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Environmental Impacts of Electricity Generation

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The behaviour of the main economic actors, including states, consumers and industry, has been changing in recent years as their awareness of environmental damage resulting from human activity (such as global warming, acid rain, depletion of the ozone layer) has grown. The commitments made at the international conferences in Rio de Janeiro in 1992 and in Kyoto in 1997 reflect the political importance attached to environmental policy. Political choices have to be made, especially in the industrialised countries, to control the emissions of greenhouse gases.

Some countries already apply fiscal measures, or “eco-taxes”, to polluting industries; Denmark, Finland, Germany, Norway and Sweden have opted for such a policy. However, the implementation of any such tax is aimed at reducing or compensating for environmental impacts. Thus, it requires the emission levels, the related impacts and the induced costs to society to be well established. The progressive reinforcement of regulatory standards is another illustration of the relationship between politics and the environment. The requirements of consumers regarding environmental performances are becoming more and more stringent. They expect comprehensive information from industry, backed by independent parties, allowing a rational examination of potential impacts.

All energy sectors have been making efforts to reduce their associated environmental burdens, in particular with the implementation of new technologies. The French nuclear industry has always put a premium on environmental and health protection. In particular, it should be highlighted that, although releases from nuclear activities have always been far below authorised limits, the French nuclear industry has been devoting considerable energies to reduce further the environmental impacts. Working groups on the environment have been set up by the French nuclear organisations Electricité de France (EDF), the Atomic Energy Commission (CEA), Cogema, ANDRA and Framatome. These groups have the task of assessing the environmental performance of the nuclear energy sector and comparing this performance with that of other energy sectors. The importance attached by energy industry organisations to the environment is also illustrated by the environmental audit campaigns launched by various utilities, and which also involve their subcontractors.

Within the last decade substantial progress has been made, notably under the political impetus which exists in Europe and the United States, to identify and quantify the social and environmental impacts connected with the production and consumption of energy, and to assess the related costs. In 1995 the US Department of Energy (DOE) issued a report on the external costs and benefits of different fuel cycles. The European Commission, recognising the necessity for a debate about the environmental and economic effects of energy use, launched the ExternE Project in the early 1990s. A first series of reports was published in 1995 concerning the coal, lignite, gas, oil, nuclear, wind and hydropower cycles. The methodology was then applied to a wider range of fuel cycles, and in 1998 the results of national implementation programmes were issued.

The purpose of this paper is to synthesize the main results of various studies and to analyse the methodologies used to compare different fuel cycles (coal, gas, hydro, nuclear, wind). The scientific and economic information contained herein stems essentially from:

- The ExternE project reports (initial publications from 1995 and subsequent reports up to 1998).[1,2,3,4]
- Life cycle analyses performed by ETH (Zurich University) and Vattenfall Energysystem, and Ecobilan studies on behalf of EDF and Cogema.[5,6,7,8,9,10]
- Other reports from ANDRA, Cogema and EDF.[11,12]
- In addition the paper will examine a method for assessing the implementation of measures to reduce the environmental burdens, using the example of CO_2 emissions reduction measures from the Kyoto Protocol, through a macroeconomic model. The main source used here is a macroeconomic study performed by French government and the CEA.[13]

Comparing Fuel Cycles

Methodology

The comparison of the environmental performance of different fuel cycles first requires the implementation of a common and comprehensive methodology. Most environmental studies related to energy production are based on one or both of the following approaches:

Life Cycle Assessment (LCA)

This approach has been developed to support the evaluation of measures for the reduction of ecological impacts. It involves quantifying all the physical interactions between the environment and a system aimed at fabricating a product. The LCA seeks to evaluate all the emissions and consumptions at all stages of a production cycle, from the extraction of raw materials to the disposal of waste. The interactions usually considered include the consumption of raw materials and energy, land occupation or loss, emissions to air and water, thermal releases, waste, noise, odour, etc.

The accounting of material and energy fluxes is not only performed for the activities directly linked to the production of a given product, but also for “upstream” or “downstream” activities (e.g. activities which are required for the fabrication of the equipment and for the dismantling of the related facilities). The environmental impact assessment then requires the qualification of such indicators, but LCA studies tend not to be specific on impact calculations. This step has not yet been harmonised in the framework of LCA studies, due notably to the complexity of modelling the transfer and exposure mechanisms, and also due to the difficulty of weighting and aggregating the selected indicators.

Impact-Pathway Methodology (IPM)

This methodology has been applied in, for instance, the framework of the ExternE project to assess the external costs related to electricity generation. IPM describes the route by which emissions generated by the reference technologies travel in the environment, potentially to impact on humans. This approach requires a review at each step of the various fuel cycles of any possible releases to the environment, and their mode of transfer to the public and workers. Inclusion of site-specific factors is one of the major features of IPM – specific locations are identified for all the fuel chain activities. All the stages (construction, operation, dismantling)[14] are generally considered, as well as normal and accident conditions. Unlike LCA, IPM has not generally been applied to upstream or downstream activities.

