Economic Analysis of Various Options of Electricity Generation - Taking into Account Health and Environmental Effects

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Based on the data given in the EU ExternE project, this report describes the health risks associated with electricity production, expressed in terms of number of deaths per TWh. The results are presented partly in the form of a summary diagram, showing the health risks associated with the use of various forms of power generation in different EU countries, and partly in the form of a number of examples, linked to Sweden and the Swedish energy debate.

Some interesting conclusions are:

- ***Coal, lignite and oil produce more extensive health risks than do other forms of energy***
- ***Hydro power and nuclear power produce health risks that are two orders of magnitude less than those resulting from coal and oil***
- ***Energy savings resulting from draughtproofing of Swedish buildings result in a greater number of deaths***
- ***The closure of Barsebäck will result in a greater number of deaths, most of which will occur in Denmark.***

The main objective of this report is systematically and clearly to present differences in health and environmental effects resulting from various ways of producing electricity and, in some cases, heat.

The risk comparisons are based on the results of the ExternE project (Ref. 1), which was financed by the EU Commission and carried out by research organisations in most EU states and in Norway. ExternE is one of the most extensive and scientifically most soundly based investigations within the field.

The final results from ExternE are expressed in terms of the external cost, i.e. cost of health effects and harm to the environment, expressed as **cost/kWh**. In some of the diagrams below the Swedish unit öre/kWh is used. One öre =1.1 EU cents. An important advantage of this method of expressing the statistics is that the health and environmental effects are both expressed in the same units as for the internal visible energy costs. In this report, we have also elected to use **deaths/TWh** as the measure of damage. This avoids the controversial approach of attempting to express human lives in monetary terms, but retains the ability to compare the results with those of other activities in society, e.g. road traffic.

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The generating cost for new capacity in Sweden has been calculated to be in the range of 2.5 to 3.5 EUcents/kWh for hydro, nuclear and gas and about twice as much for bioenergy and wind. Taxes and subsidies are not included.

Whether expressed as external costs, or (as here) as deaths/TWh, the results in ExternE provide the best instrument with today's knowledge levels to make general risk comparisons between different forms of energy. However, detailed knowledge of how air pollution spreads, and of its health and environmental effects, is still not fully satisfactory. Hopefully, further research will result in greater accuracy.

ExternE

All forms of energy source or energy carrier of significance have been analysed in ExternE. The national and international research organisations participating in the project made calculations for a large number of power stations and heating plants throughout the European Union.

It is not only the design, construction and use of the power stations etc that have been studied, but the entire fuel cycle, from the mine to waste disposal. In addition, health risks associated with operating accidents (including catastrophes) have been included.

It is health damage, mainly deaths, that dominate in the calculated external costs.

Deaths/TWh

In this report, we have elected to present the damage to health as deaths/TWh, as this is a concrete concept and easier to understand than the more theoretical term of 'external costs'. Despite a number of shortcomings, this provides a good basis for comparisons between the various forms of energy.

Adverse effects, expressed as deaths/TWh, are used as one step of the calculations of external costs, and are listed in the ExternE report.

Deaths/TWh is a coarse measure. Deaths due to air pollution tend to occur primarily among old and/or weak persons, while deaths from cancer due to for example radiation tend to occur regardless of age. It has therefore been argued that a better measure would be ' **years of life lost**'. The same reasoning could apply for other deaths, such as those occurring in traffic. A small child, killed in a traffic accident, loses a greater number of possible years of life than does an older person killed in the same accident. Nevertheless, such statistics are generally expressed only in terms of number of deaths.

The use of the concept of 'lost years of life' instead of deaths/TWh would have the effect of presenting fossil fuels in a somewhat better light in comparison with hydro power and nuclear power, but not so much that it would affect the conclusions in the report.

Methods of calculation

ExternE has used what is known as the impact pathway method for its calculations. This involves calculating or measuring emissions of pollution from each type of energy system (particulates, SO_2, NO_X and radioactive substances). This data is then used in a model that allows for the dispersion of pollution in the air and for population distributions.

A complication is introduced by the fact that the emitted air pollutants are usually chemically converted during their passage through the atmosphere, but the dispersion model allows for this.

