve and nuclear fission reactors are unlikely to be more than a stopgap, perhaps for a century or so, until cleaner sources of energy mature: solar, fusion, or perhaps the accelerator-based reactor being developed by Rubbia et al [1995]. Since details do not matter for the following argument, we take simple round numbers.

Let us suppose a simple "100 year scenario" where the above nuclear fuel cycle is used for 100 years to produce 2×10^4 TWh/yr, for a world population of 10 billion. Dreicer et al [1995] calculated a total public dose (for 10^{10} persons during 100,000 yr) of

$$\text{total dose} = 12.5 \text{ person}\cdot\text{Sv/TWh}, \tag{5}$$

which would imply a dose rate of

$$\text{total dose rate} = \frac{12.5 \text{ person}\cdot\text{Sv/TWh} \infty 2\infty10^4 \text{ TWh/yr}}{10^{10} \text{ persons}} = 25\ \mu\text{Sv/yr} \tag{6}$$

if the entire dose were incurred immediately. However, only ten percent of the dose from the production of a kWh is incurred during the first 100 years (as can be seen from the mEuro/kWh numbers in Table 5.5b since these costs are proportional to the dose). The precise time distribution of the total dose rate from "100 year scenario" would be difficult to calculate, because of the large number of different half lives. But again a rough order of magnitude estimate is sufficient, and we simply take 10% of the total dose rate to be imposed on the population living during this "100 year scenario".

$$\text{total dose rate} = 2.5\ \mu\text{Sv/yr} \qquad (7)$$

This can be compared to background radiation from other sources that people are exposed to. A typical value is in the range of 2 to 3 mSv/yr, but that includes medical x-rays, and an average value for radon in buildings [USDOE 1994]. Probably the most meaningful comparison is with the dose rate due to cosmic radiation at sea level

$$\text{cosmic radiation at sea level} = 260\ \mu\text{Sv/yr} \qquad (8)$$

because this is the very minimum all of us are exposed to and protection from which is not practical. Thus the "100 year scenario" would increase the background exposure by, very roughly, 1% of the cosmic ray background at sea level. Generations living beyond those 100 years would of course also be exposed, but at a lower rate. Incidentally, the incremental dose rate of 2.5 μSv/yr is about four times smaller than the level of 10 μSv/yr that the NCRP [1993] has recommended as "negligible dose level".

5.4. Renewable Energy Technologies

Among renewable electricity sources there is a great variety of technologies such as hydro, wind, biomass and various forms of direct solar energy utilization, in particular photovoltaics and solar thermal power plants. Hydro, wind and direct solar energy have special appeal, being not only inexhaustible but generally with little environmental impact or health risk. Of course, detailed studies are needed to check whether the impacts of these technologies are really benign. The results of studies such as ExternE [1998], summarized in Table 5.6, confirm that this is indeed usually the case, but not always.

For biomass the technologies considered are incineration with steam turbine or gasification with gas turbine. There are significant health impacts from the air pollution emitted by the power plant and by the machinery needed for the production and transport of the fuel. The net greenhouse gas emissions from growing the biomass are zero, but there are emissions from the associated machines and vehicles.

For hydro, PV and wind there are of course no emissions from power generation, but there are upstream emissions from the production of the materials. Amenity impacts are highly dependent on local conditions, in particular the population near the site. The impacts of hydro are so variable that the numbers in Table 5.6 cannot even be taken as general guidelines. The impacts can range from beneficial (for instance due to flood control or recreational facilities) to extremely harmful if large populations are displaced without compensation or if a dam breaks.

Table 5.6. Estimates of external costs of renewable electricity technologies, in mEuro/kWh, based on ExternE [1998]. The ?? highlight the fact that external costs of hydro are extremely site specific, and so are all amenity

costs. Other stages involve mainly construction of facilities and/or emissions associated with production or transport of materials.

	Power generation			Other stages			**Total**
	Amenity, noise	Ecological effects	Human health	Human health	Global warming	Other	mEuro/kWh
Hydro	0 - 2 ??	0 - 4 ??	accident ??	0.01 - 1	0.4 [a]	??	0 - 4 ??
Wind	0 - 1 ??	ng		0.3 - 0.9	0.2		0.5 - 2 ??
PV	ng	ng		0.3 - 0.9	1		1.3 - 1.9 ??
Biomass			1 - 10	0.1 - 3	0.3	benefit [b]	1 - 10

ng = negligible

[a] greenhouse gase emissions are highly variable with site; Gagnon and van de Vate [1997] indicate 15 $g_{CO2equiv}$/kWh as typical value for cold climates, and possibly much higher values in tropical zones.

