# Energy and Health 2

## Electricity generation and health

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**The provision of electricity has been a great benefit to society, particularly in health terms, but it also carries health costs. Comparison of different forms of commercial power generation by use of the fuel cycle methods developed in European studies shows the health burdens to be greatest for power stations that most pollute outdoor air (those based on lignite, coal, and oil). The health burdens are appreciably smaller for generation from natural gas, and lower still for nuclear power. This same ranking also applies in terms of greenhouse-gas emissions and thus, potentially, to long-term health, social, and economic effects arising from climate change. Nuclear power remains controversial, however, because of public concern about storage of nuclear waste, the potential for catastrophic accident or terrorist attack, and the diversion of fissionable material for weapons production. Health risks are smaller for nuclear fusion, but commercial exploitation will not be achieved in time to help the crucial near-term reduction in greenhouse-gas emissions. The negative effects on health of electricity generation from renewable sources have not been assessed as fully as those from conventional sources, but for solar, wind, and wave power, such effects seem to be small; those of biofuels depend on the type of fuel and the mode of combustion. Carbon dioxide ($CO_2$) capture and storage is increasingly being considered for reduction of $CO_2$ emissions from fossil fuel plants, but the health effects associated with this technology are largely unquantified and probably mixed: efficiency losses mean greater consumption of the primary fuel and accompanying increases in some waste products. This paper reviews the state of knowledge regarding the health effects of different methods of generating electricity.**

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This is the second in a Series of six papers about energy and health

See Comment pages 921 and 922

See Perspectives page 927

See Series page 965

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## Introduction

Economic growth through industrialisation and rapid technological change has produced a huge improvement in the living standards and health status of the population of the now industrialised countries. From 1820 to 2002, western European countries saw their real incomes per head rise from US$1204 to $19 256, or 16 times.[1] This economic growth was also accompanied by major improvements in health: life expectancy, for example, has risen from around 40 years at the beginning of the 19th century in Europe to nearly 80 years today. The increase in life expectancy is not uniform with income per head of population. It increases rapidly with income up to a level of $7500 and then rises more slowly with further increases in income.[2,3] The availability of modern forms of energy, especially electricity after 1900, has contributed substantially to these positive developments. The replacement of traditional fuels, such as wood and candles, and animal power by steam power, and then by electricity and gas, has reduced the risk of fires, made the air in homes cleaner and warmer in winter, and reduced the risk of health hazards associated with animal waste. Thus it has improved the quality of life of individuals in many ways, and continues to do so in developing countries. A 2001 World Bank study[4] looked at demographic and health data from more than 60 low-income countries and investigated the determinants of health outcomes by use of cross-country data between 1985 and 1999. It found that in urban areas, linking households to electricity is the only key factor that reduced both infant mortality rate and under-5 mortality rate, and that this effect is large, significant, and independent of incomes. In rural areas, improvement

### Key messages

- Access to electricity is pre-requisite for the achievement of health, and lack of access to it remains one of the principal barriers to the fulfilment of human potential and wellbeing
- However, electricity generation from fossil fuel—resources of which could sustain their continued dominant role in electricity production well beyond this century—is also a cause of substantial adverse health burdens
- Fossil-fuel use can be used with greater efficiency than it is currently, and with lower emissions of pollutants harmful to human health. This is especially the case in developing countries, and realising these efficiency gains will be increasingly important as demand for electricity increases sharply
- An accelerated switch to renewable sources has the potential to deliver appreciable health benefits, though a major switch will pose (superable) challenges particularly in relation to the intermittency of renewable production, land use requirements, and cost
- The demand for valuable agricultural land will limit the role of fuel crops in future electricity production in Europe, but the potential contribution of such crops is greater in regions where crops with higher energy yields per hectare can be grown
- Nuclear power has one of the lowest levels of greenhouse-gas emissions per unit power production and one of the smallest levels of direct health effects, yet there are understandable fears about nuclear accidents, weapons uses of fissionable material, and storage of waste; nonetheless, it would add a substantial further barrier to the achievement of urgent reductions in greenhouse gases if the current 17 percent of world electricity generation from nuclear power were allowed to decline
- $CO_2$ capture and storage could in future have an economic role in reducing $CO_2$ emissions from large point sources, but its effects on health are likely to be mixed because efficiency losses mean greater consumption of the primary fuel and other resources, and greater production of waste
- Fusion power offers some hope as a comparatively clean technology for future electricity generation, with environment and health risks that are substantially smaller than for nuclear fission. However, commercial viability is still too far away for it to make a significant contribution to mitigation of climate change over most of this century

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of secondary education for women is crucial for reducing the infant mortality rate, whereas expansion of vaccination coverage reduces the under-5 mortality rate. Even with allowance for the limitations of such cross-sectional studies, the results are noteworthy and not unique.