Another complicated step, and which introduces uncertainty for some applications, is calculation of how inhaled air pollutants affect human health. This is done by using what is known as the dose/effect relationship that has been estimated through measurements and theoretical studies. An example of this is that a radiation dose, or a dose of some chemical poison, as received by one person results in an effect in the form of a greater risk of cancer.

As the hazardous pollutants are distributed over long distances, and as they affect persons in other countries, it is important to determine how much the diluted pollutants can affect a large population.

Threshold value - collective risk?

An important factor in any such mortality statistics or investigations is whether there is a threshold value, below which the concentration of the pollutant is harmless. This problem has been investigated most thoroughly for radioactivity but, with no reliable experimental data to go on, it has been decided to play safe and assume that there is no lower threshold value. Systematic statistical studies also indicate that there is no threshold effect for the common air pollutants from combustion of fossil fuels or biofuels.

As far as damage caused by ionising radiation is concerned, there is at present a lively expert debate on whether it is reasonable to sum risks from the very smallest doses (near zero) to produce what is known as a collective risk.

> *ExternE uses the concept of collective risks both for radioactive substances and for chemical poisons. This means that, for the first time, it is possible to compare the health risks of different forms of energy on approximately the same terms.*

This still leaves the general criticism against the use of collective risks for low-level diluted doses, as it is not possible to verify such risks in epidemiological studies. ExternE partly accommodates this criticism by using high uncertainty levels in its estimation of risks.

It is our impression that, despite the criticism, the concept of collective risk can be used when making comparisons between different forms of power.

Sources of error and uncertainties

It is clear that there are substantial uncertainties in the ExternE calculations of health and environmental damage effects. The report accepts, for example, that it is not possible to determine the effects of carcinogenic substances in emissions from fossil fuels and biofuels to the air. Such effects have been included only for radioactivity, which means that comparisons between energy forms are to the detriment of nuclear power, for which cancer is the most important health effect.

ExternE provides figures for quantitative estimates of the uncertainty . Statistical methods are only partly applicable, as some of the uncertainties are of systematic nature. An example of this is the uncertainty relating to the dose/effect relationship for radiation damage.

The report uses the magnitude of the geometrical standard deviation in the calculated values of the dispersion of particulates from the combustion of fossil fuels as a measure of the uncertainty. It assumes a standard deviation of 2-3 to be a reasonable value of the uncertainties. A standard deviation of 2 means that if the nominal value is A then, with high probability, the true value lies between A/2 and 2A.

It could be mentioned that Swedish Meterological and Hydrological Institute, SMHI, has calculated the deposition of sulphates and nitrates over Sweden (Ref. 2) The results of SMHI indicate that it is possible to make calculations of the dispersion of air pollution with considerably better accuracy than that given by the ExternE project.

ExternE does not discuss the relationship between absolute and relative uncertainties.

For the energy forms from which airborne pollutants dominate, the sources of error are of the same nature, regardless of whether they apply to fossil fuels or nuclear power. It is therefore reasonable to assume that comparison of the health effects between the various forms of energy is considerably less uncertain than are the absolute values. As a result, comparisons of the type described in this report are meaningful, despite uncertainties in the basic data.

Future risks

Some health effects and/or environmental damage mechanisms occur only after a long time. An example of this is cancer caused by radiation at very low dose levels from radioactive isotopes with long half-lives, e.g. carbon-14 from nuclear power plants or reprocessing plants. Another such source of delayed effects is heavy metals, e.g. cadmium in the ash from firing coal or wood.

ExternE has not included the effects of heavy metals, but the effects of long-lived isotopes have been estimated by discounting, i.e. determining the present value of the future effect. As some of the effects will occur in the distant future, present-value discounting results in them being estimated as very small.

As it is health effects caused by long-lived isotopes that are the dominating effect from nuclear power, present-value discounting leads to the health effects of nuclear power becoming negligible. In this report, we have not employed the present-value method, but have calculated the effects at their maximum values.