The implementation of IPM also requires modelling of the transport and chemistry of emissions, which is often complex (for example, the formation of ozone from nitrogen oxides by photolytic reactions). The second difficulty lies in the modelling of the exposure of the population and the resulting impact (response). In particular, epidemiological studies have not yet resolved the risks from low level exposure. Cautious assumptions regarding the choice of exposure/response functions have been made, as described below.

The IPM generally considers geographical and temporal divisions to capture impacts as exhaustively as possible. Each set of effects are classified according to:

- Geographical range of the impact, e.g. local range (up to 100 km), regional range (100 to 1000 km), and global range (>1000 km).
- Temporal boundaries, which have been defined in the ExternE project as short term (immediate), medium term (1 to 100 years), and long term (100 to 100 000 years).

A comparison between different fuel cycles is possible only if common boundaries have been used in the analyses. As detailed below, this is not always the case. In particular, long-term impact assessment for fossil fuel cycles is still a weak point.

Once the impacts have been assessed, one can wonder if it is possible to determine an economic equivalent of the detriment involved, in terms of money. One way of assessing such values is to measure the individual willingness to pay for improvements, or willingness to accept drawbacks. The “willingness to pay” approach is followed in the framework of the ExternE project, allowing an evaluation of the external costs for scenarios representative of each fuel cycle. Once monetary valuations of externalities have been made, it is of great importance to assess the methods of implementing economic measures which could drive the economy towards the economic (welfare) optimum.

Several tens of indicators or impacts can be identified to analyse the detriments of fuel cycles. Overall, four families of indicators emerge:

Public health impacts, due to:

- atmospheric or aquatic chemical releases (the relevant associated indicators are the mortality and the morbidity (acute/chronic)),

- radioactive releases (the main indicators are the individual and collective doses associated with the risks of cancer (fatal and non-fatal)),
- noise pollution,
- accidents.

Occupational health impacts, due to:
- exposure to chemicals (the relevant associated indicators are the mortality and the morbidity (acute/chronic)),
- radiological exposure (the main indicators are the individual and collective doses associated with the risks of cancer (fatal and non-fatal)),
- noise pollution,
- occupational injuries.

Local and regional environmental impacts, including impacts on agriculture (yield losses), forests, fisheries, hunting areas, materials (building degradation), visual intrusion, loss of land and of recreational areas (due to the installation of the fuel cycle facilities), modification of terrestrial and aquatic ecosystems, etc.

Global impacts, including:
- global warming and ozone depletion,
- resource depletion (raw materials, water),
- energy consumption and depletion,
- volume, toxicity and quantities of wastes.

A given fuel cycle does not necessarily involve all the impacts mentioned. Preliminary analysis allows the impacts which are likely to be negligible to be determined, so that a list of “priority impacts” can be established for each fuel cycle.

Identification and Quantification of Basic Indicators

The following analysis is restricted to the indicators that have been regarded as being of major importance in terms of impact. Those indicators are based on real emissions from typical fuel cycle facilities of different energy sectors (coal, nuclear, gas, hydro, wind).

Emission of Radionuclides

The release of radioactive liquid or gaseous effluents concerns mainly the nuclear fuel cycle. All environmental studies take this indicator into account when assessing this cycle, as it is one of the major sources of impact. Numerous studies have been performed, notably by the French nuclear organisations and in the framework of the ExternE project, resulting in comprehensive and coherent data for this indicator. With the complementary studies now underway, it should be noted that an exhaustive characterisation of the radioactive source terms associated with the French nuclear fuel cycle will be available soon.

Radioactive gaseous effluents (see Figure 1) also affect the coal fuel cycle, as radon is released during coal extraction. However, the few studies conducted on that topic[9] have shown that direct emissions of radioactive elements are very low. Life cycle assessments take into account indirect radioactive releases due to the consumption of energy from nuclear power plants, i.e. that required for the fabrication of the facilities in the front end of the coal fuel cycle. Converted into environmental or health impact, this indicator is a minor contributor compared to chemical pollutants. Figure 1 shows a comparison between direct radioactive releases from the nuclear fuel cycle and direct/indirect radioactive releases from the coal fuel cycle.

Atmospheric Emissions of Pollutants and Chemical Toxicants

The main pollutants and chemical toxicants include nitrogen oxides (NO_X), sulphur oxides (SO_X), carbon oxides (CO_X), and particulates. These pollutants can be subsequently transformed through chemical reactions into secondary pollutants, especially nitrates, sulphates and ozone, which may have important impacts on health and the environment. Although thorough epidemiological studies of the effects of air pollution have been competed within the last decade, these effects are still the subject of controversy since the results of the studies are not yet conclusive. This point is discussed further below. Tables 1 and 2 qualify the health and environmental impacts resulting from the emissions of the main pollutants.

Nuclear Fuel Cycle

Generally, emissions of chemical pollutants have not been taken into account because they have been regarded as producing a marginal impact. Such releases are mainly indirect releases (in particular emissions of CO_2, NO_X, SO_2 from activities such as construction or transport of materials from one site to another).