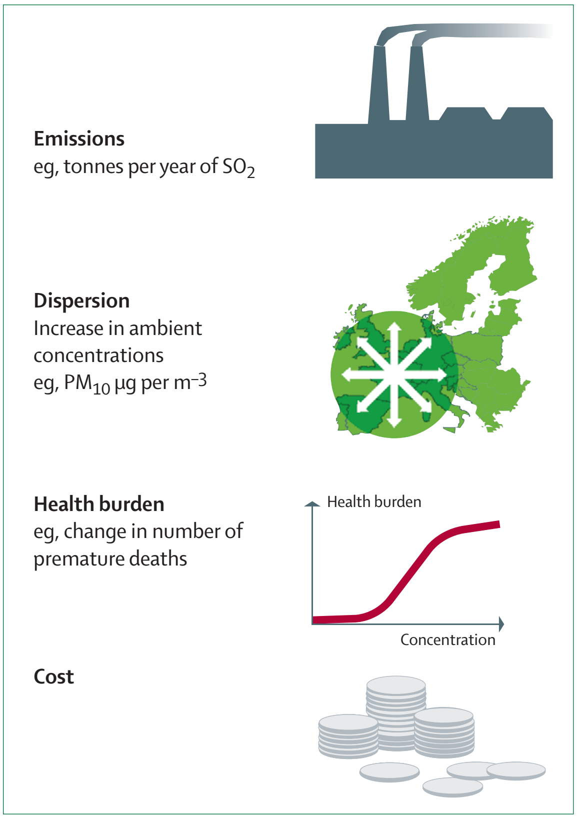


***Figure 1*: The effect pathway approach**

| Category of impact on human health | Pollutant or burden | Effects |
|---|---|---|
| Mortality | $PM_{2·5}$, sulphur dioxide, nitrogen oxides, ozone | Reduction in life expectancy |
| | Benzene benzo(a)pyrene | Cancers |
| | 1,3-butadiene, diesel particles | Fatality risk from transport of materials and at workplace |
| | Accident risk | |
| Morbidity | $PM_{10}$, sulphur dioxide, ozone | Respiratory hospital admissions |
| | $PM_{2·5}$, ozone | Restricted activity days |
| | $PM_{10}$, carbon monoxide | Congestive heart failure |
| | Benzene, benzo(a)pyrene | Cancer risk (non fatal) |
| | 1,3-butadiene, diesel particles | Cerebrovascular hospital admissions |
| | $PM_{2·5}$ | Cases of chronic bronchitis |
| | Ozone | Cough in asthma patients |
| | Accident risk | Lower respiratory symptoms |
| | | Asthma attacks |
| | | Symptom days |
| | | Myocardial infarction |
| | | Angina pectoris |
| | | Hypertension |
| | | Sleep disturbance |
| | | Risk of injuries from traffic and workplace accidents |

Data taken from ExternE.[6]

***Table 1*: Effect pathways included in analysis of the electricity sector**

Electricity has also contributed to economic development more generally by increasing the efficiency with which energy is used, so that an increased level of production is possible with the same amount of energy. Energy use in France, Germany, and the UK increased by 4·7 times between 1840 and 1990, wheres real GDP increased by 21·5 times.[5] Thus each unit of energy now produces more than 4·5 times as much output as it did in 1850.

Overall, there is little doubt that electricity has had a large positive effect on wellbeing. At the same time, new problems have emerged. The burning of large amounts of fossil fuels to produce the electricity we demand generates emissions that are harmful to health and are a source of climate change. Our paper focuses on these issues. We separate the discussion into the situation in developing countries and that in developed countries, and we offer some views on emerging trends in the relation between electricity use and health.

## Assessment of health effects of electricity generation

### Developed countries

The health effects of electricity generation can most easily be assessed by a bottom-up approach, in which emissions and hazards from each stage of the power generation cycle are measured and tracked to the endpoints at which they cause harm to individuals. The effects are calculated for specific technology and location—ie, for a given power station using specified fuel sources.

The effects are referred to as external costs because the party generating the emissions does not take full account of these effects of his or her actions when deciding on how to generate electricity.

Methods based on this approach were first used in the early 1970s and have become increasingly sophisticated. One major set of studies for Europe is the ExternE programme,[6] which is the result of over 15 years of research supported by the European Union (EU) and, to a lesser extent, the USA. ExternE is a bottom-up approach of the kind described above, in which each energy source is assessed individually and its ecological and social footprint analysed. This approach is characterised by the so-called impact pathway, in which emissions from a source are traced through as they disperse into the environment, after which the effects of the dispersed pollutants are estimated. Finally, the health burden is valued in monetary terms where possible. Figure 1 shows this pathway, and table 1 provides a description of the main effects estimated. Several points should be noted about the effects assessed.

Firstly, the emissions from a power source are dispersed into the atmosphere in ways determined by the height of the stack and by weather conditions—ie, temperature, precipitation, and especially wind speed and direction.

| | Deaths from accidents | | Air pollution-related effects | | |
|---|---|---|---|---|---|
| | Among the public | Occupational | Deaths* | Serious illness† | Minor illness‡ |
| Lignite[30] | 0·02 (0·005–0·08) | 0·10 (0·025–0·4) | 32·6 (8·2–130) | 298 (74·6–1193) | 17 676 (4419–70 704) |
| Coal[31] | 0·02 (0·005–0·08) | 0·10 (0·025–0·4) | 24·5 (6·1–98·0) | 225 (56·2–899) | 13 288 (3322–53 150) |
| Gas[31] | 0·02 (0·005–0·08) | 0·001 (0·0003–0·004) | 2·8 (0·70–11·2) | 30 (7·48–120) | 703 (176–2813) |
| Oil[31] | 0·03 (0·008–0·12) | .. | 18·4 (4·6–73·6) | 161 (40·4–645·6) | 9551 (2388–38 204) |
| Biomass[31] | .. | .. | 4·63 (1·16–18·5) | 43 (10·8–172·6) | 2276 (569–9104) |
| Nuclear[31,32] | 0·003 | 0·019 | 0·052 | 0·22 | .. |

Data are mean estimate (95% CI). *Includes acute and chronic effects. Chronic effect deaths are between 88% and 99% of total. For nuclear power, they include all cancer-related deaths. †Includes respiratory and cerebrovascular hospital admissions, congestive heart failure, and chronic bronchitis. For nuclear power, they include all non-fatal cancers and hereditary effects. ‡Includes restricted activity days, bronchodilator use cases, cough, and lower-respiratory symptom days in patients with asthma, and chronic cough episodes. TWh=$10^{12}$ Watt hours.

***Table 2:*** **Health effects of electricity generation in Europe by primary energy source (deaths/cases per TWh)**

Chemistry also plays a part in determining the composition and dispersion of the final product. This dispersion can be simulated by use of complex models that take account not only of the local effects but also of the long-distance transport of the pollutants, through the formation of particles as they are transformed into sulphates and nitrates. Long-distance effects are a substantial proportion of total effects for air pollutants, with the consequence that plants located away from centres of population can have health effects on people living quite far away.

Secondly, the health burden is assessed not just for generation stage but also for the other stages of the full cycle of the process, including the extraction of the fuel, its transportation, transformation into electric energy, disposal of the waste, and the transport of the electricity. So, for example, accidents in transportation are included.

Thirdly, the estimates of air pollution effects are based on extensive peer-reviewed epidemiological studies. Of particular importance are studies linking health effects to concentrations of small particles and ozone (webpanel 1).[7–29]

Fourthly, not all the effects can be valued in money terms, although the most important (ie, health) effects have been. Although monetary valuation remains controversial, especially when applied to health consequences such as premature mortality, methods have been developed to make such valuations and the numbers are used in making decisions about investment in stricter pollution control standards through a comparison of costs and benefits. In this paper, however, we do not report on monetary values for health effects, relying instead only on physical effects data.

