# LCA and External Costs in Comparative Assessment of Electricity Chains.
# Decision Support for Sustainable Electricity Provision?

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## Introduction

The provision of energy and electricity plays an important role in a country's economic and environmental performance and the sustainability of its development. Sustainable development of the energy and electricity sector depends on finding ways of meeting energy service demands of the present generation that are economically viable, environmentally sound, and socially acceptable and do not jeopardize the ability of future generations to meet their own energy needs.

As liberalized electricity markets are becoming widespread, according to neo-classical welfare economics, getting the prices right is a prerequisite for market mechanisms to work effectively towards sustainable development.

Life Cycle Assessment (LCA) and external cost valuation are considered to offer opportunities to assist energy policy in a comprehensive comparative evaluation of electricity supply options with regard to the different dimensions of sustainable energy provision as well as in the implementation of appropriate internalisation strategies.

The paper addresses life cycle assessment and external cost analysis carried out for selected electricity systems of interest under German conditions. Results from a comprehensive comparative assessment of various electricity supply options with regard to their environmental impacts, health risks, raw materials requirements as well as their resulting external cost will be summarized. The use of LCA based indicators for assessing the relative sustainability of electricity systems and the use of total (internal plus external) cost assessment as measure of economic and environmental efficiency of energy systems will be discussed.

Open problems related to life cycle analysis of energy chains and the assessment of environmental damage costs are critically reviewed, to illustrate how in spite of existing uncertainties the state of the art results may provide helpful energy policy decision support. The paper starts with some remarks on what the concept of sustainability in terms of energy systems means.

## The concept of sustainable development: What does it mean for the energy system?

According to the Brundtland Commission, and the Rio Declarations, the concept of 'sustainable development' embraces two intuitively contradictory demands, namely the sparing use of natural resources and further economic development. The Brundtland Commission defines sustainable development as a "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs".

Even if this definition has arisen against a background of environmental and poverty problems, it nevertheless represents an ethically motivated claim which is derived from considerations of fairness with future generations in mind. The challenge is to simultaneously help to deliver economic prosperity, to reduce and eventually eliminate poverty, to provide environmental quality and social equity and to maintain the natural foundations of life.

Therefore, the aim of sustainable development is to bequeath future generations with a stock of natural resources which will enable them to satisfy their needs at least at the level we enjoy today. This general definition of sustainability, which is acceptable to many, is not very specific about how we can guarantee satisfying the needs of future generations, for example with reference to the energy supply. It is both vague and open-ended and therefore leaves room for different interpretations.

Any attempt to define the concept of sustainability in concrete terms can only be sound if – as far as the material-energetic aspects are concerned – it takes the laws of nature into account. In this context the second law of thermodynamics which the chemist and philosopher Wilhelm Ostwald called "The law of happening" [Das Gesetz des Geschehens] acquires particular significance. The fundamental content of the second law of thermodynamics is that life and the inherent need to satisfy requirements is vitally connected with the consumption of workable energy and available material.

Within the context of defining the concept of sustainability in concrete terms the need to limit ecological burdens and climate change can certainly be substantiated. It becomes more difficult when confronted with the question of whether the use of finite energy resources is compatible with the concept of ”sustainable development”, because oil and natural gas and even the nuclear fuels which we consume today are not available for use by future generations. This then permits the conclusion that only the use of ”renewable energy” or ”renewable resources” is compatible with the concept of sustainability.

But this is not sound for two reasons. On the one hand the use of renewable energy, e.g. of solar energy, also always goes hand in hand with a claim on non-renewable resources, e.g. of non-energetic resources and materials which are also in scarce supply. And, on the other hand, it would mean that non-renewable resources may not be used at all – not even by future generations. Given that it is, therefore, obviously impossible to pass on un-changed the non-renewable resource base, the important thing within the meaning of the concept of sustainable development is to bequeath to future generations a resource base which is technically and economically usable and which allows their needs to be satisfied at a level at least commensurate with that which we enjoy today.

However the energy and raw material base available is fundamentally determined by the technology available. Deposits of energy and raw materials which exist in the earth’s crust but which cannot be found or extracted in the absence of the requisite exploration and extraction techniques or which cannot be produced economically cannot make any contribution towards securing the quality of life. It is therefore the state of the technology, which turns valueless resources into available resources and plays a joint part in determining their quantity. As far as the use of limited stocks of energy is concerned this means that their use is compatible with the concept of sustainability as long as it is possible to provide future generations with an equally large energy base which is usable from a technical and economic viewpoint. Here we must note that in the past the proven reserves, i.e. energy quantities available technically and economically, have risen despite the increasing consumption of fossil fuels. Moreover, technical and scientific progress has made new energy bases technically and economically viable, for instance nuclear energy and part of the renewable energy sources.