Information on this point is however available from LCA studies performed notably in Sweden[6] and Switzerland.[9] Complementary data on direct releases can be found in studies performed by the French nuclear organisations (Cogema for mining, conversion and reprocessing, EDF for power generation).[11]

Coal and Gas Fuel Cycles

Direct emissions from the operation of power plants predominate markedly over indirect emissions (such as production of materials for constructing power plants, etc.). Values have been recently been produced from studies in France.[2] Some LCA studies[6,9] give complementary information.

Hydro and Wind Cycles

Among the studies analysed, only two[6,10] include an inventory of emissions of chemical pollutants, which are exclusively indirect emissions.

Figure 2 summarises the maximum values proposed in quantifying the chemical emissions associated with the nuclear, coal, gas, hydro and wind cycles. CO_2 emissions are displayed separately in Figure 3. The emissions of chemical pollutants for the wind and hydro options are less than 0.008 g/kWh (for all pollutants). Examining Figures 2 and 3, the nuclear, wind and hydro cycles clearly stand out.

Release of Chemical Liquid Effluents to Water

This indicator has been generally studied in much less detail than atmospheric emissions. The ExternE analysis in particular is limited to radioactive liquid discharges.

Ultimate Waste

Although the waste issue concerns all the energy options, it is of particular importance for the nuclear fuel cycle since the associated high level waste may have environmental and health impacts in the long run. It is important to highlight that the nuclear industry is the energy sector most closely involved in the short-term and long-term management of the waste it produces. In France, the process for preparing a repository aimed at confining these wastes is underway, conducted by ANDRA. As required by the French nuclear safety authorities, the confinement barriers will be designed to ensure public individual doses lower than 0.25 mSv/year, corresponding to negligible radiological consequences.

Even if such a facility does not exist yet, impact assessments have already been published considering radionuclide releases from the repository (from normal evolution of the site, and from abnormal situations such as human intrusion). For example, an assessment performed in the framework of the Everest European Project for normal evolution of the site indicates a maximum individual dose[15] of 2×10^{-4} mSv/year. Even if such studies need to be refined as the repository concept progresses, the order of magnitude obtained so far is clearly very low.

In the case of other energy options, the disposal of ultimate waste has not been studied thoroughly. However, one should remember that while the toxicity of nuclear waste decays, this is not the case for the toxicity of chemical pollutants, which remains constant. An IAEA study[16] (see Table 3) points out that various energy chains are likely to exceed the concentration limit of chemical toxicants defined for the nuclear industry in their own waste management.

It should also be noted that the production of electricity by French nuclear power plants leads to about 1 kg of radioactive waste per year per inhabitant, of which only 5 grams are high level wastes. The mass of radioactive waste is 100 times smaller than that of total industrial toxic wastes.

Other Burdens

Other burdens capable of causing an impact, such as noise and emissions of heat, are not quantified here. However, the related external costs are low as far as electricity generation is concerned.

Quantification of Impacts

The transition from quantified fluxes to impacts requires sophisticated models designed to describe complex mechanisms such as the dispersion of pollutants. Identical time–space grids have to be used in order to allow comparisons between the different fuel cycles (local/regional/global models valid for the short/medium/long terms). Moreover, exposure scenarios must be identified (for example, location and size of the population reference groups, age distribution). The IPM is fully consistent with such an approach, unlike LCA studies when considered individually.

The definition of “exposure/response” (E/R) functions is crucial for the evaluation of environmental or health impacts. Important work has been devoted to the assessment and the reliability of these functions in the framework of the ExternE project, including analysis of uncertainties. These relations are generally derived from epidemiological studies. But the quantity and the quality of data on response mechanisms vary considerably between the different pollutants. One should in particular emphasise the importance (and the remaining uncertainties) of recent epidemiological data on nitrate and sulphate aerosol effects.

First of all, no consensus has been reached within the scientific community that would allow a clear choice of a specific model. For example, the choice of a linear model without threshold to represent the biological response to low dose exposure (to chemical products, particles, radiation, etc.) is a matter of controversy. In the framework of the ExternE project, linear E/R functions have been assumed for all types of emissions, introducing uncertainties for some pollutants (especially nitrates and sulphates). Thus the current process consists of assessing the collective dose (expressed in "man-Sieverts") and linking this dose to the cost induced. This method, based on collective dose, may over-emphasise the cost of low level doses, as has been confirmed by recent epidemiological studies. These difficulties explain why most LCA studies limit their scope to the identification and quantification of emissions.

Since it is impossible to provide details on all the potential effects, we have selected some relevant impacts, which will be discussed in conclusion.

Health Impact

Three main indicators allow a characterisation of health impacts:

- Morbidity (acute/chronic),
- Mortality (acute/chronic),
- Accidents.

As an illustration, Figures 4 and 5[1,2] allow a comparison between the coal, gas, hydro, nuclear and wind cycles regarding occupational and public health impacts. The selected indicator in this case is the number of deaths per TWh of electricity produced (accidents and mortality). The dominance of the coal cycle for this indicator is due to the public health impact of emissions of nitrates and sulphates.[2]

Global Warming

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the main contributors to global warming. The specific contributions of methane and nitrous oxide have been assessed respectively as 21 and 320 times that of CO_2. These rates are referred to as the "global warming potential". Although the warming potential of CO_2 is the lowest, its contribution remains predominant due to the size of the related emissions. The global impact of human activities on the greenhouse effect can be assessed as equivalent CO_2 emissions (CO_2 eq) resulting from the sum of the different emissions weighted by their global warming potential.