Lastly, the scientific data on which the health effects are based are not certain. This uncertainty can be seen in the ranges of effects that are given. As new information becomes available, the values will also change and indeed we have seen some changes in the estimates of health effects over the past 15 years. Table 2 summarises the main health effects that have been estimated for different fuel cycles by the ExternE approach.

Because of the long-range dispersion of the pollutants, some effects can be felt more than 1000 km from the source. The following individual fuel cycles are worth noting.

*Coal and lignite*

The occupational health effects associated with mining are well known, although the rate of deaths and injuries has been declining. Nevertheless, studies have shown that up to 12% of coal miners develop one of several potentially fatal diseases (pneumoconiosis, progressive massive fibrosis, emphysema, chronic bronchitis, and accelerated loss of lung function).[33]

At the generation stage the main effects arise from the emissions of primary small particles (less than 2·5 μm or $PM_{2.5}$) and the creation of secondary small particles (less than 10 μm or $PM_{10}$). Sulphur dioxide and nitrogen oxides emerge as important in this context because they contribute to the creation of secondary particles, in chemical oxidation involving atmospheric gases. Direct health effects of sulphur dioxide and nitrogen oxides are much less pronounced and are not included in the main estimates reported above.

See Online for webpanel 1

*Oil and gas*

The health effects from gas are more than an order of magnitude lower than those from coal, mainly because the effects from primary and secondary particles are much smaller. The technologies used in Europe and assessed in our study are also state of the art and very efficient, hence reducing emissions per unit of energy generated. The health burdens associated with oil are higher than those from gas but still much lower than for coal or lignite. Accidents from this fuel source are estimated to be 50% higher than for gas but only 20% of those associated with coal and lignite.

*Biomass*

The biomass technologies addressed here refer to state of the art plants that meet EU environmental standards (ie, almost all plants that were assessed for the data reported in table 2). Sources are mainly energy crops but also some forest residues. The resulting impact, although substantial, is still well below that from coal and lignite. As an indication, the resulting chronic mortality rates are less than 20% of those from the lignite reference technology reported above. The most important emissions are those of ozone precursors—such as nitrogen oxides and volatile organic compounds.

*Nuclear*

The sources of the effects and indeed the effects themselves for the nuclear fuel cycle are very different from those for the fossil fuel cycles. They can arise from occupational effects (especially from mining), routine radiation during generation, decommissioning, reprocessing, low-level waste disposal, high-level waste disposal, and accidents. The data in table 2 show occupational deaths of around 0·019 per TWh, largely at the mining, milling, and generation stages. These numbers are small in the context of normal operations. For example, a normal reactor of the kind in operation in France would produce 5·7 TWh a year. Hence, more than 10 years of operations would be needed before a single occupational death could be attributed to the plant. Likewise, numbers of deaths through cancer, severe hereditary effects, and non-fatal cancers caused by normal operations are extremely small.

See Online for webpanel 2

The main sources of potential damage are accidents and non-routine radiation, and there is a lack of agreement between expert assessments from the industry and the public perception of these damages. The concerns about safety remain high, although the safety record has been improving steadily in most respects since 1990,[34] and the new generation of reactors are widely acknowledged to be much safer than earlier ones. After the events of Sept 11, 2001, designs have considered safety against the impact of a fuel-laden passenger aircraft.[35]

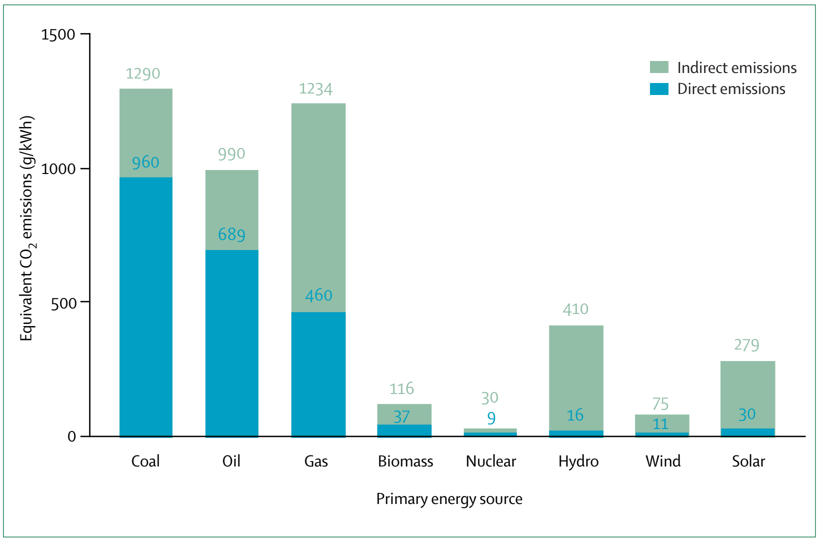


***Figure 2*: Full energy chain $CO_2$ equivalent emissions by primary energy source**
Data from IAEA, 2001.[40]

Safety procedures have also improved at the older reactors that are not considered as safe (especially the light water-cooled graphite-moderated reactor of the kind that was used in Chernobyl and of which 15 remain in operation in Lithuania and Russia). Not all indicators show steady improvement. The number of unplanned automatic shutdowns (scrams) declined in the 1990s but has remained stable since.[34]

There are also unresolved problems associated with the disposal of nuclear waste. The world's 441 operating reactors generate more than 10 000 tonnes of heavy-metal spent-fuel every year.[34] A cumulative 190 000 tonnes are in storage and, although increased reprocessing will reduce the rate of growth of the stockpile, much will remain and will need safe long-term storage. Finland, Sweden, and the USA have made the most progress in developing safe high-level waste repositories, although none is expected to be operating before 2020. To date there have been no serious incidents arising from the high-level waste.

Despite these mostly positive developments and several attempts to bridge the gap, there remains a firm divide between lay and expert estimates of the probability of nuclear accidents (webpanel 2).[36–38] There also remains the long lead time, in many cases of around 10 years, for approval and construction of nuclear power plants, though construction times can be cut to as little as 4 years for some modular designs.[39]

*Costs of $CO_2$ and other greenhouse gases*

The calculations reported in table 2 do not include any contribution from global warming. The different forms of power generation have very different contributions to $CO_2$ emissions (figure 2).

