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PUBLIC HEALTH IMPACT OF AIR POLLUTION AND IMPLICATIONS FOR THE ENERGY SYSTEM

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■ **Abstract** Low environmental damage is one of the main justifications for continued efforts to reduce energy consumption and to shift to cleaner sources such as solar energy, especially now that supply security has slipped from public consciousness. In recent years there has been much progress in the analysis of environmental damages, in particular thanks to the ExternE (External Costs of Energy) Project of the European Commission. This paper presents a summary of the methodology and key results for the external costs of the major energy technologies. Even though the uncertainties are large, the results provide substantial evidence that the classic air pollutants (particles, NO_x and SO_x) from fossil fuels impose significant public health costs, comparable to the cost of global warming from CO_2 emissions.

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1. INTRODUCTION

In recent years there has been much progress in the analysis of environmental damage costs, thanks to several major projects to evaluate the external costs (costs that are not taken into account in the market price of goods) of energy in the United States (1, 2) and in Europe (3, 4). This review, by participants in all the phases of the ExternE (External Costs of Energy) Project (3, 4) since 1993, presents an overview of the methodology and the results; the focus is on public health impacts, but results for other impacts, including global warming, are also cited.

To evaluate impact and damage cost of a pollutant, one needs to carry out an impact pathway analysis, tracing the passage of the pollutant from 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 pollutants (e.g. kg of NO_x per GWh emitted by power plant);
2. Dispersion: calculation of increased pollutant concentrations in all affected regions (e.g. incremental concentration of ozone, using models of atmospheric dispersion and chemistry for ozone formation due to NO_x);
3. Impact: calculation of the dose from the increased concentration and calculation of impacts (damage in physical units) from this dose, using a dose-response function (e.g. cases of asthma due to this increase in ozone);
4. Cost: economic valuation of these impacts (e.g. multiplication by the cost of a case of asthma).

The impacts and costs are summed over all receptors of concern. The temporal and spatial scope of the analysis must be sufficiently large to take into account all significant contributions of a pollutant. Certain radionuclides disperse globally and some may have an impact for many thousands of years. For long-lived greenhouse gases the geographic range is global and the effects may be significant for the next century or two. For most other air pollutants the range extends over thousands of kilometers, and the time horizon is short for acute health impacts, or medium for chronic health impacts (but in any case limited to the present generation). Pollution of soil and ground water are local, and so are amenity impacts such as noise and visual intrusion.

Since the results, other than for globally dispersing greenhouse gases, can vary strongly with the site where a pollutant is emitted, there is the question of how to generalize site-specific results to representative numbers that may be needed for decision making. ExternE (4) has evaluated over 50 sites in different countries of the European Union (EU), and the results are sufficiently representative to permit general conclusions to be drawn about power plants (5).

Most energy forms involve a chain of processes, for instance from the mining of coal to the disposal of ash from a coal-fired power plant. To allow meaningful comparisons, a life cycle assessment of the entire so-called fuel chain (or fuel cycle) should be carried out. Here we consider electricity only, although the conclusions are applicable for several other end uses.

We warn against the temptation to cite cost/kilowatt-hour numbers out of context, for instance "the damage cost of wind energy." Quite apart from the variation of impacts with the site of an installation, the very term fuel chain is misleading because it suggests a simple monolithic system, whereas 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 owing to improved technologies and tightened environmental regulations (e.g. flue gas desulfurization cuts SO_2 emissions about tenfold), and further progress can be expected.

There are several reasons why we present only the results of the 1998 phase of the ExternE Project (4) of the European Commission, rather than those of the earlier studies. The basic methodology of the 1998 studies (1–4) is the same; in fact, ExternE and the Oak Ridge National Laboratory/Resources for the Future study were started as a joint EU-U.S. project. The authors of all the studies were in close contact, comparing assumptions and results. There are, of course, differences in some input parameters and dispersion models, but with relatively minor differences in the results. The studies also differ somewhat in scope and in the type of impacts studied. For instance, at the beginning (1, 2, 3) there was greater emphasis on impacts on workers, following the tradition of earlier comparative risk assessments. This emphasis shifted when public health impacts were found to dominate the external costs. Numerically, the main differences in the results reflect real differences between the analyzed sites (differences in population density, meteorological conditions, technologies, etc, which render a direct comparison difficult).

However, the main reason for not showing the results for the older studies is that since 1995 two developments have led to major changes: (*a*) the measurement by Pope et al (25) of chronic effects of air pollution on mortality; and (*b*) the recognition that for the valuation of air pollution mortality it is not appropriate to simply multiply the number of deaths by the value of statistical life (VSL;

determined from accidents), but that one should multiply the reduction of life expectancy by the value per life year. Unfortunately the teams in the United States have not been able to update their results because funding for this type of work dried up in the United States, in contrast to ExternE, which has been continually updated to incorporate the latest scientific findings.

2. ECONOMIC VALUATION

The goal of the monetary valuation of damages is to account for all costs, market and nonmarket. For example, the valuation of an asthma attack should include not only the cost of the medical treatment but also the willingness-to-pay (WTP) to avoid any residual suffering. If the WTP for a nonmarket good has been determined correctly, it is like a price, consistent with prices paid for market goods. Economists have developed several tools for determining nonmarket costs; of these tools contingent valuation (6) has enjoyed increasing popularity in recent years. The results are considered sufficiently reliable.

It turns out that damage costs of air pollution are dominated by nonmarket goods, especially the valuation of mortality. The single most important parameter is the VSL (an unfortunate term for what is really the willingness to pay for reducing the risk of premature death). In ExternE (4), a European-wide value of 3.1 MEuro ($3.4 million US) was chosen for VSL, close to similar studies in the United States; this value was chosen as an average of the VSL studies that had been carried out in Europe.