Although the rise in greenhouse gas concentrations in the atmosphere has been well established, the effects on climate, the subsequent damage, and the kinetics of its occurrence are more uncertain. However, it is well known that a slight increase in the mean global temperature (a few degrees) would modify considerably the face of the Earth, in particular with a rise in sea levels. But global temperature change and the related consequences are currently (and perhaps for the long term) the subject of scientific debate and controversy. The available results of the related studies have to be considered with caution.

The ExternE analysis (in particular for the French situation) has been essentially based on the study prepared by the Intergovernmental Panel on Climate Change (IPCC),[18] the most recent and comprehensive study in that field. The external cost has been assessed to be in the range of 18 to 46 euros per tonne of CO_2 equivalent.

Another way to take account of the burdens of environmental or health impacts is to set physical limits by law. In fact, this is the approach followed by the international community with respect to greenhouse gases, through the Kyoto Protocol. The method of implementing this protocol (through various economic means) leads to monetary equivalents of the burdens. In mathematical terms the implicit level of the burden is the "dual" value of the constraint (see section "Valuation" below).

Major Accidents

Most of the fuel cycles involve some risk of major accidents, which could occur due to structural or mechanical deficiencies, process failures, human errors or external events such as natural phenomena. Assessment of the economic costs associated with severe accidents may allow a comparison between the different fuel cycles. However, to date very few studies have been dedicated to this point, except for the nuclear fuel cycle.

A study published recently[3] concerns only the nuclear fuel cycle and is based on the assumption of a core melt accident. The public aversion to hazard has been taken into account, leading to an increase in the external costs by a factor of about 20. In that case, the external costs range from 0.01 to 0.46 euro mills/kWh (1 euro mill = 0.001 euro; 1 euro = US$0.95). These figures are the outcome of very careful accident assessment corresponding to a realistic and very low probability of occurrence (» 10^{-6}/reactor.year).

Valuation

External Costs (Microeconomic Level)

The potential impacts previously cited induce costs that are not accounted for by the energy market (one should underline that while most of the impacts analysed herein are negative, some of them are beneficial). The related costs are thus referred to as "external costs". They are assessed for a given amount of production e.g. 1 kWh of electricity produced. As previously mentioned, the IPM aims to cover all the stages of the fuel cycles. The individual costs can be aggregated, thus facilitating a global comparison between the different fuel cycles.

External costs are, at this microeconomic level, powerful tools for driving the market towards the optimum. In the "perfect world" where the standard hypotheses of neoclassical microeconomics apply, the optimum taxes to be applied to the sources of the burdens are equal to the external costs.

If some of the goods affected by the burdens previously cited are marketable, they are easy to value (such as crops, building materials, etc.). However, this is not the case for human life and ecological systems. Economists have developed several concepts aimed at proposing monetised values for non-marketed goods. In the framework of the ExternE project, the assessment of external costs associated with human health is based on the "value of statistical life" (VSL). The VSL has been assessed at 3.1 million euros (1995 value) using methods determining the individual "willingness to pay" (WTP) for reducing the risk of dying. The valuation of morbidity is usually based either on individual WTP, or on statistical data coming from insurance companies or welfare organisations (hospital admissions, restricted activity days, etc.).

Studies which have led to the costing of global warming impacts to between 18 and 46 euro/tCO_2 eq[18] are not detailed here. However, to summarise the main assumptions used:

- Temperature rise of 2 K.
- Linear damage function.
- Damage amounting to 1% to 3% of worldwide GNP.
- Time boundary set at 2100.

It is important to remember that all these evaluations heavily depend on the discount rate assumed. Since the choice of a discount rate value is widely debated, most of the studies are parameterised using 0%, 3% and 10%. The external costs assessed in the framework of the ExternE project for the nuclear, coal, gas, hydro and wind fuel cycles are presented in Figure 6. These results correspond to a discount rate of 3%.

In order to appraise the importance of external costs, it is necessary to link them to the production costs (Figure 7). The results of a perspective study, published in 1997 by the French Directorate of Gas, Electricity and Coal (DIGEC) of the Ministry of Industry compares the competitiveness of various power generation systems (for a 5% discount rate, advanced technologies, and baseload operation). These results[19,20] are summarised here:

- Nuclear fuel cycle: 25.5–26.2 euro mills/kWh.
- Gas fuel cycle: 27.7–41.5 euro mills/kWh.
- Coal fuel cycle (pulverised coal): 29.7–36.1 euro mills/kWh.

The calculations and results presented here must be treated with caution. However, some broad conclusions emerge when comparing external costs and production costs. The nuclear fuel cycle has by far the lowest external cost (<0.6 euro mills/kWh), amounting to a small fraction of the internal cost (a few per cent). Hydro (£6 euro mills/kWh) and wind (£5 euro mills/kWh) have externalities which are a sizeable fraction of production costs. The external costs for gas, despite a large uncertainty (20–55 euro mills/kWh), are comparable to the production costs. The uncertainty is even larger on the externalities for coal (69–213 euro mills/kWh), but they may exceed the production costs (by a ratio of about 7:2).