These contributions are the result of higher summer temperatures (increased costs), warmer winter temperatures (often decreased costs), flooding, increases in vector-borne diseases, and so on. The health costs of increased greenhouse-gas emissions are difficult to estimate and are controversial. A WHO study has estimated that the increase in greenhouse gases since 1990 has resulted in around 150 000 excess deaths in 2000. Almost all of these deaths took place in countries that are not members of the Organisation for Economic Cooperation and Development, where increased risk factors for malnutrition, diarrhoea, malaria, floods, and cardiovascular disease are attributed to climate change.[41]

The method for deriving these results involves taking linear approximations on increases in concentrations of greenhouse gases in 2025 and beyond; this approach does not lend itself to estimation of deaths per tonne of greenhouse gases and hence per TWh emitted between 1990 and 2000. A better way to estimate the health consequences of greenhouse gases in terms of emissions is to do a baseline run of a model with greenhouse-gas emissions, and then add a small amount of greenhouse gases and see the additional effect. This method was used in a study by Bosello and colleagues.[42] Their results, although not directly comparable with those of the WHO study, paint a somewhat different picture. Instead of excess deaths worldwide, the net results were of savings of about 840 000 by 2050. However, both approaches do agree that developing countries face an increase in mortality. Moreover, later in the 21st century the number of deaths might increase everywhere.

Although these specific consequences remain controversial, figure 3 shows the correlation between the direct health effects of power generation (as quantified in table 2) and the estimated contribution of the relevant technology to greenhouse-gas emissions (equivalent $CO_2$ emissions per kWh of production). Figure 3 shows that the modes of generation that have the greatest immediate effects are also those that make the strongest contribution to climate change.

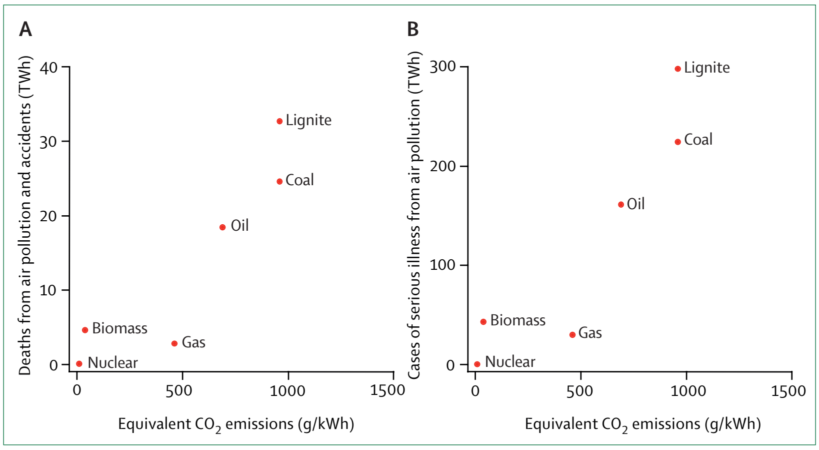


***Figure 3*: Health effects of electricity generation per TWh**
(A) deaths from air pollution and accidents involving workers or the public; (B) cases of serious illness attributed to air pollution. Data for $CO_2$ equivalent emissions from IAEA, 2001.[40]

*Putting the health costs of electricity generation in perspective*

The ExternE results can be viewed from two comparative perspectives: in terms of the total health burdens caused by electricity generation, and relative to other sources of health burden, such as smoking. The total health burden of electricity generation will depend on which fuels are used and the total amount generated. In the UK, for example, total generation was around 386 TWh, of which 34% came from coal and lignite, 37% from gas, 23% from nuclear sources, 2% from oil, and the remaining 4% from hydro, wind, biomass, and other fuels.[43]

Taking the figures for health burdens by fuel type in table 2 we get the overall burden from electricity as given in table 3. The data indicate that about six accidental deaths and 13 occupational deaths can be attributed to the generation of electricity in the UK per year. Also, around 3800 deaths arise from the associated air pollution. There are around 35 000 cases of serious illness a year and 1·9 million cases of minor illnesses, as defined in table 2. These findings can be put in perspective by comparison with general mortality and morbidity data. There were roughly 260 000 deaths in England and Wales from respiratory and circulatory diseases in 2001, so, the estimates from electricity generation account for about 0·014% of the total. In terms of morbidity, there were around 667 000 episodes leading to hospital admission for respiratory and cerebrovascular diseases in England in 2001.[44] Over the same period the estimates of serious illnesses in these two categories arising from electricity generation in the UK amounted to about 840 (table 2). Although the electricity data are for the UK emissions all over Europe and hospital admissions are for England alone, one can see that electricity generation accounts for a very small part of the total admissions in these categories.

Another useful point of comparison is with the health effects of smoking. In terms of excess deaths per year, the process by which air pollution affects mortality is through accelerated ageing, and a shrinking of the probability of survival curve across the population. The consequence can be reported as an increase in the observed death rate, or as a change in life expectancy. Calculations made by the ExternE team indicate that the current concentrations of $PM_{2\cdot5}$ in the EU and USA of around 20 μg/m-3 result in a loss of life expectancy of around 8 months. A UK review suggests a much smaller figure for the loss of life expectancy, or between 1 month and 1 year. This amount, however, includes only the acute effects of exposure to particulate matter and is certainly an underestimate of the total effect (chronic and acute).[45] We should also note that the gains in air quality from halving concentrations of particles will require reductions in emissions from not only power stations but also transport and other sources.[46]

A reasonable policy goal would be to reduce the life expectancy deficit of around 8 months by half, which would increase life expectancy by 4 months. By comparison, regular smoking is judged to cause a loss of life expectancy of 5–8 years, or about ten times the effects of $PM_{2\cdot5}$ air pollution and 20 times the effects of a plausible reduction in air pollution. We should also note that the gains from reductions in air pollution apply to a much larger population than those from cessation of smoking.

| | Cases | Percentage due to coal |
|---|---|---|
| **Accident-related deaths** | | |
| Among the public | 6 | 44% |
| Occupational | 13 | 99% |
| **Air pollution** | | |
| Deaths | 3778 | 85% |
| Serious illness | 35 186 | 84% |
| Minor illness | 1 853 152 | 94% |