Uranium mines

Waste heaps at uranium mines have presented a special problem in connection with radiation. The waste contains uranium that could not be recovered from the ore. Uranium has a long half-life, and emits the radioactive gas, radon. If the waste is well covered with gravel and earth, the radon decays before it reaches the surface, which renders it harmless.

ExternE has used an old model for the spread of radon, which was developed at an early stage of the work of UNSCEAR (United Nations Scientific Committee on Effects of Atomic Radiation).

The latest report from UNSCEAR (Ref. 3) notes that the earlier model gave incorrect results, indicating health effects that were more than 20 times too large.

UNSCEAR's revised values for health effects have been used throughout this report.

The heavily debated (in Sweden) question of final disposal of used nuclear fuel has also been included in the ExternE calculations. However, due to the small volume of waste, and the fact that it is disposed of far below the surface of the earth, the corresponding external cost is very low.

Some results of calculations based on ExternE

Diagram 1 (from Ref. 4) shows data taken directly from ExternE. It shows the external costs for some of the energy forms involved in the Swedish debate.

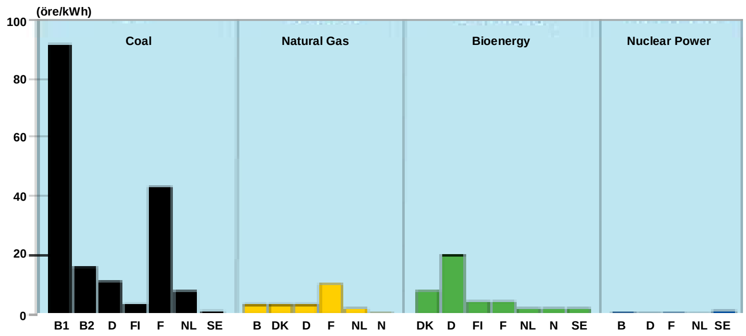

Diagram 1. External costs in öre/kWh for a number of important types of energy in a selection of European countries. The greenhouse effect is not included. This information has been taken from the ExternE report. The Swedish currency unit öre = 0.11 EU cents.

In this report, we express the health risks for various energy systems in a number of EU states, as taken from the ExternE report, as deaths/TWh, Diagram 2.

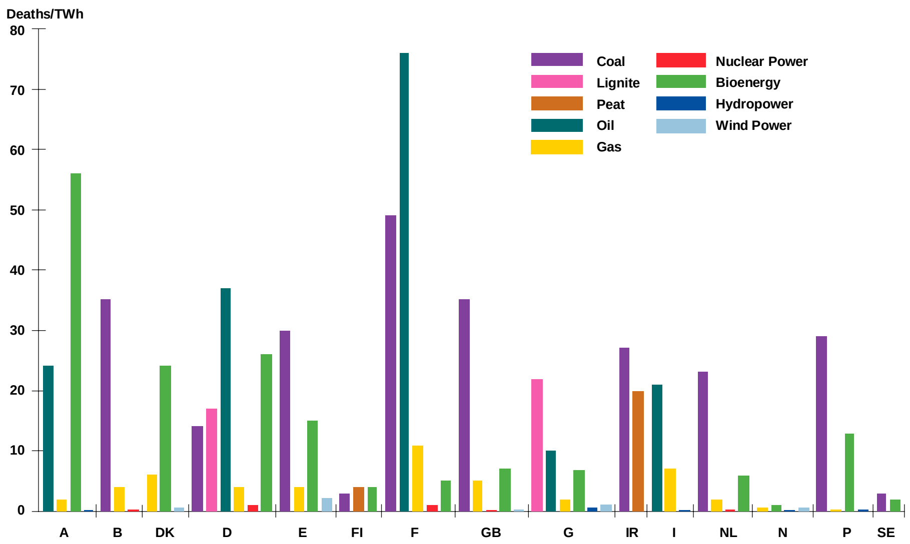

Diagram 2. Most of the health risk calculations in ExternE, presented as deaths per TWh (electricity). The diagram shows electricity production facilities in all EU states and in Norway

Effects caused by the greenhouse effect have not been included in the diagram. Due to their special nature, these effects are considered separately, further on in this report.

In a number of cases, ExternE presents results for existing facilities, although most of the data is based on hypothetical power stations located at sites where there are power stations today.