A crucial question for air pollution mortality is whether one should simply multiply the number of premature deaths by VSL, or whether one should take into account the years of life lost (YOLL) per death. The difference is very important because premature deaths from air pollution tend to involve far fewer YOLL per death than accidents (on which VSL is based). The ExternE (1998) numbers, used here, are based on YOLL and thus significantly lower (for the same dose-response function) than the simple VSL valuation assumed in most previous external cost studies. For the value of a YOLL ExternE (4) assumes 0.083 MEuro for chronic mortality and 0.155 MEuro for acute mortality, the difference arising from assumptions about latency and discounting (for an explanation of the terms chronic and acute mortality see Section 4.1). We also assume 0.45 MEuro for nonfatal cancers and 1.5 to 2.5 MEuro for fatal cancers (depending on the YOLL for each cancer type).

3. ATMOSPHERIC DISPERSION

3.1 Dispersion Models

The total damage D due to a quantity Q of a pollutant is obtained by integrating the damage at a point $\mathbf{x}$ over all points $\mathbf{x}$ of the region affected by the pollutant; the damage at a point $\mathbf{x}$ is the product of the receptor density $\rho(\mathbf{x})$, the slope of

f_{CR} of the dose-response function (here called concentration-response (CR) function because it is based directly on concentration) and the concentration increment $c(\mathbf{x})$ due to Q. $c(\mathbf{x})$ is calculated by models of atmospheric dispersion and chemistry.

For most air pollutants atmospheric dispersion is significant over hundreds to thousands of kilometers (7, 8). Both local and regional effects are important. We have therefore used a combination of local and regional dispersion models. To model dispersion over the short range we have used the Industrial Source Complex model (9) recommend by U.S. Environmental Protection Agency.

At the regional scale we have used two different models, the Harwell Trajectory model as adapted by ExternE (3, 4), and the EMEP model of the Norwegian Meteorological Service (10, 11), the model chosen for the official allocation of acid rain budgets among European countries. The results presented here are a synthesis of calculations carried out in the ExternE Project (3, 4, 12, 13).

These dispersion calculations have been coupled with an integration over population data, using two software packages developed independently for this purpose: ECOSENSE (14) and PATHWAYS2.0 (15). ECOSENSE includes the Harwell Trajectory Model; for the PATHWAYS2.0 calculations we have used EMEP results for atmospheric dispersion. Both sets of calculations use the Industrial Source Complex model for the local dispersion. We have compared the results for total damage per kilogram of pollutant between these 2 sets of calculations and found agreement within approximately 20% (16). For ozone damage due to the precursor NO_x the EMEP results of Simpson (11) have been used.

3.2 Site Dependence of Impacts

Site dependence is illustrated in Figure 1. This figure shows two variations: with stack height and with source location for five specific sites in France. Plume rise is included for typical conditions of large combustion installations. As an example, we consider a specific impact: the increase in acute mortality (YOLL) due to an emission of $Q = 10^6$ kg/yr of SO_2 (chosen arbitrarily). The damage is shown on two scales, as number of YOLL per year on the right hand scale, and in units of D_{uni} (to be explained below) on the left. At a stack height of 100 m the impact for the site near Paris is about 3 times larger than D_{uni}, and for Cordemais (a relatively rural site on the Atlantic Ocean) it is only 0.4 times D_{uni}. The impact for Martigues is rather small, despite the proximity of a large city, because the prevailing wind carries the pollutants out to sea.

Site dependence is particularly strong for primary pollutants (i.e. pollutants emitted directly by a source); this is shown by the examples in Figure 1. For secondary pollutants (created by chemical reactions of primary pollutants) such as sulfates, nitrates, and ozone, the sensitivity to local detail is much lower because these pollutants are created some distance from the source. For nitrates and sulfates this occurs over tens to hundreds of kilometers from the source, and so the site dependence is relatively weak; based on ECOSENSE results, we estimate that variations of sulfate or nitrate damage, per kilogram of SO_2 or NO_2, with site

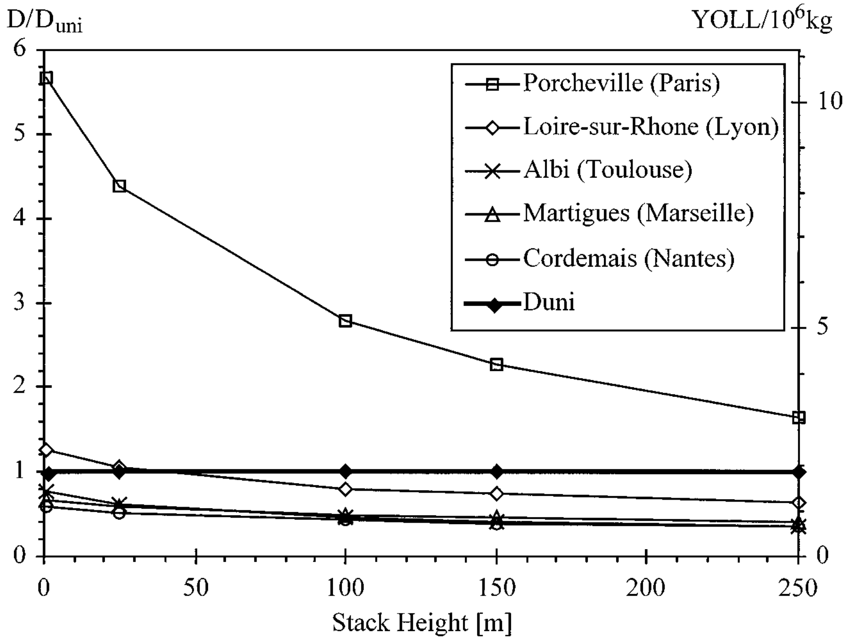

Figure 1 An example of dependence on site and on height of source for a primary pollutant with linear dose-response function: damage D from SO_2 emissions, for five sites in France, in units of D_{uni} for uniform world model Equation 1 (the nearest big city, 25 to 50 km away, is indicated in parentheses). Scale of right indicated years of life lost/year (acute mortality) from a plant with emission 10^6 kg/year.

are around 50%. The creation of ozone is more rapid, within several to tens of kilometers from the source; based on EMEP data we estimate that ozone damage per kilogram of precursor could vary with site by about a factor of four in Europe (17).