***Table 3*: Health burdens from electricity generation in the UK, 2001**

## Developing countries

As countries become more industrialised their use of electricity and petroleum products for transportation increases, which in turn creates new environmental health problems, largely in the form of respiratory diseases, cardiac diseases, and cancers. Although most estimates of such effects of commercial energy have been made for developed countries, some studies are available for countries such as China, India, and Brazil. The large effects are due in some cases to lack of adequate emission regulations but also in many countries to ineffective enforcement of existing regulations. In India, for example, concentrations of suspended particulate matter (roughly equivalent to total suspended particulate matter) and respirable suspended particulate matter (roughly equivalent to $PM_{10}$) are frequently well in excess of national standards. In 2003, levels of suspended particulate matter exceeded national standards in 77 of the 91 residential monitoring stations more than 25 times and the standard respirable suspended particulate matter of 120 μg/m$^3$ (yearly average) was exceeded in most cities.[47] Such levels are associated with substantial health effects in other countries, and emerging research in India indicates that effects are similar there.[48] Thus, this failure of the environmental regulations to work effectively is having important consequences for human wellbeing. A study by the Institute of Economic Growth in New Delhi,[49] for example, has estimated yearly damage from urban air pollution in 15 major cities in India to be 111 billion rupees (US$2·5 billion). Much of this cost, however, is attributable to sources such as transport and industry. In some states these costs are as high as 8% of the state domestic product.

Studies in China have also revealed important health effects from the operations of coal-fired power stations. A study of such plants in Shandong province estimated around 77 deaths per TWh from a normal coal-fired plant that met Chinese environmental standards.[50] This estimate is much higher than that for European plants, indicating both a lower population density in Europe as well as the use of cleaner technology. Estimates of effects on serious morbidity (respiratory and cerebrovascular hospital admissions, congestive heart failure, and cases of chronic bronchitis) are estimated at 975 per TWh compared with around 225 per TWh in Europe.[50]

Although the health consequences of commercial fuel in developing countries are beginning to be felt, and studies show that the benefits of adopting cleaner technologies to reduce emissions from power generation and transport are almost invariably justified, we should recognise that even the dirtiest commercial fuels are less damaging in health terms than the traditional fuels they could potentially replace. A comparison is provided in table 4 of replacement of traditional fuels in the home with electricity generated from coal. The estimates of the health costs of indoor air pollution are based on epidemiological studies as summarised in Desai and colleagues,[51] whereas the health consequences of electricity generated from a state-of-the-art coal plant in India are taken from ExternE (table 2). The results refer to a plant producing 1 TWh ($10^9$ kW) of electricity in 1 year (a plant of about 150 MW would generate such an amount of electricity per year). This amount could provide enough electricity for basic lighting, cooking, and other needs for 333 000 households or about 1·6 million individuals, on the basis of a household size of five people.

| | Indoor air pollution | Lignite-based electric energy |
|---|---|---|
| Mortality (cases per year) | 1962* | 33† |
| Morbidity (cases per year) | 502 000* | 18 000‡ |

Details of calculations available from the author. *Caused by acute respiratory infection in children and chronic obstructive pulmonary disease in women. †Caused by occupational and public accidents in the mining and transportation of fuel and in the generation of the electricity, and from respiratory and cardiovascular deaths associated with the emissions from the generation. ‡Respiratory hospital admissions, cerebrovascular hospital admissions, restricted activity days, bronchodilator usage (in asthmatic adults and children), cough (in asthmatic adults and children), lower respiratory symptoms (in asthmatic adults and children), chronic bronchitis in adults and children and chronic cough in adults and children.

***Table 4:* Health costs of indoor air pollution against that from electric power (per TWh of generation)**

Table 4 shows that the indoor fuels cause in the region of 1962 premature deaths and half a million cases of acute respiratory illness and chronic obstructive pulmonary disease in a year. If these fuels could be replaced by electricity then the health burden would be somewhere in the region of 33 premature deaths and 18 000 cases of illness, ranging from severe (hospital admissions for respiratory failure) to mild (a cough day). Even with allowance for the uncertainties that exist in these estimates, the difference between the two options, which is more than an order of magnitude, makes the case for a shift to cleaner commercial fuels unanswerable in health terms.

## Role of $CO_2$ capture and storage

Because of the major contribution of fossil-fuel use in electricity generation to global emissions of $CO_2$, there has been interest in the potential of $CO_2$ capture and storage to mitigate climate change. In this process, $CO_2$ from large point sources such as power plants is captured and stored in isolation from the atmosphere. The technology of capture is already commercially available for large $CO_2$ emitters, such as power plants, but the long-term storage of $CO_2$ is mostly untested.[52] In theory, however, the capture and storage of a high proportion of $CO_2$ emissions from large point sources of fossil-fuel combustion, such as power stations, is possible.

There are three main methods of capture. Post-combustion capture, suitable for a modern pulverised coal power plant or a natural gas combined cycle plant, entails separation of $CO_2$ from the flue gases derived from the combustion of the primary fuel in air. Typically, an organic solvent such as monoethanolamine is used to capture the $CO_2$, which is present at concentrations of 3–15% in flue gases. In pre-combustion capture, the primary fuel is mixed with steam and air or oxygen to generate a synthesis gas high in carbon monoxide and hydrogen, which is further treated with steam to yield more hydrogen and $CO_2$ at concentrations of around 15–60% by dry volume. This method is suitable for power plants based on integrated gasification combined cycle technology. The third system (oxyfuel) uses oxygen at 90–95% purity instead of air for combustion to yield a flue gas high in $CO_2$ and water. The resulting high concentration stream of $CO_2$ is compressed and dried for transportation by pipeline or tanker for storage in geological formations, in deep ocean waters, or by mineral carbonation (figure 3).