Most of the fossil power stations, hydro power stations and nuclear power stations have outputs of more than 500 MW electricity. One exception is the Danish natural gas-fired power station, which has an output of only 77 MW. The report has been forced to restrict itself to small power plants for bioenergy and wind, with outputs in the range of 1-40 MW. The only exception to this is the use of bioenergy in Sweden, at 100 MW.

Variations in the results

The major variations in the health risk effects between plants using the same fossil fuel are due mainly to population distributions within the areas suffering from their pollution.

The Swedish coal-fired power station shows what can be done when using the best possible technology in a low population density area.

Environmental friendliness has been further improved by using data for a CHP plant, thus producing a higher efficiency for electricity production than for the large coal condensing power stations.

A special effect applicable to countries such as Finland, Norway and Greece is that they exhibit relatively low health effects due to the fact that ExternE includes only effects within the European Union. Air pollution from Finnish power stations, for example, blows over Karelia in Russia, and thus makes no contribution to the calculated health or environmental damage effects.

The importance of the flue gas cleaning technology used is illustrated in Diagram 1, for a Belgian coal-fired power station. Calculations were made both for the power station in its present state, with only limited flue gas cleaning equipment (B1), and for a hypothetical power station using modern flue gas cleaning technology at the same site (B2).

The latter example produces a result of 18 deaths/TWh, as against 92 for the actual existing power station (unless the health effects of CO_2 emissions are included).

The health effects caused by nuclear power are dominated by the global distribution of Carbon –14. Of this, the greatest contribution comes from reprocessing of used fuel in the French reprocessing facility. This explains why the health effects for nuclear power are greater for France and Germany, which send their fuel for reprocessing to this facility, than for Sweden which intends to send its used fuel to final repository storage without reprocessing. ExternE does not, however, discuss the case of nuclear fuel in Sweden.

Bioenergy

The results for bioenergy show substantial variations, mostly because they are calculated for plants using completely different technologies, e.g. a modern 100 MW (electricity) CHP plant in Sweden and a 1 MW (electricity) gasification plant for farm manure in Denmark.

Sweden has highly efficient flue gas cleaning in its larger bioenergy facilities. However, the presently available flue gas treatment technology would be far too expensive to fit to smaller plants (less than 5-10 MW), such as district heating plants for smaller urban areas.

As a result, such facilities even in Sweden will result in health risks at the same level as those that ExternE presents for other countries. The smaller heating plants in Sweden are not intended for electricity production, but merely to provide heat that replaces electricity in previously electrically-heated homes.

Comparison of EU mean values for the various forms of energy is naturally a method that should be used with care, as both large and small plants, and areas of varying population density, are treated together. However, the mean values can be of interest as illustration of the differences between the different types of energy.

Mean values for the health risks associated with the various forms of energy are expressed as deaths/TWh for the EU facilities, and have been calculated from the ExternE report. The results are shown in Diagram 3.

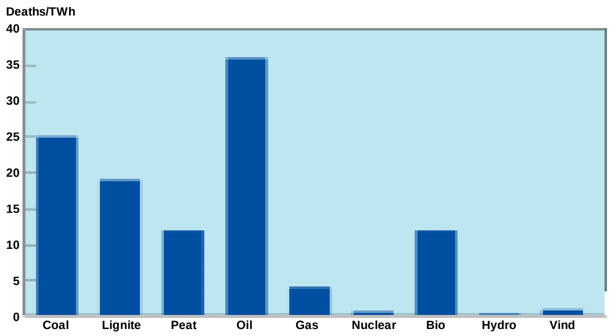

Diagram 3. Mean values of health effects, presented as deaths/TWh, for the respective forms of electricity generation throughout the EU. These calculations are based on the same data as in Diagram 2.