[b] benefit = benefit if biomass plantation replaces crops such as corn that need more pesticides and fertilizers

6. Conclusions

6.1. General Conclusions

1. Much progress has been made in recent years in the assessment of fuel chains, and at least the order of magnitude of most major damages and costs from normal operation can be estimated now. However, the results should be revised to account for ongoing progress in epidemiology (the dominant source of uncertainty).

2. The uncertainties are large, easily a factor of about four in either direction. However, uncertainty does not render the results useless; a finite uncertainty range is always better than the infinite range one would have in the absence of analysis. The effect of uncertainty depends on the decision to evaluated, in particular whether it changes the ranking of choices.

3. The main controversies concern global warming for fossil fuels, and accidents, high-level waste disposal, and nuclear proliferation. These issues involve complex social and political questions in addition to science .

4. "Fuel chain" is not a well defined concept. In reality there is a set of activities and processes, at different sites and with a wide spectrum of different technologies. It can be very misleading to present or compare costs that have been aggregated over the stages of a fuel chain.

5. Since most damages are proportional to the rates at which pollutants are emitted, one can account for technology dependence by rescaling the respective damages.

6. Apart from long lived globally dispersion gases (greenhouse gases, C-14, I-129), most impacts are site dependent. For air pollutants such as particles, NO_X and SO_X, the impacts can easily vary by an order of magnitude with conditions of site and stack. Site dependence is particularly strong for water pollution, solid wastes, and mining (including accidents).

7. Different fuel chains incur different types of impacts that are more or less incommensurate (e.g. cancers and damage to buildings). Only a multi-criteria comparison can take into account the complexities of incommensurate impacts, but the larger the number of

criteria, the more difficult the comparison. Using a single metric (monetary values) can be both instructive and misleading.

8. As a compromise between the complexity of a large number of criteria and the simplicity of a single damage cost, the results have been presented in terms of a few major categories of space, time and impact type.

9. For the discounting of intergenerational costs, a crucial variable has usually been overlooked: the evolution of future costs. For instance, if a cure for cancer is found, most of the costs of the nuclear fuel chain become negligible after that time. Therefore the weighting of long term impacts involves a choice of scenarios. In any case monetization is problematic for impacts in the far future.

6.2. Conclusions for Fossil Fuels

10. For fossil fuels the dominant impacts are global warming and mortality from air pollution (particles, NO_x and SO_x). Obviously, natural gas is cleaner and has lower impacts than coal, with external costs about two to four times smaller.

11. The external costs of fossil fuels are large, especially for coal (in the range of ten to a hundred percent of the market price of electricity).

6.3. Conclusions for Nuclear

12. For nuclear the dominant impacts from normal operation are cancers and hereditary effects. For the public the individual risks are extremely small, but summed over the world population and over very long times, they appear significant - if the dose-response function is linear without threshold (all studies of the nuclear fuel chain have assumed this as precautionary principle).

13. Compared to the natural background of radiation, the collective dose from the normal operation of the nuclear fuel chain is extremely small. Even if the entire world consumption of electricity were supplied by current French technology for 100 years, the incremental dose would be two orders of magnitude less than the background dose from cosmic radiation at sea level.

13. Assuming a mature and stable political system, with strict verification of compliance with all regulations, the external costs of nuclear power are small (a few percent of the market price of electricity), much smaller than those of the fossil fuels. But low external costs do not suffice to allay concerns about accidents, long lived radioactive waste, the right to impose impacts on future generations, and proliferation; these issues involve questions of acceptability.

6.4. Conclusions for Renewables

14. There is a great variety of different renewable energy technologies. Their impacts from emission of pollutants tend to be small, with the exception of biomass (combustion or

gasification) and some hydroelectric plants. Some can have appreciable amenity impacts. Impacts of hydro, and amenity impacts in general, are extremely site-specific.

6.5. Comparisons

15. The external costs of nuclear and of most renewables appear to be much smaller than those of the fossil fuels. The costs, at zero discount rate, are an indication of the physical impacts since mortality is the dominant contribution to the cost (more than 80% for particles, NO_X and SO_X; a large portion for global warming; and essentially all for nuclear). It would not be rational to reject one technology in the name of risks imposed on future generations, if as alternative one chooses technologies that cause an even greater loss of life.