*Environment and health risks and benefits*

Because $CO_2$ capture and storage is still a fairly new technology, our understanding of its health implications is incomplete. An assessment needs to be based on a life-cycle approach that takes into account the extraction and processing of the primary fuel, the generation and distribution of electricity, and the handling and storage of waste products. The benefits include the reduction of $CO_2$ emissions, which are estimated to be around 85–95% lower than with similar technology and no $CO_2$ capture and storage. The concentrations in the flue gas of other substances harmful to human health are likely to be similar to, or lower than, those of plants without capture and storage technology. This is because the capture process entails the removal of some emissions or the upstream removal of impurities, such as sulphur compounds, and is required for the efficient operation of the technology. However, plants with such technology operate at lower efficiency (have higher energy requirements) than similar plants without it. The increase in fuel consumption per kWh associated is in the range 10–40%.[52] As a result, there is a need to process more of the primary fuel. Thus, even where the concentration of an impurity in the flue gases is reduced, the overall emissions per kWh could still be higher.

A study by Rubin and colleagues,[53] reported also in the 2005 IPCC Special Report on Carbon Dioxide Capture and Storage, is one of the few published assessments of the resource and emission consequences of common fossil-fuel power plants (pulverised coal, integrated gasification combine cycle, and natural gas combined cycle technology) using $CO_2$ capture (table 5). With all three plant types, the increase in primary fuel use and the need for capture and storage reagents is clear. With pulverised coal, additional amounts of limestone (for control of sulphur dioxide) and ammonia (for control of nitrogen oxides) is required. All three also have increases in solid waste products. Sulphur dioxide emissions are lower for pulverised coal, but higher for integrated gasification combined cycle technology, whereas emissions of nitrogen oxides are higher for all three, and emissions of ammonia are increased in pulverised coal and natural gas combined cycle plants. The effect of these emission changes on human health has not been systematically estimated, but it would be reasonable to assume proportionate increases in occupational and other risks associated with the increased consumption of the primary fuel and other resources, net adverse effects relating to solid wastes, and mixed effects relating to the changes in atmospheric emissions.

| | Pulverised coal | | Integrated gasification combined cycle system | | Natural gas combined cycle plant | |
|---|---|---|---|---|---|---|
| | Rate | Increase | Rate | Increase | Rate | Increase |
| **Resource consumption** | | | | | | |
| Fuel | 390 | 93 | 361 | 49 | 156 | 23 |
| Limestone | 27·5 | 6·8 | .. | .. | .. | .. |
| Ammonia | 0·80 | 0·19 | .. | .. | .. | .. |
| $CO_2$ capture and storage reagents | 2·76 | 2·76 | 0·005 | 0·005 | 0·80 | 0·80 |
| **Solid wastes or by-products** | | | | | | |
| Ash or slag | 28·1 | 6·7 | 34·2 | 4·7 | .. | .. |
| FGD residues | 49·6 | 12·2 | .. | .. | .. | .. |
| Sulphur | .. | .. | 7·53 | 1·04 | .. | .. |
| Spent $CO_2$ capture and storage sorbent | 4·05 | 4·05 | 0·005 | 0·005 | 0·94 | 0·94 |
| **Atmospheric emissions** | | | | | | |
| Carbon dioxide | 0·07 | –704 | 97 | –720 | 43 | –342 |
| Sulphur oxides | 0·001 | –0·29 | 0·33 | 0·05 | .. | .. |
| Nitrogen oxides | 0·77 | 0·18 | 0·10 | 0·01 | 0·11 | 0·02 |
| Ammonia | 0·23 | 0·22 | .. | .. | 0·002 | 0·002 |

Values shown are rates in kg per megawatt hour for the capture plant, plus increases over the reference plant rates for the same plant type. FGD=flue gas desulphurisation. Data from IPCC.[52]

*Table 5:* **Illustrative consequences of $CO_2$ capture and storage energy requirements on plant-level resource consumption and non-$CO_2$ emission rates for three current power plant systems**

Additionally, there are health and safety issues relating to the transport of concentrated $CO_2$ by pipeline or tanker (eg, a small risk of asphyxia with local build up of $CO_2$, toxicity from hydrogen sulphide; figure 4), although such risks probably differ little from those associated with hydrocarbon pipelines already in operation. Leaks of $CO_2$ after its storage in geological formations probably carries a low risk to human health comparable to that associated with current activities such as natural gas storage and enhanced oil recovery. The effects of the injection of $CO_2$ into deep ocean waters on ecosystems remain uncertain.

Thus, whatever the potential contribution of $CO_2$ capture and storage to mitigation of climate change, and whatever the economic case (which is closely tied to the price of the primary fuels), the effects of this technology on health seem mixed. Its use does not fundamentally