Conclusions

Some of the more straightforward conclusions that can be drawn from the results shown in Diagrams 2 and 3 are:

1. *Coal, lignite and oil result in considerably greater external costs and thus health effects than do the other forms f energy. This difference becomes even greater if the greenhouse effect is also included in the results: see Diagram 7.*

2. *The external costs of hydro power and nuclear power are about two orders of magnitude less than those from the above-mentioned fossil fuels.*

3. *Among the fossil fuels, natural gas has considerably less effect on the environment than do the other forms of energy.*

4. *The external costs of bioenergy, as shown in the ExternE results, lie close to those for fossil fuels, but it should be noted that, in most cases, the results are based on technology for which there is a considerable potential for improvement.*

The Swedish example for bioenergy shows what can be achieved in a sparsely populated area with a large plant using the best available technology.

The health effects from hydro power, wind power and nuclear power are so small that, within the accuracy of the calculations, they could very well be given a value of 0, but we have instead chosen to use the calculated values differing from 0 in this discussion.

These conclusions are also valid if we use the concept of ' **years of life lost**' instead of **deaths/TWh**.

Most of the technology on which ExternE is based is as used in the middle of the 1990s. The development of new technology will make it possible to reduce the health risks of all forms of energy. This applies particularly for bioenergy, which can at present be regarded as an immature technology, as well as also for fossil fuels and nuclear power. Many power stations were built before attention began seriously to be paid to environmental problems. There is therefore a significant potential for improvement in the next generation of plants through the use of new technology.

Even when allowance is made for future technical development and for the uncertainties of calculation, the ranking of the health effects of the various forms of energy remain unchanged. Hydro power, nuclear power and wind power present the lowest health risks, while the greatest health risks are presented by oil, coal, lignite and peat. Natural gas and bioenergy fall in between these two extremes. If the greenhouse effect is included in the discussion, the differences between the three groups will be accentuated.

Application examples

Example 1: The health effect of electricity production in a number of countries
Using the data presented in Diagrams 2 and 3, it is possible to calculate the total health effects of electricity use in a country, expressing them as deaths per year.

ExternE does not provide processed basic data for all forms of energy in all EU states. However, this is not a serious problem, as it is possible to use data from 'similar' countries. We have calculated the total health risks for a number of countries that would be interesting in terms of a comparison with Sweden: i.e. Belgium, Denmark, Finland and Holland. The results are shown in Diagram 4.

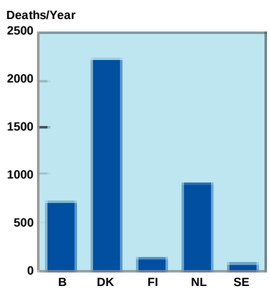

Diagram 4. Health risks expressed as deaths per year, resulting from total electricity production in a number of EU states. The figures relate to production values in 1995.

Diagram 4 shows that the health risk effects in countries having a high proportion of coal and oil power production are considerable, while the Swedish energy mix results in a very low level of health hazards.

Electricity production data for the various countries in the tables is as of 1995, and is shown in Diagram 5.

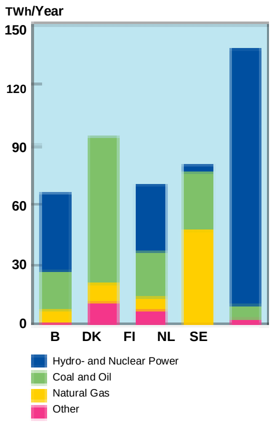

Diagram 5. Breakdown of electricity production sources in a number of EU states (the same states as in Diagram 4). The figures relate to 1995.

Example 2: Improvement of the indoor environment

Householders were encouraged to reduce ventilation rates in Swedish homes during the 1970s and 1980s in order to save energy. According to Reference 5 (Report of the Environmental Health Commission, 'Environment for Sustainable Health Development', SOU 1996:124), this resulted in an increase of 125 cases per year in the number of deaths due to lung cancer caused by radon.

In order to increase ventilation in older houses to the level required by the present Building Regulations, and thus reduce the frequency of cancer, while maintaining the same heating standard, would require an additional electrical energy production of 6 TWh/year.

As electricity production in Sweden cannot be increased, and Norway will not have any electrical energy surplus, the increased ventilation energy requirement will necessitate the import of electricity from coal-fired power stations, mainly from Denmark. The resulting increase in the number of deaths (mostly in Denmark) will be 200-250 per year.