3.3 A Simple Model for Typical Damage Estimates

Curtiss & Rabl (18) have shown that the total damage D for a linear dose-response function and steady state conditions can be calculated in closed form if one assumes that the receptor density and the depletion velocity of the pollutant from the atmosphere are the same everywhere in the affected region. The depletion velocity is defined as ratio $k(\mathbf{x}) = F(\mathbf{x})/c(\mathbf{x})$ of concentration $c(\mathbf{x})$ and total depletion flux $F(\mathbf{x})$ (due to dry deposition, wet deposition, or decay) at a point $\mathbf{x}$ of the Earth's surface. Under these conditions of uniformity one finds, as a consequence of mass conservation, the following very simple "uniform world model" for the

TABLE 1 Values of k_{uni} in "uniform world model" for different pollutants, used in this paper. Except for CO, they have been derived by nonlinear regression to dispersion results of ECOSENSE

Primary pollutants, D_{uni} of Equation 1 with k_{uni}

Pollutant	**k_{uni} [m/s]**
PM_{10} (including metals and dioxins)	0.0067
SO_2	0.0073
NO_2	0.0147
CO	0.001

Secondary pollutants, D_{2uni} of Equation 3 with $k_{2uni,eff}$

Pollutant	**$k_{2uni,eff}$ [m/s]**
$NO_2 \rightarrow$ nitrates	0.0071
$SO_2 \rightarrow$ sulfates	0.0173

total damage D_{uni} [in impact units of the CR function]

$$D_{uni} = f_{CR}\, \rho\, Q/k \qquad 1.$$

where ρ = receptor density [receptors/m^2], Q = emission rate of pollutant [g/s], f_{CR} = CR function slope [impacts/(receptor $\cdot$ (g/m^3))], and k = depletion velocity [m/s]. The quantity Q/k represents the concentration increment caused by Q, averaged over the affected receptors. As an illustration we calculate D_{uni} for the CR function used in Figure 1, whose slope is f_{CR} = 5.34E-06 YOLL/(pers $\cdot$ yr $\cdot$ μg/m^3) [see the acute mortality entry for SO_2 in Table 2W, available in the Electronic Materials section of the Annual Reviews Web site (http://annualreviews.org)]. The depletion velocity is k = 0.0073 m/s for SO_2 (see Table 1). Inserting these numbers into Equation 1 with the regional average population density ρ = 8.0E-5 person/m^2 (see below) we obtain for Q = 10^6 kg/yr = 3.17E07 μg/s

$$D_{uni} = \frac{5.34 \times 10^{-6}\,\text{YOLL}/(\text{person} \cdot \text{yr} \cdot \mu\text{g/m}^3) \times 8.0 \times 10^{-5}\,\text{person/m}^2}{0.0073\,\text{m/s}} \times 3.17 \times 10^{7} \mu\text{g/s} = 1.86\ \text{YOLL/yr}. \qquad 2.$$

This is shown as the horizontal line in Figure 1. It lies right in the middle of the curves for the five sites.

Equation 1 can be generalized to yield the damage D_2 caused by a secondary pollutant.

$$D_{2uni} = \frac{f_{CR2}\rho_{uni}}{k_{2uni,eff}} Q_1, \qquad 3.$$

where Q_1 = emission rate of the primary pollutant, f_{CR2} = CR function slope of the secondary pollutant, and $k_{2uni,eff}$ = "effective depletion velocity," taking into account the depletion velocities of the primary and secondary pollutants and the transformation rate.

We have determined numerical values of k_{uni} and $k_{2uni,eff}$ by fits to the dispersion results of ECOSENSE. Table 1 shows the values of k_{uni} for different pollutants that we will use in this paper. For carbon monoxide (CO) we assume 0.001 m/s based on lifetime estimates of 36 to 110 days given by Manahan (19), about a factor of 10 longer than for PM_{10} and SO_2 (PM_d designates particulate matter measured by detectors that try to admit only particles with aerodynamic diameter less than d μm).

In the region bounded by Sicily to the south, Portugal to the west, Scotland to the north and Poland to the east, the average population density is 80 persons/km^2. This is about half the average EU15 population density of 158 persons/km^2 per land area because it includes much water. Examining the results of detailed site-specific calculations for more than 50 installations in the EU15 countries (4), we have found that D_{uni} of Equations 1 and 3, with k_{uni} of Table 1 and ρ_{uni} = 80 persons/km^2, does indeed provide representative results for power plants with typical stack heights.

The reason for this remarkable success of the simple "uniform world model" is that with tall stacks much of the total impact occurs in regions sufficiently far from the source that the pollutant is fairly well mixed vertically in the planetary boundary layer, and variations of $k(\mathbf{x})$ are not too large. Furthermore, averaging site-specific results over a range of emission sites is mathematically equivalent to averaging over population distributions, thus bringing the effective population distribution closer to uniformity. If one wants typical results for public policy, without being able to evaluate each and every site, D_{uni} seems as good a choice as any—and it has the advantage of being simple and transparent. Also, it is a convenient tool for estimating damages for sites outside the EU. Therefore, we will use D_{uni} for all the damage estimates in this paper.

4. HEALTH IMPACTS AND COSTS

4.1 General Remarks

A consensus has been emerging among public health experts that air pollution, even at current ambient levels, is associated with a variety of health problems, especially respiratory diseases and mortality (20–23, 23a–d). However, the mechanisms of action are not understood. It is difficult to identify causes by epidemiology because people are exposed to a mix of pollutants and the different air pollutants tend to be correlated with each other. Most recent studies have suggested fine particles as a prime culprit; ozone has also been directly implicated. There may also be significant direct health impacts of SO_2, but for direct impacts of NO_x the evidence is less convincing. The uncertainties are large and the risk of double counting when summing the damage costs over pollutants cannot be entirely ruled out.

For the classic air pollutants (particles, NO_x, SO_x, CO) the dose-response functions are usually based directly on concentrations in ambient air, hence the names ER function (exposure-response) or CR function (concentration-response) are also used. Depending on the epidemiological approach used to determine a CR function, we talk about acute and chronic CR 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 CR functions. This approach has the great advantage of being easy to implement and insensitive to confounders (such as smoking). The certainty is relatively high (95% confidence intervals around ±50%), but only part of the full impact is observed.