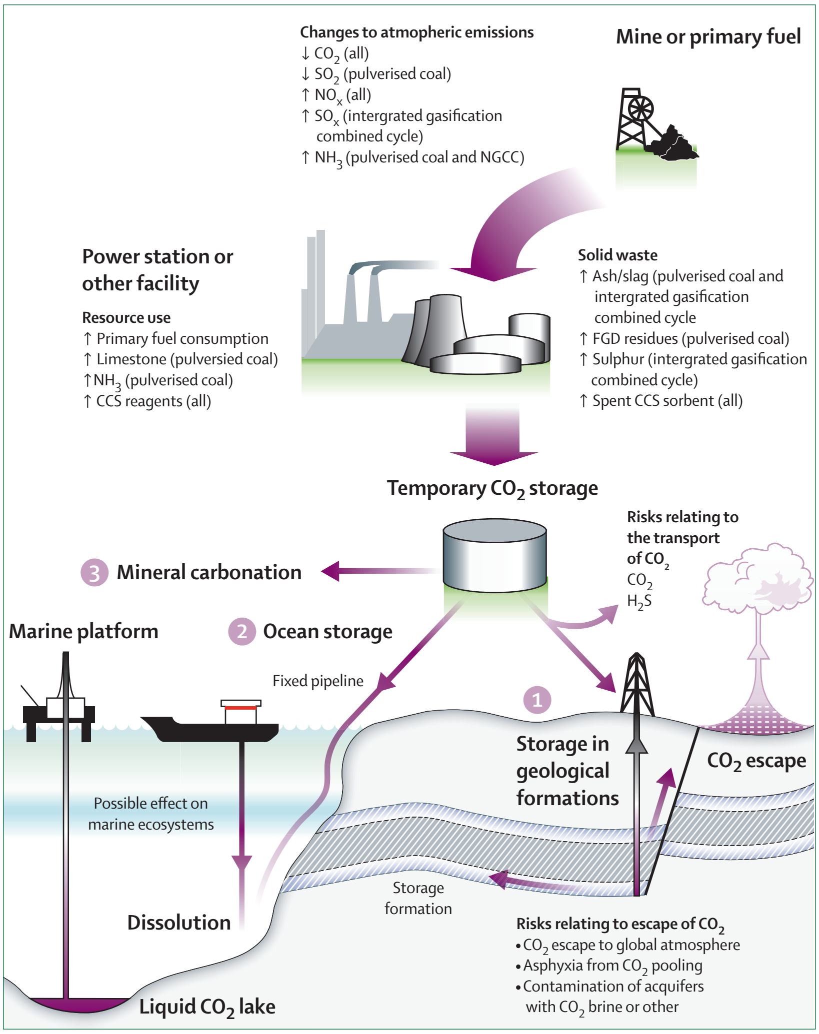


***Figure 4*: Summary of the principal $CO_2$ capture and storage processes and associated sources of environment and health risks**

NGCC=natural gas combined cycle. FGD=flue gas desulphurisation. CCS=$CO_2$ capture and storage. Adapted from figures in the IPCC special report on Carbon Dioxide Capture and Storage.[52]

See Online for webpanel 3

alter the sources of adverse health effects associated with fossil fuels, and it could in some cases increase immediate and near-term consequences because of efficiency losses and need for additional resource use. From an environment and health perspective, therefore, $CO_2$ capture and storage is at best only a partial solution.

## Health effects of renewable energy

In view of the evident health and environmental costs of conventional fossil-fuel combustion, the modern debate has appropriately turned towards other energy sources: the so-called renewables, derived directly or indirectly from the energy of sunlight (direct solar, hydroelectricity, wind, wave, biofuel production, and surface heat), the gravitational pull of the moon (tidal), or the radioactivity of the Earth's interior (geothermal). In varying degrees these sources share four main drawbacks: low energy density—ie, the power production per square metre of land area is low, which places constraints on large-scale production; intermittency, which means that methods have to be found to store their energy or to supplement it by more controllable forms of power generation to manage variations in production and demand; constraints on their location, which is generally governed by geological, hydrological, meteorological, and other factors, and which might therefore require long-distance transmission from the site of generation to the place of use; and environmental effects, aesthetic effects, or both, that might in part offset the broader environmental and health gains derived from lower air pollution and greenhouse-gas emissions.

With the exception of biomass, most renewable power systems do not rely on combustion and thus do not produce notable amounts of air pollution directly. However, some emissions of air pollutants can arise during manufacture and construction, such as in the production of steel for wind turbines and concrete for dams, but these are low compared with any but the cleanest system relying on combustion for electricity generation.

### *Hydroelectric*

There are some 48 000 large dams in operation worldwide, contributing to provision of drinking water, irrigation, flood control, and 20% of the world's electricity. Although apparently a clean form of electric power, hydroelectricity is controversial because of its social, health, and environmental costs (webpanel 3).[54–59]

Concerns about these issues have caused a re-appraisal of role of hydroelectricity, and a much more cautious policy towards its further development[54]—notwithstanding the current ambitious programmes in China, India, and elsewhere.

Despite these concerns, hydropower from large dams has several important advantages. Among the non-fossil-fuel forms of power generation, it provides a comparatively constant source and store of energy, which, with large reservoir heads, can be very rapidly mobilised to meet surges in demand. Also relevant is that the untapped potential for hydroelectric development is greatest in regions (Asia, sub-Saharan Africa, South America) where many of the 2 billion people currently without access to electricity live. In these regions, hydroelectricity could have an important role in future energy provision, provided projects follow good practice guidance.[54] However, the unexploited capacity is limited and they are associated with appreciable emission of $CO_2$ and methane from anaerobic fermentation in the static water (webpanel 3).

Among the range of social and health effects are the occupational risks during construction, and the low but finite chance of dam failure. The probability of such events is extremely difficult to establish, since they can be triggered by earthquakes, wars, terrorist activity, or engineering failures.

*Solar*

The theoretical potential of the direct capture of solar energy either through photovoltaic systems or by heat generation is enormous. After allowance for energy reflected by the atmosphere, around $3 \cdot 9 \times 10^{24}$ J are incident on the Earth's surface per year—almost 10 000 times more than current global energy consumption. Thus, the capture of less than 1% of photonic energy would serve all human energy needs. The limited assessment available by a full cycle analysis[38] indicates few drawbacks, though possible concerns might arise in relation to the production, handling, and disposal of the photovoltaic materials, and if battery or other technology is needed for energy storage.

The constraint on much wider use is primarily technical. With photovoltaic systems (which depend on quantum excitation of electrons in layered semiconductors), the efficiency of solar capture—the ratio of power output to the power of the incident radiation—is limited by, among other factors, the fact photovoltaic cells capture energy from across only a limited range of the solar electromagnetic spectrum. The best overall efficiency with current technology is around 10–15%. Given the time-averaged rate of incident solar energy of 100–300 W, this means little more than 10–45 $Wm^{-2}$ as a global average. Although thermal systems might be more cost-effective than photovoltaic systems, they too capture only a fraction of the incident energy. Thus, solar systems suffer problems of cost, large requirements for land area, and intermittency. Nonetheless, from a health perspective, the potential benefits of direct solar capture seem very desirable.

*Biomass*

Fresh (as opposed to fossilised) biomass is a potentially large store of renewable energy, which can be transformed into useful power by combustion or by thermochemical or biochemical conversion to liquid (ethanol, methanol) or gaseous fuels (methane, hydrogen).[60] However, its usefulness as a major energy source is limited by the inherent inefficiency of photosynthesis, which captures no more than a small percentage of solar energy reaching the Earth's surface.[61] The energy yield of even the most productive cultivated crops is therefore little higher than 1 $Wm^{-2}$; the imperfect efficiency of the energy conversion means that the power density is less than 1 $Wm^{-2}$—an order of magnitude lower than direct solar capture through photovoltaic or thermal systems, and up to four orders of magnitude lower than fossil-fuel combustion. To substitute for even a modest fraction of current or future coal use, for example, would require substantial land area to be given over to fuel crops—often in competition with food production. However, some high-yielding crops, for example South American sugar cane, are already being used successfully as fuel sources, though mainly for transport. And bioelectricity could have an important function in supporting electricity needs particularly of rural populations in lower-income countries. Furthermore if fuel crops are used in state of the art power-generating plants that meet the latest EU environmental standards the health consequences of bioelectricity production, although substantial, are still well below those from coal and lignite.