Improved ventilation will not, in other words, be justifiable in health terms, as the deaths will simply be transferred from Sweden to Denmark. If, instead, the electricity could be supplied by Swedish hydro or nuclear power, there would be an increase of 2 energy-related deaths, as against the 125 lives that could be saved as a result of increased ventilation.

Example 3: The Swedish energy scenario in 2010

The National Energy Administration's energy scenario for 2010 (Ref. 6) expects electricity production for meeting electricity demand in Sweden to increase from the present 150 TWh/year to 170 TWh/year.

Electricity production in Sweden will remain unchanged, which means that 20 TWh/year will have to be imported, mainly from Denmark. This will increase the number of energy-related deaths by 500-600 per year.

Again, it is Denmark that will suffer most. Greater use of Swedish hydro and nuclear power would enable Denmark to avoid this fate.

Major accidents

All energy production is associated with a risk of accidents, and this risk has been included in the results presented in ExternE.

The method of calculation used in ExternE has been criticised, as severe consequences, when multiplied by very low probabilities, result in insignificant increases in the risk level. This is the case for nuclear power, where the probability of an accident in a Western power station has a very low value. For the same reason, it can be appropriate to consider the results of major accidents as a special case.

The standard work for global presentation of major accidents is 'Severe Accidents in the Energy Sector', published by the Paul Scherrer Institute in Switzerland (Ref. 7). This shows that in terms of the number of major accidents, and the total number of acute deaths between 1969 and 1996, it is coal and oil that have the worst performance. It is not until the number of persons having to be evacuated is taken into consideration that nuclear power makes a major contribution (the Chernobyl accident).

Diagram 6 is a summary of accidents anywhere in the world in the energy sector, from 1969 to 1996 (from Ref. 7). The reason for the domination of hydro power in this diagram, despite the fact that the actual number of accidents is less than those for coal and oil, is due to a number of particularly severe accidents outside Europe.

Barsebäck

The risk of major effects, and the need for extensive evacuations in the event of an accident at Barsebäck, have dominated the debate in Sweden and Denmark. Using the results presented in this report, it can therefore be of interest to make a comparison between the health risks resulting from a nuclear power station accident and those from normal operating emissions from Danish coal-fired power production.

Closing the Barsebäck reactors will result in a loss of production in Sweden which, during a statistically average climate year, cannot be compensated for by energy savings or by increased production of nuclear power and/or water power in Sweden and Norway. For a number of years into the future, the only possibility is a greater import of electricity produced in coal-fired power plants, mainly in Denmark.

According to data given in ExternE, the increased pollution from operation of these coal-fired power stations, which would otherwise have not been operated if Barsebäck had not been shut down, will amount to about 200 deaths per year, of which most will occur in Denmark but a few also in Sweden.

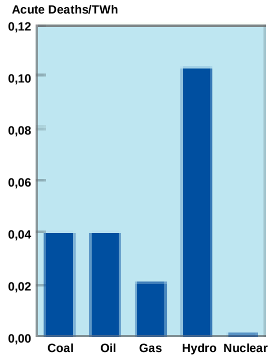

Diagram 6. The number of acute deaths per TWh resulting from major accidents for the most important forms of electricity production. These figures relate to the entire world, and cover the period from 1969 to 1996.

According to the same calculations, operation of Barsebäck results in one death from cancer per year: a health risk that would disappear if Barsebäck was shut down.

The final report from the 1994 Energy Commission (Ref. 8) states that, in the event of a severe accident, emissions from a Barsebäck reactor would result in 100-500 deaths in Europe over 50 years. This assumes that the emission filters operate in accordance with statutory requirements, which permit a maximum of 0.1 % of the total radioactive contents of the core to be emitted. In actual fact, measurements of the installed filters show that their efficiency is up to ten times better than required by the authorities.

The higher value (500 deaths) applies for a highly improbable weather pattern.

The risk of such an accident is regarded by the authorities as approximately equal to one per 100 000 reactor-years, while the probability of 200 deaths per year when replacement power is produced from coal, is 100 %, when calculated from the data in the ExternE report.