End-points that show up only after a longer period require observations of individuals or populations that are exposed to different levels of pollution. Dose-response functions for chronic effects are notoriously difficult to establish with confidence, and there are few studies that have determined chronic CR functions. Of particular importance are the studies of Dockery et al (24), Pope et al (25), and Abbey et al (26, 27), which find significant chronic effects of air pollution on mortality. The difference between chronic and acute CR 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 an exposure or only after a longer period? By analogy the terms acute and chronic are also applied to CR functions for mortality, even though the attributes appear strange in that context.

Here we assume all dose-response functions for health impacts of air pollution to be linear. This is suggested by the fact that the numerous studies in many regions of the world with widely different pollution levels have found roughly comparable CR function slopes, without evidence for no-effect thresholds. Furthermore, several studies that have attempted to map an entire dose-response function for one of the classic air pollutants have observed linearity, for instance Dockery et al (24) for PM and ERPURS (23) for SO_2. Note that this linearity holds at the level of a population with its mix of different individual sensitivities, and it does not exclude the possibility of nonlinearities or thresholds at the level of an individual.

A detailed documentation of the dose-response functions and unit costs can be found on the Electronic Materials section of the Annual Reviews Web site (http://annualreviews.org). Here we merely list the key assumptions in Table 2 and the resulting damage cost per kilogram of pollutant in Table 3.

4.2 Particles

In air pollution studies PM designates anything that collects on the filters of particle detectors. It is a mixture of combustion particles, sulfate aerosols (including droplets of sulfuric acid), and nitrate aerosols, as well as particles from soil or sea spray. Most monitoring stations measure only the mass concentration of PM without any detail on composition. Unfortunately very little is known about the effects of individual components or characteristics (such as acidity, solubility, oxidizing potential, etc) of PM.

Particles of more than 10 μm diameter are stopped in the upper respiratory ducts and appear less harmful. Between 2.5 and 10 μm, the particles penetrate more deeply into bronchi and bronchioles; particles smaller than 2.5 μm reach the alveoli of the lungs. In the past most monitoring stations have measured PM_{10}; in recent years some have also measured $PM_{2.5}$. We assume a ratio of $PM_{2.5}/PM_{10} = 0.60$ based on typical ambient concentration data in the United States and the EU. Particle emissions from modern boilers and furnaces are almost entirely PM_{10}.

Among the impacts of PM quantified by ExternE, chronic mortality makes by far the largest contribution. That is based on several important cohort studies that have found effects of particulate air pollution on chronic mortality (24, 25, 27). By far the largest of these, Pope et al (25) finds clear associations of mortality with fine particles ($PM_{2.5}$) and with sulfates. Since these chronic mortality studies determine a change in age-specific mortality, one can derive implicit estimates of the YOLL (4, 28, 29).

4.3 Oxides of Nitrogen and Sulfur

Whereas epidemiological studies in the United States had generally concluded that direct effects of SO_2 did not appear significant, recent studies in Europe have found significant correlations for acute mortality and for respiratory hospital admissions; they have been used by ExternE (4); see Table 2W of the Web page, available in the Electronic Materials section of the Annual Reviews Web site (http://annualreviews.org). In any case the resulting costs are relatively small. There have also been some studies that find direct effects of NO_x or NO_2, but ExternE (4) concluded that they were not sufficiently convincing. NO_x is, however, implicated as a precursor of nitrates and ozone.

4.4 Carbon Monoxide

Carbon monoxide (CO) is certainly toxic at concentrations much higher than found in typical urban environments. There seem to be harmful effects even at typical ambient concentrations, and several recent studies have proposed linear CR functions

TABLE 2 Key assumptions for the calculations in this paper (4)

Atmospheric dispersion models	
Local range:	ISC (Industrial source complex) gaussian plume model (9).
Regional range (Europe):	Harwell Trajectory Model as implemented in ECOSENSE software (14) of ExternE. Ozone impacts based on EMEP model (11), as interpreted by Rabl & Eyre (17).
Global warming	Physical impacts according to IPCC (35).
Impacts on health	
Form of dose-response functions	Linearity of incremental impact due to an incremental dose for all health impacts.
Chronic mortality	Dose-response function slope $f_{CR} = 4.1E\text{-}4$ YOLL (years of life lost) per person per year per $\mu g/m^3$ derived from increase in all-cause age-specific mortality due to $PM_{2.5}$ (25), by integrating over age distribution and assuming it applies only to people over age 30.
Acute mortality	For SO_2 and ozone, with 0.75 YOLL per death.
Nitrate and sulfate aerosols	Dose-response functions for nitrates same as for PM_{10}. Dose-response functions for sulfates same as for $PM_{2.5}$ (slope = 1.7 times slope of PM_{10} functions).
Radionuclides	Linear dose-response functions: 0.05 fatal cancers/man · Sv, 0.12 nonfatal cancers/man · Sv, 0.01 severe effects hereditary/man · Sv.
Micropollutants	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 owing to SO_2 and ozone.
Impacts on buildings and materials	Corrosion and erosion owing to SO_2 and soiling owing to particles.
Impacts not quantified but potentially significant	Reduced visibility owing to air pollution; disposal of residues from fossil fuels.
Economic valuation	
Valuation of premature death	Proportional to reduction of life expectancy, with value of a YOLL (years of life lost) derived from VSL = 3.1 MEuro: ^{v}YOLL = 0.083 MEuro for chronic mortality, ^{v}YOLL = 0.155 MEuro for acute mortality.

(*Continued*)

TABLE 2 (*Continued*)

Valuation of cancers	0.45 MEuro nonfatal cancers, 1.5 to 2.5 MEuro (depending on YOLL) 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 discount rate" (= discount rate–escalation rate of cost).

for CO. The evidence for a correlation with hospital admissions is quite strong, and ExternE (4) has included it. There may also be mortality impacts due to CO but the case is less clear. The resulting damage cost is very small (see Table 3). One may well wonder if this is an artifact of the inability of epidemiological studies to correctly identify the full impact of CO.