*Wind, wave, and geothermal*

Wind energy, mainly produced by horizontal-axis turbines of varying sizes, is one of the more cost-effective forms of renewable energy with today's technology. As with solar power, the obvious variability of its generation raises questions about solutions for energy storage and so-called despatchable capacity in other parts of the electricity grid. With connections across a wide network, the natural geographical variation in wind speed could help to smooth out fluctuations, but this might not entirely avoid the need for additional generation capacity elsewhere. Similar considerations obtain in relation to wave power. However, the balance of health risks and benefits, though imprecisely defined, would seem strongly favourable, as it does for geothermal energy. The latter is an option only in selected locations worldwide, though ground-source heat pumps using surface pipes or bore holes are local options for space heating and offer good energy return (around 3 W back for every 1 W of energy expenditure). Although geothermal generation has some local air pollution associated with it, the effects are much smaller than for fossil-fuel sources and it can be considered a much cleaner source.[41]

*Nuclear fusion*

A nuclear technology that offers some hope for future electricity generation is fusion.[62] However, its commercial development is still some way off because of major technical challenges (webpanel 4). If these issues can be overcome, nuclear power offers comparatively clean electricity production with little contribution to greenhouse-gas emissions. It shares the range of environmental and health risks of fission technology but at generally lower levels. The main product of normal operation is helium-4 (webpanel 4), which is an inert gas, but the fusion reaction also requires a radioactive isotope of hydrogen, tritium, which is difficult to capture completely, so some leakage is inevitable. The short half-life of just 12 years will help limit the build-up in the environment, but there could be important effects on health in an economy with a substantial number of fusion plants. The high-energy neutrons produced in a reactor make the structural materials surrounding the fusion chamber radioactive, with a similar inventory of radioactive materials to a fission reactor. The half-lives of the radioisotopes produced by fusion are substantially less than those for fission, they tend to be less biologically active, and there is potential to use low activation materials that do not easily become radioactive with neutron bombardment. Most materials of the core would

See Online for webpanel 4

be radioactive for around 50 years, and other low-level waste for another 100 years or so. Thus the difficulties of handling and storing radioactive waste would be smaller than for fission.

The risk of major accident is also substantially less. Fusion is not a chain reaction and requires very demanding control conditions (extremes of temperature and pressure, and magnetic containment), which, if disrupted, would rapidly halt the reaction. Moreover, unlike a fission reactor, the fusion chamber contains very little fuel—enough only to perpetuate the reaction for a minute or so—and stopping the supply would result in rapid shut-down. Fusion also has much less overlap with weapons technology. Plutonium (needed for atomic bombs) can be bred by use of the neutrons from a fusion reactor, but only with extensive redesign of the reactor—which would therefore be easy to monitor.

Although nuclear power has promise as a future energy technology, more than half a century of research with several experimental reactors has failed to produce net energy output in controlled production. The best estimates are that perhaps another 50 years will pass before the technology is developed to the point of commercially viability, which will be too late to make a significant contribution to mitigation of climate change over this century. Nuclear energy is not therefore a solution to climate change, but it remains an attractive hope for electricity production for future generations.

## Conclusion

The generation of electricity has both health benefits and costs. The health benefits of a shift away from non-commercial fuels to commercial ones, particularly when they are used for electricity generation, are evident from the evidence in developed countries in the past century and which is still taking place in developing countries. Moreover, the substitution of dirty energy for clean is not the only change that increases wellbeing. Efficient lighting, refrigeration, clothes washers, radios and TVs, computers, and numerous appliances that use electricity make possible those activities that otherwise would not be possible.

Although there are health costs associated with the generation of electricity, especially from fossil fuels, they are much smaller than those associated with indoor air pollution from burning fuels directly in homes. The drawbacks lie mainly with their contribution to outdoor air pollution, occupational risks, and greenhouse gas emissions.

See Online for webpanel 5

Assessment of the health effects of electricity generation should include all stages of the fuel cycle, such as mining, transportation, and disposal of waste. Studies in Europe, based on the ExternE methods, have provided estimates of the effect, in terms of excess deaths and various categories of morbidity.[30–32] The effects are not unimportant, especially from the use of coal and lignite.

The study also reports estimates of the effect of nuclear generation. The role nuclear power should have in future energy production depends on a balance of (perceived) risks. It currently accounts for around 17% of global electricity production and makes a small contribution to reducing greenhouse gases; thus, a decision not to replace current nuclear capacity would correspondingly increase the challenge of limiting greenhouse-gas emissions. Such a decision would be welcome in health terms if the nuclear plants were replaced by capacity in renewable production additional to the level of renewable production that would otherwise occur.

Forms of renewable energy generation are still in the early phases of their technological development, but most seem to be associated with few adverse effects on health and to contribute little to the longer-term environmental threat of climate change. Their rapid expansion is partly constrained by the intermittency and low density of energy production.

Much work is under way to improve the technologies used in electricity generation, and policymakers have been raising standards at all stages of the fuel cycle. The case for raising environmental standards is made on grounds of cost benefit, which requires the health impact to be valued in monetary terms. Although such values are not reported in this paper, regulatory impact studies have almost always confirmed that the benefits (which are predominantly health related) of the higher standards exceed the costs, in both the quickly industrialising and the more industrialised countries.

Although these are complex and rapidly evolving issues, the key messages from a health perspective are clear. Population health will substantially benefit from improved access to electricity and from modal switch away from fossil fuels towards renewable sources of electricity generation where possible. The case for such switching cannot be judged purely on traditional cost-effectiveness comparisons of current technology, since investment in renewable sources and increases in volume of production should bring cost efficiencies to newer (often the renewable) technologies; moreover, the cost-benefit equation is more favourable to renewable technologies where proper account can be taken of environmental and health effects. In addition to increasing access to electricity (see the first paper in this Series), our progress towards those strategic goals can be measured (webpanel 5).

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**Conflict of interest statement**

We declare that we have no conflict of interest.

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