If the emission-restricting equipment did not work at all, the consequences of a reactor accident at Barsebäck would be considerably more serious. According to the Energy Commission, this would result in 2000-8000 deaths from cancer occurring in Europe over a 50-year period (40-160 per year). However, the likelihood of such an accident is regarded as being less than one per million reactor-years.

The greenhouse effect

The two fundamental questions are:

- *Has it been shown that the earth's average temperature has increased during the 1900s, and is continuing to increase?*

- *If so, is this a phenomenon related to human activities, i.e. something due to emissions of greenhouse gases, primarily CO_2 and CH_4?*

Most scientists involved in work in this area today answer Yes to both questions. However, there is a not inconsiderable number of scientists who are sceptical, and who feel that the scientific base is inadequate. A troublesome complication is introduced by the fact that the question has achieved considerable political significance, with the result that the scientific aspects have been overshadowed.

Final storage of CO_2?
One way of dealing with the CO_2 problem would be to avoid emissions of the gas to the atmosphere. This could be done by removing it from flue gases and disposing of it in suitable geological formations, known as aquifers. An investigation of the feasibility of this procedure has been carried out by Vattenfall Utveckling (Ref. 9), and shows that:

1. Removal of CO_2 from flue gases is successfully performed today on a large scale, e.g. in a boiler plant in the USA that removes 200 tonnes of CO_2 per day.

2. Since 1996, Statoil in Norway has condensed and re-injected one Mtonne/year of CO_2 into a gas field in the North Sea, which means that such injection into sandstone aquifers is already being practised on a commercial scale.

3. There are major aquifers beneath south-western Sweden and beneath the Baltic. The one beneath south-western Sweden is so large that it could store Swedish CO_2 production (60 Mtonne/year) for more than a century.

4. Methods of transporting CO_2 in pipes and by ship are well developed.

Cost budgets for dealing with CO_2 emissions from a large coal-fired power station indicate a price in the range SEK 150-400/tonne of CO_2, which is equivalent to an external cost of about 15-40 öre/kWh of electricity.

External costs
ExternE has performed an extensive investigation into the external costs of the greenhouse effect. An important conclusion of this work is that the material on which the calculations are based is very uncertain, which means that the results are also uncertain.

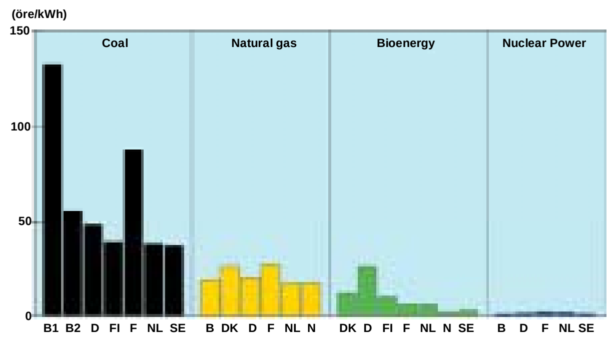

Diagram 7. External costs in öre/kWh of a number of important energy sources in a selection of European countries. Costs for damage caused by the greenhouse effect, equivalent to SEK 400/tonne of CO2, are included. (The present Swedish CO2 tax is SEK 370/tonne.) The Swedish currency unit öre = 0.11 EU cents.

Two different models of the greenhouse effect have been considered. Both are based on climate development scenarios presented by IPCC, the *International Panel for Climate Change*. ExternE avoids mentioning mean values or recommending any 'best value'. The values of external cost that are discussed lie in the range SEK 35-1 250 per tonne of CO_2. This interval covers not only the above-calculated cost for disposal of CO_2, but also the Swedish CO_2 tax. Diagram 7 shows some of the results from ExternE (Ref. 4).

According to ExternE, the most serious effect is in the form of human health effects, mainly due to the spread of malaria, due to the warmer climate, to areas that are at present free of it. For comparison, it can be pointed out that the sum of the other effects is of approximately the same order as the effects caused by the greenhouse effect.

If there is to be any attempt to draw a conclusion from this uncertain material, it must be that damage due to the greenhouse effect will neither dominate nor be negligible in comparison with the other external effects due to the energy forms which contribute to the greenhouse effect.

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