4.5 Ozone

The ExternE (4) estimate of the damage costs for ozone formation has been derived by Rabl & Eyre (17). The underlying assumptions for CR functions and cost per case are listed in Table 3W of the Web page, available in the Electronic Materials section of the Annual Reviews Web site (http://annualreviews.org). The step from cost per parts per billion ozone to cost per kilogram of NO_x and per kilogram of volatile organic compound precursor is based on results of the EMEP model for ozone formation (11) as well as the Harwell Global Ozone model (30). The resulting costs are listed in Table 3. Only a single European average of regional damages was derived, and we do not know how much the results would change if local ozone modeling were included.

4.6 Sulfate and Nitrate Aerosols

SO_2 and NO_x are transformed in the atmosphere to sulfates and nitrates, respectively, thus becoming a component of PM. ExternE (4) applies the CR functions for particles to these aerosols per concentration of pollutant mass. In particular, nitrate aerosols are considered like PM_{10} and sulfate aerosols like $PM_{2.5}$. There is much uncertainty about this. Although there are studies that report correlations of mortality and other end-points with sulfates, there are no CR functions for nitrates because in the past nitrates have not even been monitored as a separate component of air pollution.

4.7 Other Pollutants

Among the heavy metals the following are considered carcinogenic: arsenic (As), cadmium (Cd), chrome (Cr, in oxidation state VI), and nickel (Ni). The

TABLE 3 Typical damage costs per kilogram of pollutant emitted by power plants in Europe

Pollutant	Impact	Cost [a, b], Euro/kg_{poll}
PM_{10} (primary)	mortality and morbidity	15.4
SO_2 (primary)	crops, materials	0.3
SO_2 (primary)	mortality and morbidity	0.3
SO_2 (via sulfates)	mortality and morbidity	9.95
NO_2 (primary)	mortality and morbidity	negligible
NO_2 (via nitrates)	mortality and morbidity	14.5
NO_2 (via O_3)	crops	0.35
NO_2 (via O_3)	mortality and morbidity	1.15
VOC (via O_3)	crops	0.2
VOC (via O_3)	mortality and morbidity	0.7
CO (primary)	morbidity	0.002
As (primary)	cancer	171
Cd (primary)	cancer	20.9
Cr (primary)	cancer	140
Ni (primary)	cancer	2.87
Dioxins, TEQ	cancer	1.85×10^7
CO_2	global warming	0.029

[a] Calculated with uniform world model D_{uni} of Equations 1 and 3, with population density 80 people/km^2.

[b] Multipliers for variation with site (proximity of big city, local climatic conditions) and stack conditions (stack height h, temperature T, exhaust velocity v): no variation for CO_2; weak variation for dioxin because noninhalation pathways dominate: ≈0.7 to 1.5; weak variation for secondary pollutants: ≈0.5 to 2.0; strong variation for primary pollutants: ≈0.5 to 5 for site, ≈0.6 to 3 for stack conditions (up to 15 for ground level emissions in big city).

corresponding toxicity data are summarized in Table 4W, available in the Electronic Materials section of the Annual Reviews Web site (http://annualreviews.org); they are based on dose-response functions published by the U.S. Environmental Protection Agency. Only inhalation dose has been taken into account because the available slope factors are for inhalation. By contrast to the classical air pollutants and carcinogens, for noncancer impacts of heavy metals we only have data for thresholds below which no adverse effects have been observed. Therefore, impacts of mercury and lead have not yet been quantified. We also consider dioxin, a pollutant emitted from the incineration of municipal solid waste. Dioxin is widely feared because it (or more precisely TCDD, one of the congeners of the dioxin family) is one of the most toxic substances known. However, with modern technologies one can readily keep the emitted quantities of dioxin so low that the impact is negligible, as shown by Rabl et al (31), a paper to which we refer for a more detailed analysis of dioxin impacts.

4.8 Health Impacts of Radiation

Incremental doses to the public from routine operations of the nuclear fuel chain, with French technology, are very small compared to the typical background exposures 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 (32, 33). The recommended dose-response functions for nuclear radiation are shown in Table 2.

5. OTHER IMPACTS

5.1 Impacts Other Than Health

A major contribution to the external costs arises from global warming, which we include but do not have the space to discuss in detail. For the global warming costs of ExternE (4) the detailed derivation can be found in reference 34; it is based on the physical damage estimates of the Intergovernmental Panel of Climate Change (35). The impacts include both nonhealth and health effects (increased tropical diseases such as malaria, as well as changes in mortality from increased heat and decreased cold stress).

Air pollution damage to buildings and agricultural crops has been found to make a relatively small contribution to the external costs, only a few percent of the total. Estimations of ecosystem impacts, other than agricultural losses, have remained extremely uncertain, when 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, especially for open pit mines, can certainly be very destructive to local 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.

However, 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 surprising because 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. However, if any human dies prematurely, we care a great deal. For the same reason the environmental impacts of radionuclides from the normal operation of the nuclear fuel cycle are totally negligible.

The situation is different for certain aquatic impacts: Acidification of rivers and lakes has been shown to have significant detrimental effects on 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.

5.2 Upstream Impacts

In a fuel chain analysis the impacts upstream and downstream from the power plant should not be overlooked. 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 Oak Ridge National Laboratory/Resources for the Future (1) and ExternE (see Table 4).

The impacts of fuel transport are more difficult to assess because in most cases it takes place in regions different from where the electricity is generated. Significant air pollution is emitted by coal transport by ship (12), but its impact can be small because of low population density on the ocean.

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 small or negligible, and most of the impacts arise upstream (but they tend to be small; see Section 7.3).

Generally, we have found that upstream and downstream impacts, relative to those from the power plant, are most important for nonfossil fuel chains where they can in fact dominate the result. For fossil fuel chains their contribution is of secondary importance.

5.3 Downstream Impacts

Among downstream impacts, those from wastes tend to be the most important. 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

TABLE 4 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	171	$\approx 2 \times 10^{-5}$	$\approx 3.4 \times 10^{-3}$		ng		ng
cadmium	20.9	$\approx 1 \times 10^{-6}$	$\approx 2.1 \times 10^{-5}$		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 (global warming potential) of 20 for CH_4.

[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.

Abbreviations: FGD, flue gas desulfurization; ESP, electrostatic precipitator; ng, negligible.