However, handling these values requires the greatest caution. They are not necessarily directly comparable, since the individual assessments may not be based on the same bibliographical sources, the same countries, the same scales of time or space, and they do not always cover all the stages of the fuel cycles.

The structure of these costs is detailed in Figure 8. It should be first noted that the contribution of major accidents to the nuclear fuel cycle external cost reaches 50%, while it has been neglected for the other cycles (due to a lack of studies in that field). Although this ratio may seem significant, one has to keep in mind the very low absolute value of that item, which is assessed in a very cautious way (using a factor of 20 as quoted above).

The cost related to public health is important in the case of fossil fuel (73% of the global cost for coal, 40% for gas). It represents 25% for wind and only 10% in the case of the nuclear fuel cycle. Hydro is characterised by a negligible public health externality.

The contribution of occupational health impacts seems only significant for the nuclear fuel cycle, reaching 40% of the global cost (due to the strong influence of assumptions on collective dose, as we have seen above), and for the wind fuel cycle, with 20%, once more with very low levels in absolute terms.

Environmental impacts are clearly dominant in the case of hydro (100%) and wind (55%); they only concern the local and regional areas. Due to significant CO_2 eq emissions, global environmental impacts have an important weight in the external costs, since they reach 60% for gas and 25% for coal. It should be noted that the external costs for coal and gas are mainly due to the operation of power plants (rather than fuel cycle operations).

Macroeconomic Assessment of Nuclear Energy and CO_2 Emissions

A comparison of external costs and generation costs is the best way, even with large uncertainties which remain, to measure how the competitiveness of the different electricity sources may evolve in the future. In short, neoclassical economic theory states that imposing the external costs as taxes at the source of the burdens is the best way to reveal the real cost of electricity consumption. This is classically the best way to lead the economy to the social optimum.

However, several difficult questions arise in the reality. The first one is the difficulty of applying appropriate measures for each electricity consumer. This difficulty is a very strong one if one wants to implement emission limits (as is the case in the Kyoto Protocol) at the country scale. However, the use of economic tools such as taxes and/or tradable permits is a powerful means to overcome this difficulty. In that case, it is generally possible to compute the level of taxes equivalent to a global emission limit.

Other well known difficulties also play an important part. For example, possible initial bias in the taxation system, the (political) possibility of using or not using a given economic tool (and the rules to be defined for its use), the dynamics of the target, and the rigidity of capital stocks. In the case of greenhouse gases emissions it appears very difficult to assess the cost of the induced damages, and thus the level of the related externalities. Thus, a practical way to obtain an acceptable value is to start from the Kyoto Protocol, assuming that it is the best available reference of what the optimum for the planet can be.

Starting from that point, it becomes possible to use an economic model to calculate the increase in tax on carbon fuels which would lead to the desired level of CO_2 emission. A first assessment is possible using simple models linking energy consumption to energy prices. However, the most powerful tools are macroeconomics models, which can take account of changes in the whole economy, such as modifications in income of different economic sectors, including households.

In this context, the CEA developed jointly with the Ministry of Transportation and Housing a world, multi-country, multi-period, multi-sector general equilibrium model, known as GEMINI-E3.[13] The most recent version of the model, GEMINI-E3/GemWTrap, has been especially designed to appraise the Kyoto Protocol according to several scenarios.

For France, where 80% of the electricity in 1999 came from nuclear, it is not possible to reach the Kyoto targets only through the electricity generation sector. However, in order to ascertain the actual contribution of nuclear to the Kyoto commitment, an imaginary scenario of "nuclear moratorium" has been integrated into the model. Such a moratorium is, of course, not scheduled, the goal being to show the benefit from nuclear power. This scenario is based on the assumption that France would decide not to make new investments in nuclear power plants and would progressively decommission existing facilities.

This model also allows assessment of the consequences for the French economy of fulfilling the Kyoto commitments with or without tradable permits and with or without domestic taxes. Those consequences have been assessed in terms of "welfare cost". Analysis covers the period 1990 to 2040.

The GEMINI-E3 model allows us to conclude that countries like France which depend heavily on nuclear energy have a large advantage in terms of the economic consequences of fulfilling the Kyoto Protocol. This can be shown when examining the economic consequences of the most constrained situation (a nuclear moratorium without tradable permits). At the end of the assessed period, the price of electricity would multiply by as much as 3.5 times compared to the present level. Simultaneously the relative welfare loss (as a percentage of households' final consumption) is about 3%; this loss would be 3 to 6 times that of other OECD countries in implementing the Kyoto Protocol. This loss is equivalent to about 760 euros (US$720) per household each year.

The GEMINI-E3 model also allows the level of carbon tax (or the equivalent level of externality) in different situations to be assessed. At the end of the simulation period, this value would be about US$1000/tonne of carbon (i.e. US$300/t$CO_2$). This rises to US$1600/tC if nuclear could not contribute to CO_2 emission management.