Acknowledgments

This work has been supported in part by the ExternE Program of the European Commission DG12. We have enjoyed helpful discussions with many colleagues, especially Jérôme Adnot, Jacquie Berry, Didier Beutier, Denis Clodic, Peter Curtiss, William Dab, Mark Delucchi, Brigitte Desaigues, Nick Eyre, Rainer Friedrich, Renaud Gicquel, Mike Holland, Fintan Hurley, Wolfram Krewitt, Jacques Lochard, Yoshio Matsuki, Jérôme Pellissier-Tanon, Thierry Schneider, Bent Sørensen, Joe Spadaro, Véronique Tort and Andrej Strupczewski.

References

Abbey DE, PK Mills, FF Petersen, and WL Beeson. 1991. "Long term ambient concentrations of total suspended particulates and oxidants as related to incidence of chronic disease in Califormina Seventh-Day Adventists". *Environmental Health Perspectives*, Vol 94, p43-40.

Ball DJ, LEJ Roberts and ACD Simpson. 1994. "An analysis of electricity generation health risks: a United Kingdom perspective." Research report 20. ISBN 1 873933 60 6. Centre for Environmental and Risk Management, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK.

Bascom R, PA Bromberg, DL Costa, R Devlin, DW Dockery, MW Frampton, W Lambert, JM Samet, FE Speizer, and M Utell. 1996."Health effects of outdoor air pollution.". *Amer. J. of Resp. Critical Care Med.* vol.153, 3-50 (Part 1) and 477-498 (Part 2).

Bouville A, K Eckerman, W Griffith, O Hoffman, R Leggett and J Stubbs. 1994. "Evaluating the reliability of biokinetic and dosimetric models and parameters used to assess individual doses for risk assessment purposes". Radiation Protection Dosimetry, vol.53, p.211-215.

Cline WR 1992. *The Economics of Global Warming*. Institute for International Economics. 11 Dupont Circle, NW. Washington, DC 20036-1207.

Curtiss PS and A Rabl. 1966. "Impacts of air pollution : general relationships and site dependence". *Atmospheric Environment*, Vol.30, p.3331-3347 (1996).

Derwent RG and K Nodop. 1986. "Long range transport and deposition of acidic nitrogen species in North-West Europe". *Nature*, vol. 324, p.356-358.

Dockery DW and CA Pope III. 1994. "Acute respiratory effects of particulate air pollution". *Ann. Rev. Public Health*. vol.15, p.107-132.

Dockery DW, CA Pope III, Xiping Xu, JD Spengler, JH Ware, ME Fay, BG Ferris and FE Speizer. 1993. "An association between air pollution and mortality in six US cities". *New England J of Medicine*, vol.329, p.1753-1759 (Dec. 1993).

Dreicer M, V Tort and H Margerie 1995. "Nuclear fuel cycle: implementation in France". Final report for ExternE Program, contract EC DG12 JOU2-CT92-0236. CEPN, F-92263 Fontenay-aux-Roses. This report is included in Rabl et al [1996].

Dreicer M, A Aarkrog, R Alexakhin, L Anspaugh, NP Arkhipov, K-J Johansson. 1996. " Consequences of the Chernobyl Accident for the Natural and human Environments" Background paper 5, Proceedings of an *International Conference One Decade After Chernobyl: Summing up the Consequences of the Accid*ent, International Atomic Energy Agency, Vienna Austria 8-12, April 1996.

EC 1988. Performance Assessment of Geologic Isolation Systems for Radioactive Waste, Summary, DIR11775 EN, Brussels, Belgium.

EdF 1990. "Etude probabiliste de sûreté des REP de 1300 MWe". EPS 1300. Electricité de France.

Ehrhardt J and JA Jones 1991." An outline of COSYMA, A New Program Package for Accident Consequence Assessments". *Nuclear Technology* No. 94, p. 196 -203.

ExternE 1995. ExternE: Externalities of Energy. ISBN 92-827-5210-0. Vol.1: Summary; Vol.2: Methodology; Vol.3: Coal and Lignite; Vol.5: Nuclear. Published by European Commission, Directorate-General XII, Science Research and Development. L-2920 Luxembourg.

ExternE 1998. ExternE: Externalities of Energy. New results, to be published by ExternE Program of European Commission, Directorate-General XII, Science Research and Development.