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 zone 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 an additive in building materials. Fly ash can be stabilized in concrete or glass. For coal none of the externality studies have succeeded in quantifying physical risks from solid wastes.

In attempts to solve radioactive waste management problems, numerous studies have been done over the years for both hypothetical and real 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 transpire. The probability of a leak should be accounted for but it is very difficult to estimate.

6. RESULTS FOR DAMAGE COSTS PER KILOGRAM OF POLLUTANT

Before proceeding to fuel chain results, we summarize the key assumptions in Table 2 and present the damage costs per kilogram of pollutant for typical European conditions in Table 3 and Figure 2. The health damage costs in Table 3 correspond to the "uniform world model" with the parameters of Section 3.3, in particular a population density of $\rho = 80$ persons/km^2. For other regions these numbers should be scaled according to regional average (land and water) population density. Figure 2 also shows the damage cost for particles from motor vehicles, calculated by Spadaro et al (36). It is much larger because the emission is at ground level close to population; in addition, the particles are more toxic by virtue of being smaller, ExternE (4) assuming that $PM_{2.5}$ is 1.67 times more harmful than PM_{10}.

The error bars in Figure 2 indicate the uncertainties as estimated by Rabl & Spadaro (16). One of the largest sources of uncertainty lies in the VSL. Whereas ExternE (4) assumes VSL $=$ 3.1 MEuro, there is no general consensus and one could argue for other values in the range of 1 to 4 MEuro. There is also considerable uncertainty about the relation between VSL (which has been determined for accidents) and the value of a YOLL due to air pollution, because it involves the period at the end of life about which valuation studies are only just beginning. In ExternE (4) the value of a YOLL has therefore been calculated on theoretical grounds by considering VSL as the net present value of a series of discounted annual values. The ratio of VSL and the value of a YOLL thus obtained depends on the discount rate; it is typically in the range of 20 to 40. With discounting, the value of a YOLL for chronic mortality is lower than for acute mortality because of the time delay between exposure to a pollutant and the premature death. Because

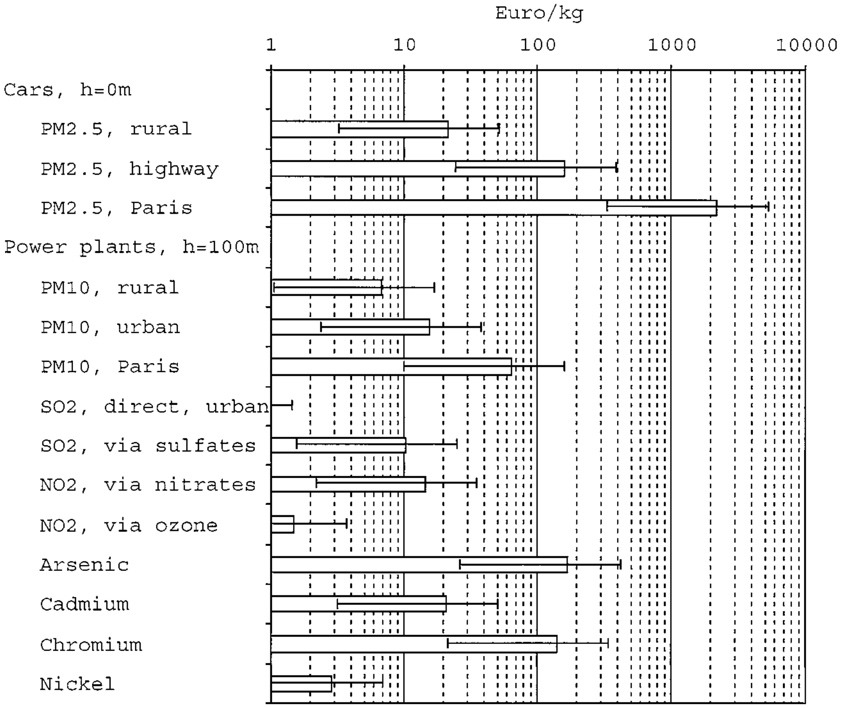

Figure 2 Mean damages per kilogram of pollutant emitted by power plants in Europe. Values for cars from Spadaro et al (36). Error bars indicate uncertainties as 1 geometric standard deviation intervals.

most of the damage cost is due to mortality (82% to 85% of the cost of PM, NO_x and SO_2), it is simple to estimate the effect of changing the value of a YOLL. For instance, if a term that contributes 84% of the total is reduced by 3, the total is reduced from 100% to $84/3 + 16\% = 44\%$.

The uncertainty owing to the valuation of a YOLL can be avoided to some extent by comparing the risks of technologies directly on the basis of YOLL per kilowatt-hour. This is easy to do with the numbers in this paper because 85% of the damage cost for PM, sulfates, and nitrates is due to chronic mortality. For example, from the cost of 15.4 Euro/kg of PM10 one finds $(0.85 \times 15.4$ Euro/kg$)/(83000$ Euro/YOLL$) = 0.00016$ YOLL/kg.

7. RESULTS FOR DAMAGE COSTS PER KILOGRAM OF POLLUTANT

During the latest phase of ExternE (4) a wide variety of power plants at over 50 sites in the EU has been analyzed. Extracting typical numbers from results that cover different technologies and sites involves a certain amount of subjective judgment. Here we offer a summary of typical results, based on the cost per kilogram of pollutant numbers in Table 3.

7.1 Fossil Fuels

For the fossil fuel chains the lion's share of the external costs comes from air pollutants emitted by power plants, the main impact categories being global warming and public health. Air pollutants from upstream and downstream activities make a relatively small contribution (roughly 10% of the greenhouse gases). Apart from CO_2, the damage cost is mostly due to health impacts, especially mortality.

Table 4 shows what the costs per kilogram of pollutant imply for the cost per kilowatt-hour of electricity for new power plants. They generally involve best available technology, but lacking a precise definition for this term, we indicate the emissions per kilowatt-hour that we have assumed. They do not necessarily correspond to a particular installation but are readily achievable with off-the-shelf equipment as used to comply with current regulations in the EU (which will probably be tightened). 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 General Electric offers a gas turbine combined cycle plant whose rated NO_x emissions are about eight times lower than the number in Table 4.