Thus, the use of such a macroeconomic model confirms the role of nuclear power as a very efficient tool for limiting the social cost of the Kyoto Protocol. In addition, it confirms clearly two major points:

- The implicit value of the CO_2 externality derived from the Kyoto Protocol could be high.
- Building in the first decades of the twenty-first century a significant number of nuclear reactors is a very efficient insurance against large but still uncertain damage from global warming, for a negligible additional cost.

Conclusion

For electricity generation, each of the energy options previously studied has specific advantages. The choice of any option is clearly dictated by socio-political, economic and environmental factors. Within the last decade, interest in health and environmental impacts associated with electricity generation has grown considerably. Impressive efforts have been made by all energy sectors to reduce the associated burdens. The external costs and their structure highlight the present status of such efforts.

The very low external costs of the nuclear option reflects a long-run process (several decades) implemented by the nuclear industry to minimise and internalise the effects of its activities. Such a process has led to emission levels far below authorised limits, even though these limits are very low and tend to become increasingly stringent.

As previously mentioned, significant and efficient measures have been taken by the fossil fuel industry to reduce health and environmental impacts. Concerning external costs, the gas option seems to be significantly ahead of the coal fuel cycle. Efforts are obviously continuing to further improve environmental performance. The major contribution of fossil fuels to worldwide electricity production will continue, even if these options seem to induce higher externalities than the others. The fact that the gas and coal options are characterised by the lowest investment cost per kWh (according to a 1998 OECD study) is a possible justification for such a situation.

The pollution issued from hydro and wind energy only affects the local and the regional areas (acidification, impacts on buildings and land). Indeed, the related effects are limited to the vicinity of the site location. The direct impacts of the wind option are mainly the noise and the loss of land. It is, for example, interesting to point out that it would require up to 20 000 km^2 to reach present French electricity production capacity with the wind option.[21] In comparison, the ground occupied by French nuclear fuel cycle facilities amounts to a few tens of km^2. The impacts of the hydro option are in particular linked to the modification of land use (e.g. the loss or the gain of recreational areas).

The waste issue has been thoroughly considered only in the framework of the French nuclear fuel cycle assessment. In this case, the waste management programme as envisaged by the nuclear organisations (especially ANDRA) should lead to negligible radiological impacts. Different scenarios have been studied, leading to satisfactory results. The economic valuation of these impacts has not been carried out yet. Equivalent work remains to be done for the other energy options. Disposal of highly toxic chemicals is one of the crucial topics.

The nuclear fuel cycle clearly allows minimisation of CO_2 emissions, thus taking the lead in combating the greenhouse effect. The health impacts resulting from the emissions of chemical pollutants such as SO_2, NO_X, nitrates and sulphates are also clearly reduced with the nuclear option. A macroeconomic assessment performed with an up-to-date model shows that the long-term commitment of France to nuclear electricity production is able to drastically limit the consequences of the fulfilment of the Kyoto Protocol, in terms of households' welfare.

Keeping in mind the above mentioned points, with their associated uncertainties, one can conclude that the nuclear option is not only a major actor in the worldwide energy market, but also a major contributor to the preservation of health and the environment. Significant and sustained efforts have been made to minimise its impacts through expenditures on improving safety, radioprotection and training, and on minimisation of the volume and activity of waste and effluents. These costs are already integrated in the generation cost. Such an “internalisation” places the nuclear sector in an enviable situation.

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21. American Solar Energy Society and American Wind Energy Association.

Table 1. Health impacts due to chemical pollutants and toxicants.

Pollutant		**Health Impact**
Primary	**Secondary**	
Particles		Chronic mortality Respiratory and cardio-vascular morbidity
SO_X	Sulphates	Acute mortality Respiratory and cardio-vascular morbidity
SO_2		Chronic mortality
NO_X	Nitrates	Respiratory morbidity Eye irritation
NO_2	Ozone	Chronic mortality
NO_2, VOC		Acute mortality Respiratory morbidity
Hydrocarbons		Cancers
CO		Mortality (asthma) Cardio-vascular morbidity
Dioxin		Cancers
Heavy metals		Cancers Neurotoxic morbidity

Table 2. Environmental impacts due to chemical pollutants and toxicants.

Pollutant		Environmental Impact
Primary	**Secondary**	
CO_2		Global warming
NO_2, CH_4		Global warming
SO_X, NO_X, NH_3, HC, HF		Atmospheric acidification
NO_2	Ozone	Loss of crops
VOC	Ozone	Loss of crops
SO_2		Loss of crops Effects on buildings

Table 3. Comparative concentrations of substances in wastes from various fuel chains (from Reference 16).

Material	Example concentration (mg/kg)		
	Chromium	**Mercury**	**Nickel**
Coal ash/slag	1–200	Not reported	50–300
PP wash water sludge	< 1–10 000	0.1–3	28–20 000
FGD sludge	3–210	< 1–70	20–240
NPP decommissioning steel	3000	Not reported	2000
MSW ash/slag	200–2300	50	50–180
Oil refinery sludge	10–5080	2.1–4	40–2000
Limits*	70	5	1000

*Limiting concentrations for near surface disposal of wastes as calculated in Reference 17.