Eyre N, T Downing, R Hoekstra, K Rennings and RSJ Tol 1998. "Global Warming Damages". Final Report, September 1998, Contract JOS3-CT95-0002. To be published by ExternE Program of European Commission, Directorate-General XII, Science Research and Development.

Gagnon L and JF van de Vate 1997. "Greenhouse gas emissions from hydropower: the state of research in 1996". *Energy Policy*, vol.25, pp.7-13.

Fankhauser, S. 1993. "Global warming damage costs: some monetary estimates". CSERGE working paper GEC 92- 29 . University College London.

Holland M 1996. "Quantifying the externalities of fuel cycle activities outside the European Union". Maintenance Note 1 for the ExternE CORE Project. Energy Technology Support Unit, B 156 Harwell Laboratory, Didcot, Oxfordshire OX11 0RA, UK.

ILO 1995. "Recent developments in the coal mining industry". International Labor Organization, International Labor Office, Geneva.

IPCC 1995. *Climate Change 1995*. Intergovernmental Pancel on Climate Change. Cambridge University Press, Cambridge.

ICRP 1990. INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. Recommendations of the International Commission on Radiological Protection, Report 60, Annals of the ICRP, Pergamon Press, UK, 1991.

Krewitt W, A Trukenmueller, P Mayerhofer, and R Friedrich. 1995. "EcoSense - an Integrated Tool for Environmental Impact Anaylsis". in: Kremers, H., Pillmann, W. (Ed.): *Space and Time in Environmental Information Systems*. Umwelt-Informatik aktuell, Band 7. Metropolis-Verlag, Marburg 1995.

Krupnick, AJ and D Burtraw. 1996. "The social costs of electricity: do the numbers add up?". Discussion paper 96-30. Resources for the Future, Washington DC 20036.

Lipfert FW 1994. *Air Pollution and Community Health: a Critical Review and Data Sourcebook*. Van Nostrand Reinhold. New York.

NCRP 1993. *Limitation of Exposure to Ionizing Radiation*. National Council on Radiation Protection and Measurements. NCRP report No.116. Bethesda, MD.

NRPB 1995. "Risk of radiation-induced cancer at low doses and low dose rates for radiation protection purposes". Documents of the NRPB, volume 6, No.1. National Radiological Protection Board, Chilton, Didcot, Oxon OX11 0RQ, United Kingdom.

OECD 1995. *OECD Environmental Data Compendium 1995*. Organization for Economic Cooperation and Development, 2 rue André-Pascal, F-75775 Paris.

ORNL/RFF 1994. *External Costs and Benefits of Fuel Cycles*. Prepared by Oak Ridge National Laboratory and Resources for the Future. Edited by Russell Lee, Oak Ridge National Laboratory, Oak Ridge, TN 37831.

Ottinger RL et al 1991. *Environmental Costs of Electricity*. Oceana Publications, New York.

Pearce DW, C Bann and S Georgiou 1992. "The social costs of fuel cycles", report for the UK Department of Trade and industry, CSERGE, University College London.

Pearce DW 1995. "Development of externality adders in the UK". Presentation at Workshop on *External Costs of Energy*, organized by EC, IEA and OECD, 30-31 January 1995, Brussels, Belgium.

Pope CA, MJ Thun, MM Namboodri, DW Dockery, JS Evans, FE Speizer, and CW Heath. 1995."Particulate air pollution as a predictor of mortality in a prospective study of US adults". *Amer. J. of Resp. Critical Care Med.* vol.151, 669-674

Rabl A 1996. "Discounting of long term costs: what would future generations prefer us to do?" *Ecological Economics*, Vol.17, p.137-145 (1996)

Rabl A 1998. "Mortality risks of air pollution: the role of exposure-response functions". Journal of Hazardous Materials, vol.61, pp.91-98.

Rabl A 1999. "Air Pollution and Buildings: an Estimation of Damage Costs in France". To be published in *Environmental Impact Assessment Review*.

Rabl A and JV Spadaro 1999. "Environmental Damages and Costs: an Analysis of Uncertainties". *Environment International*, Vol.25(1), 29-46 (1999)

Rabl A and N Eyre 1998. "An Estimate of regional and global O_3 Damage from Precursor NO_x and VOC Emissions". *Environment International*, vol.24, 835-850.