The emission of toxic metals is highly uncertain and variable from one source of fuel to another; the numbers shown are not necessarily typical. However, they are in any case so small that their contribution to the total damage cost is negligible. The results are plotted in Figure 3.

7.2 The Nuclear Fuel Chain

The impacts of the nuclear fuel chain range from local to global, and much of the damage will be imposed on generations in the far future. In view of the controversies about far future impacts, we present the results, broken down by space, time, and impact category, in Table 5. The costs are an upper bound because they have been calculated with zero discount rate.

The numbers in Table 5 and Figures 3 and 4 include all stages of the fuel cycle, even waste disposal and major accidents (although any estimate of the latter is controversial). All of the damage cost of low level radiation is due to human health effects (cancers and hereditary effects), whereas environmental impacts are negligible. The contribution of waste storage has been estimated to be about 1% of the total. Emissions of conventional pollutants by the nuclear fuel chain are negligible, if one allocates energy use upstream and downstream of the power plant to nuclear (as appropriate for the assessment of nuclear power as a baseload electricity source for the future).

TABLE 5 Damage costs of nuclear fuel chain by time, space and impact category, at 0% discount rate (12)

Breakdown by impact category

	Deaths/TWh	mEuro/kWh
Worker, nonradiological	0.019	0.07
Worker, radiological	0.02	0.07
Public, total	0.65	2.38
Environment	na	negligible
Total		2.52

Breakdown by time and space

		mEuro/kWh
Short term (<1 yr)	Local	0.068
	Regional	0
	Global	0
Medium term (1–100 yr)	Local	0.084
	Regional	0.06
	Global	0.19
Long term (100–100,000 yr)	Local	0.026
	Regional	0.002
	Global	2.1
Total		2.52

These results are for the technologies currently used in France, including reprocessing (3, 12). The damage cost from the routine operation of the nuclear fuel chain with best available technology is small, a few percent of the market price of electricity. It is interesting to illustrate the smallness of the nuclear impacts by another comparison: Even if the entire current electricity demand of the world were supplied by this technology for the next 100 years, the increased average dose rate per person would be less than 2.5 μSv/yr (as can be estimated from data in Vol.5 of reference 3); this is about 1% of the cosmic radiation background at sea level.

All this assumes, of course, a mature and stable political system, with strict verification of compliance with all regulations. Low external costs do not suffice to allay concerns about accidents, long-lived radioactive waste, the right to impose impacts on future generations, and risks from terrorists and rogue governments; these issues involve acceptability and defy quantification in terms of external costs. The following simple example can illustrate why external costs are not the only decision criterion. Suppose someone invents an energy system that can supply the world's electricity (roughly 10^{13} kWh/yr) at the bargain price of \$0.075/kWh (about one tenth of typical current prices)—with one little catch: There is a probability

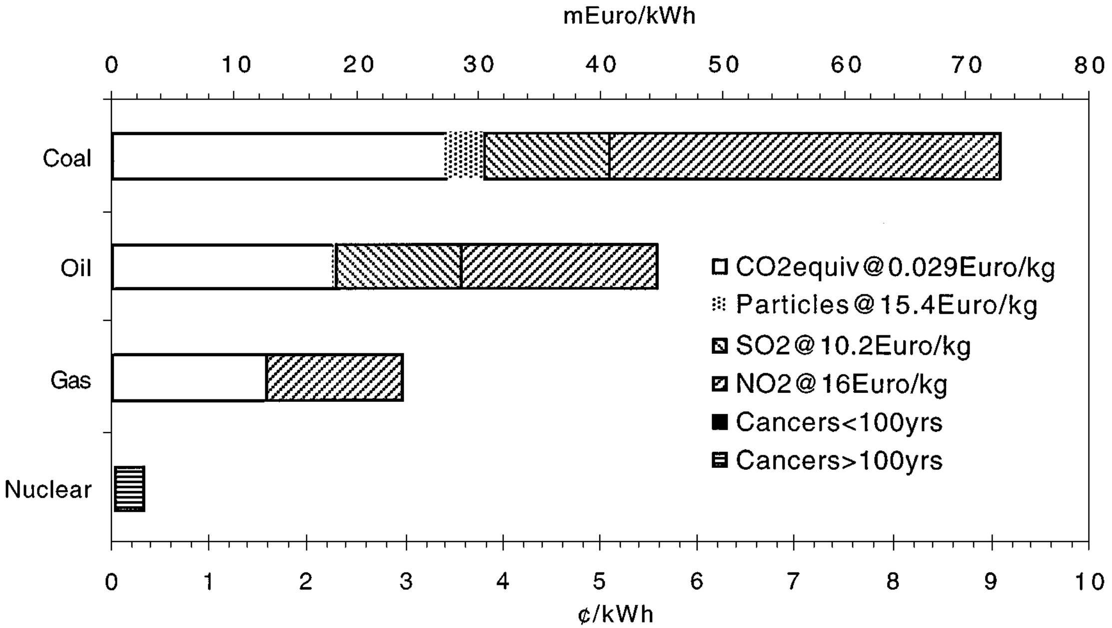

Figure 3 Typical damage costs of Table 4 for the fossil fuel chains, assuming average European conditions and new baseload power plants. For existing power plants the emissions of NO_2 and SO_2 can be several times higher. Costs for nuclear are upper bound (0% effective discount rate). Range of typical retail prices of electricity, 40 to 80 mEuro/kWh.