Notes: PP = power plant; NPP = nuclear power plant; FGD = flue gas desulphurisation; MSW = municipal solid waste.

Figure 1. Direct radioactive emissions from the nuclear fuel cycle, and direct/indirect radioactive emissions from the coal fuel cycle (for some radionuclides) (Reference 12).

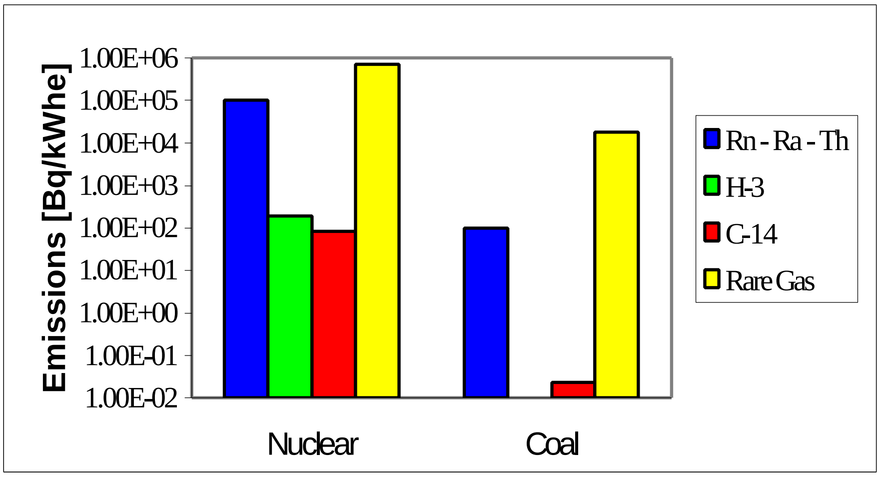

Figure 2. Emissions of chemical pollutants from different fuel cycles (Reference 12).

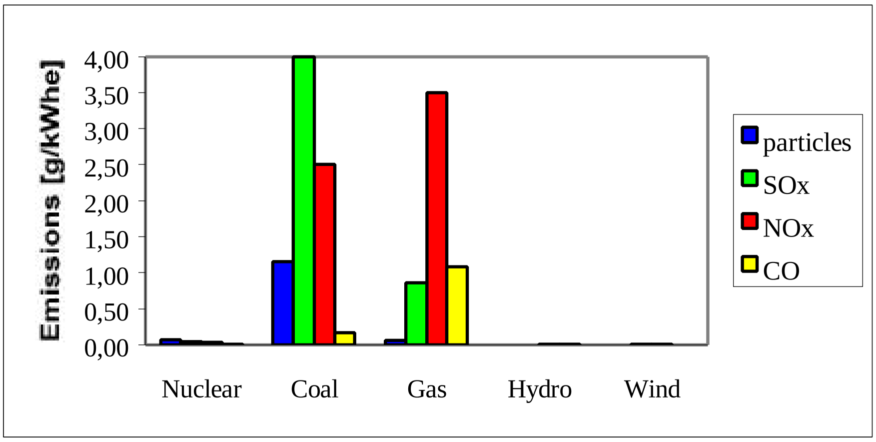

Figure 3. Emissions of carbon dioxide from different fuel cycles (Reference 12).

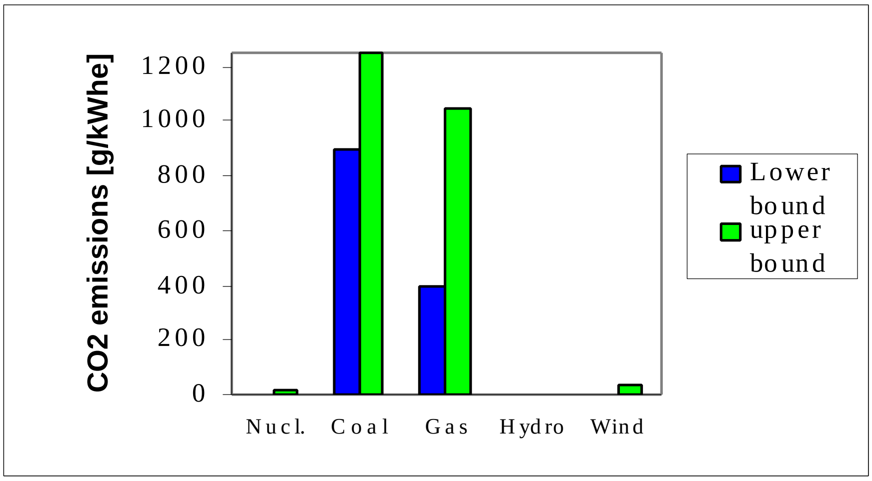

Figure 4. Occupational health impact of the different fuel cycles.