Rabl A, PS Curtiss, JV Spadaro, B Hernandez, A Pons, M Dreicer, V Tort, H Margerie, G Landrieu, B Desaigues and D Proult. 1996. *Environmental Impacts and Costs: the Nuclear and the Fossil Fuel Cycles*. Report to EC, DG XII, Version 3.0 June 1996. ARMINES (Ecole des Mines), 60 boul. St.-Michel, 75272 Paris CEDEX 06.

Rowe RD, CM Lang, LG Chestnut, D Latimer, D Rae, SM Bernow and D White. 1995. *The New York Electricity Externality Study*. Oceana Publications, Dobbs Ferry, New York.

Rubbia C, JA Rubio, S Buono, F Carminati, N Fiétier, J Galvez, C Gelès, Y Kadi, R Klapisch, P Mandrillon, JP Revol and C Roche 1995. "Conceptual design of a fast neutron operated high power energy amplifier". Report CERN/AT/95-44. European Organization for Nuclear Research, Geneva.

Sandnes H 1993. "Calculated budgets for airborne acidifying components in Europe". EMEP/MSC-W Report 1/93. July 1993. Norwegian Meteorological Institute, P.O.Box 43, Blindern, N-0313 Oslo 3.

Simpson D 1993. "Photochemical model calculations over Europe for two extended summer periods: 1985 and 1989. Model results and comparison with observations". *Atmospheric Environment*, vol. 27A, p.921-943.

Suter P, E Walder, R Frischknecht, P Hofstetter, I Knoepfel, M Ménard, R DOnes and E Zollinger 1995. "Ökoinventare für Energiesysteme". Report for BEW/NEFF project "Umweltbelastung der End- und Nutzenergiebereitstellung". Eidgenössische Technische Hochschule, Zürich, Switzerland.

Tol RSJ 1995. "The damage costs of climate change: toward more comprehensive calculations". *Environmental and Resource Economics*, vol.5, p.353-374.

UNSCEAR 1993. UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, Sources, Effects and Risks of Ionising Radiation, UNSCEAR 1993 Report, United Nations, New-York, 1993.

USDOE 1994. "Radiation in the Environment". Brochure published by Office of Environmental Management, US Department of Energy.

Wackter DJ and JA Foster 1987. *Industrial source complex (ISC) dispersion model user's guide*. 2nd edition. Vol.1, EPA 450/4-88-002a. US Environmental Protection Agency, Research Triangle Park, North Carolina.

Wilson R and JD Spengler, editors. 1996. "Particles in Our Air: Concentrations and Health Effects". Harvard University Press, Cambridge, MA.

Glossary

As = arsenic
Bq = Becquerel = unit of radioactivity = 1 disintegration per second = 2.7E-11 Ci
C = carbon, CO = carbon monoxide, CO_2 = carbon dioxide
Cd = cadmium
Cr = chromium
CRA = comparative risk assessment
Discount rate = rate r that allows comparison of monetary values incurred at different times, defined such that an amount P_n in year n has the same utility as an amount $P_0 = P_n (1+r)^{-n}$ in year 0.
EC = European Commission
Euro = ECU = European currency unit (1 Euro = $ 1.00 to 1.25 in recent years; here we use 1.25)
EMEP = European Monitoring and Evaluation Programme, of Norwegian Meteorological Institute, for transboundary air pollution.
EPA = Environmental Protection Agency of USA
EU = European Union (EU15 = the current 15 member countries)
External costs = costs that arise when the social or economic activities of one group of people have an impact on another for which the first group does not fully account, e.g when a polluter does not compensate others for the damage imposed on them.
FGD = flue gas desulfurization
GWP = global warming potential (damage per t of pollutant relative to CO_2)
Hg = mercury
kWh = kilowatthour (with subscript $_t$ if thermal and $_e$ if electric)
MEuro = million Euro
mEuro = milli Euro
N = nitrogen
Ni = nickel
NO_x = unspecified mixture of nitrogen oxides, especially NO and NO_2
O_3 = ozone
PM_d = particulate matter with aerodynamic diameter smaller than d μm.
PV = photovoltaics
PWR = pressurized water reactor
S = sulfur
SO_x = unspecified mixture of sulfur oxides, especially SO_2 and SO_3
Sv = Sievert = unit of radiation dose = 100 rem
t = ton = 1000 kg
VOC = volatile organic compounds.
VSL = reference value of life (also called value of statistical life VSL)
YOLL = years of life lost (reduction of life expectancy)