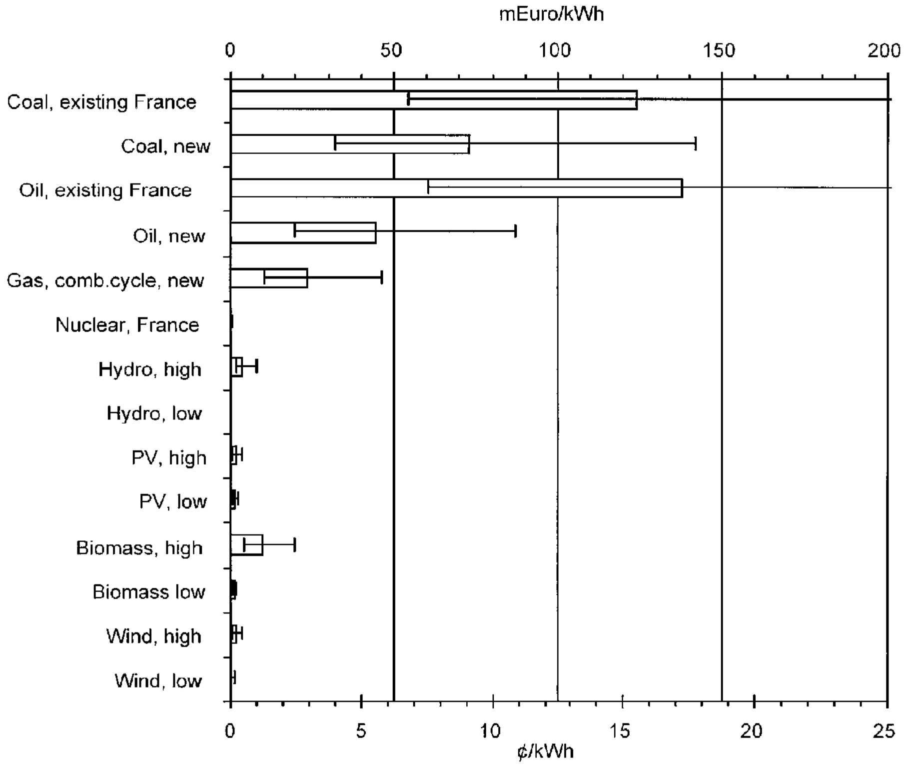

Figure 4 Typical damage costs of Table 4 for the fossil fuel chains, assuming average European conditions and new baseload power plants. For existing power plants the emissions of NO_2 and SO_2 can be several times higher. Costs for nuclear are upper bound (0% effective discount rate). Range of typical retail prices of electricity, 40 to 80 mEuro/kWh.

TABLE 6 Estimates of external costs of renewable electricity technologies, in mEuro/kWh, based on ExternE (4)

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

[a] Greenhouse gase emissions are highly variable with site; Gagnon & van de Vate (37) indicate 15 $g_{CO2equiv}$/kWh as typical value for cold climates, and possibly much higher values in tropical zones.

[b] Environmental benefit if biomass plantation replaces crops such as corn that need more pesticides and fertilizers. Abbreviations: ng, negligible; SD, extremely site dependent; PV, photovoltaic.

of an accident occurring once every 100 years that will kill 25,000 (roughly the total expected toll for Chernobyl if one multiplies the U.N. Scientific Committee on the Effects of Atomic Radiation estimate of committed dose by the standard linear dose-response function). Even at $3 million/life and zero discount rate, the levelized cost of such an accident has an expectation value of only

$$2.5 \times 10^4 \times 3 \times 10^6\ \$/(100\,\text{yr} \times 10^{13}\ \text{kWh/yr}) = 0.75 \times 10^{-4}\ \$/\text{kWh},$$

a mere 1% of this low electricity price. But would people accept such a deal?

7.3 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. It would also be logical to count energy from municipal solid waste and other waste as renewable, but we do not show it here because it is most often used for heat or cogeneration; we note, however, that modern technologies allow the damage costs to be kept very small, as shown by Rabl et al (31). Hydro, wind, and direct solar energy have special appeal, being not only inexhaustible but generally having 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 (4), summarized in Table 6, confirm that this is usually the case, but not always. We have no explicit results for solar thermal, but there is no reason to expect larger damage costs than for wind and photovoltaic, as the general characteristics (material intensity, efficiency, etc) are very roughly comparable.

For biomass, the technologies considered are combustion 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, photovoltaic, and wind there are of course no emissions from power generation, but there are upstream emissions from the production of the materials. Amenity impacts (e.g. noise) 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 6 cannot even be taken as general guidelines. The impacts can range from beneficial (irrigation, flood control, or recreational facilities) to extremely harmful if large populations are displaced without compensation or if a dam breaks. There is a tremendous variability in the quality of dams, the risks with good new design and construction being orders of magnitude smaller than for some of the older ones.

8. CONCLUSIONS

We have presented an overview of the methodology of the principal studies of external costs of energy (1–4) carried out during the past decade, and we have shown the results of the most recent phase of the ExternE Project, (4) which for reasons explained at the end of the Introduction, now represents the state-of-the-art. The uncertainties are large, some of the issues are controversial, and the science (or perhaps one should still call it art) of estimating environmental damages and costs is evolving. Nonetheless, some conclusions are emerging that merit attention. They can be illustrated by the comparison of the external costs of fuel chains in Figure 4:

- The damage costs of fossil fuels are significant; even with current new power plants the damage costs for coal are comparable to the market price of electricity (although much cleaner technologies exist for fossil fuels).
- Natural gas is cleaner and has lower impacts than coal, with damage costs about two to four times smaller; oil is intermediate.
- For older plants with little or no pollution control the damage costs can be much larger.
- The damage costs of the French nuclear fuel chain and of most renewables are much smaller than those of fossil fuels, only a small fraction of the price of electricity.

Naturally, the question arises of how these results can be transferred to other situations. Scaling of the emissions for different technologies is straightforward. Adjustments for population density can be made, very roughly, according to the discussion in Section 3.3 or with greater accuracy using the models for simplified impact assessment developed by Spadaro (38). More problematic would be the application outside the EU or the United States, because the crucial dose-response function for chronic mortality is based on studies in the United States (25) for lack of analogous studies elsewhere (the transfer to the EU is plausible in view of general similarities in age structure and health).

The ExternE Project has continued and the report on the latest phase has just been issued (39). Gradually, the results of ExternE are diffusing into the world of decision makers. For example, ExternE is recognized as the reference for comparative risk assessment by agencies such as the International Atomic Energy Agency. In the EU, ExternE is increasingly used as an input to environmental decisions, via cost-benefit analyses that justify even tighter regulations for the emission of pollutants from power plants (40).

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