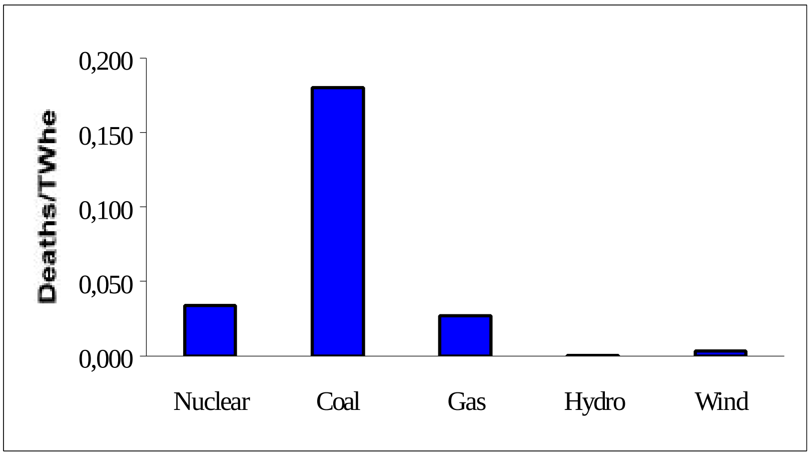

Figure 5. Public health impact of the different fuel cycles.

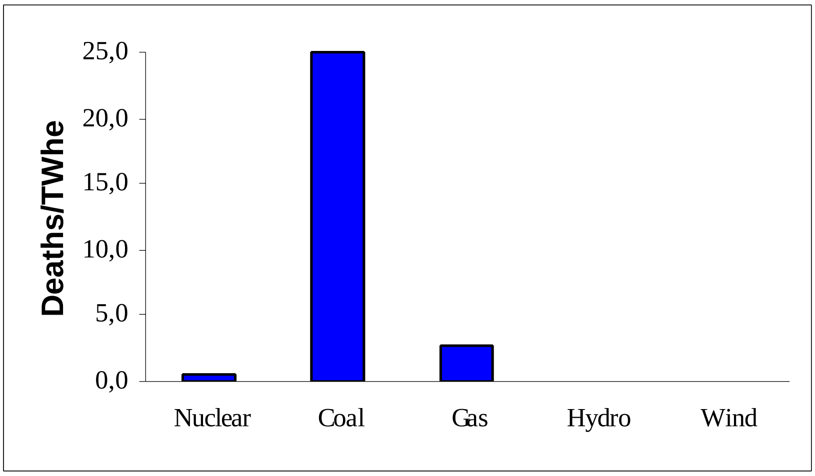

Figure 6. External costs of different fuel cycles compared.

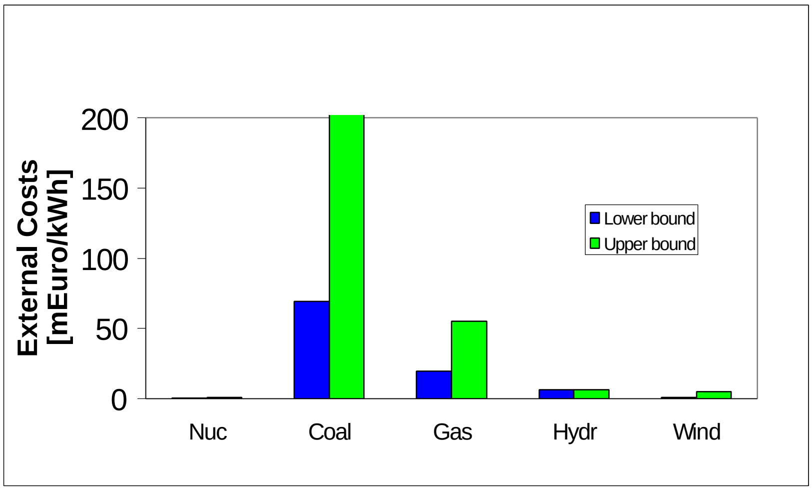

Figure 7. Generation costs of different fuel cycles compared.

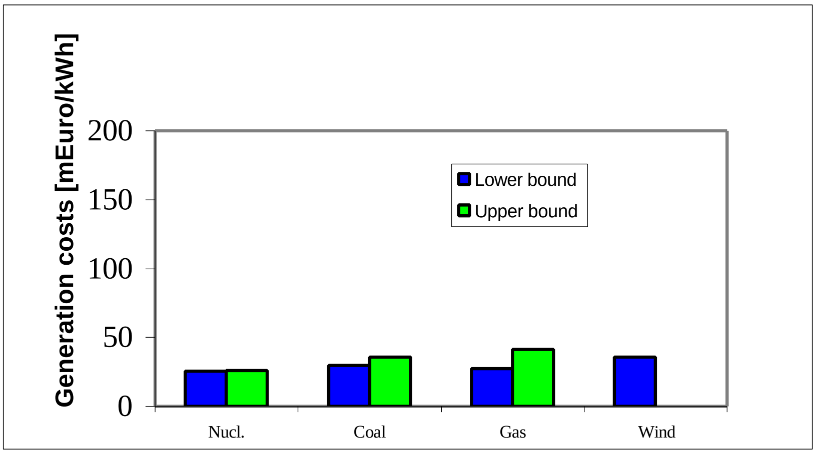

Figure 8. External cost structures of the various fuel cycles.