As far as the environmental dimension of sustainability is concerned, the debate should take greater note of the fact that environmental pollution, including those connected with today’s energy supply, are primarily caused by anthropogenic flows of substances, by substance dispersion i.e. the release of substances into the environment. It is not, therefore, the use of the working potential of energy which pollutes the environment but the release of substances connected with the respective energy system, for instance the sulphur dioxide or carbon dioxide released after the combustion of coal, oil and gas. This becomes clear in the case of solar energy which, with the working potential – solar radiation – it makes available is, on the one hand, the principle source of all life on earth but is also, on the other hand, by far the greatest generator of entropy, because almost all of the sun's energy is radiated back into space after it has been devalued as heat at the ambient temperature. Since its energy, the radiation, is not tied to a material energy carrier, the generation of entropy does not produce any pollution in today's sense of the word. This does not, of course, exclude the release of substances and associated environmental pollution in connection with the manufacture of the solar energy plant and its equipment.

The facts addressed here are of such particular significance because this entails the possibility of uncoupling the consumption of energy and the pollution of the environment. The increasing use of working potential (energy) and a reduction in the burdens on the climate and the environment are not, therefore, a contradiction in terms. It is the emission of substances that have to be limited, not the energy flows themselves, if we want to protect the environment.

In addition to expanding the resource base available, the economical use of energy or rather of all scarce resources is, of course, of particular significance in connection with the concept of ”sustainable development”. The efficient use of resources in connection with the supply of energy does not only affect energy as a resource since the provision of energy services also requires the use of other scarce resources including, for instance, non-energetic raw materials, capital, work and the environment. The efficient use of all resources as can be derived from the concept of sustainability also corresponds to the general economic principle, however. Both allow for the conclusion that an energy system or an energy conversion chain for the provision of energy services is more efficient than another if fewer resources, including the resource environment, are utilised for the energy service.

In the economy costs and prices serve as the yardstick for measuring the use on scarce resources. Lower costs with the same use mean an economically more efficient solution which is more considerate on resources. The argument that can be raised against using costs as a criterion for evaluating energy systems is that the external effects of environmental damage for instance are not currently incorporated in the cost-calculations. This circumstance can be remedied by an internalisation of external costs. Without addressing the problems associated with external cost valuation here, the concept of total social costs that is combining the private costs with the external ones could serve as a suitable yardstick for measuring the utilisation of scarce resources. Total social costs could therefore serve as an integrated indicator of the relative sustainability of the various energy and electricity supply options and it would be appropriate if, in this function, they were again to be afforded greater significance in the energy policy debate. Furthermore, cost efficiency is also the basis for a competitive energy supply in order to secure the energy side of economic development and adequate employment and it is also the key to avoiding intolerable climate change. Both of these issues are central aspects of the concept of ”sustainable development”.

Following this clarification of the concept of sustainable development with regard to the supply of energy we will now like to examine various electricity production options as regards their contribution towards a sustainable development of energy supply. The assessment will be based on a set of sustainable development indicators, including emissions to the environment, the requirement of both energetic and non-energetic non-renewable resources, health impacts and economic performance.

## LCA results – a first comparison of energy systems with a view to sustainability

The approach of Life Cycle Assessment (LCA) provides a conceptual framework for a detailed and comprehensive comparative evaluation of electricity supply options with regard to their resource, health and environmental impacts as important sustainability indicators. Full scope LCA considers not only the direct emissions from power plant construction, operation and decommissioning, but also the environmental burdens and resource requirements associated with the entire lifetime of all relevant upstream and downstream processes within the energy chain. This includes exploration, extraction, fuel processing, transportation, waste treatment and storage. In addition, indirect emissions originating from material manufacturing, the provision and use of infrastructure and from energy inputs to all up- and downstream processes are covered. As modern technologies increasingly tend to reduce the direct environmental burdens of the energy conversion process, the detailed assessment of all life cycle stages of the fuel chain is a prerequisite for a consistent comparison of technologies with regard to sustainability criteria.

The LCA was carried out for a set of important electricity generation’s option, which is considered as representative for near-future technologies to be operated in Germany. Table 1 summarises some central technological parameters for the selected reference technologies.

The following figures and tables will summarise results for some of the key impact categories. Although based on our present level of knowledge this is not a complete and comprehensive comparison of all the indicators that are important from the point of view of sustainability, but it does provide an initial indication of the potential contribution of specific electricity supply options to a future sustainable energy system.

**Table 1: Characterisation of the reference electricity production technologies**

| | Technology | Power installed | Efficiency | Life |
|---|---|---|---|---|
| **Coal** | Pulverised Fuel Firing | 600 MW | 43.0 % | 35 a |
| **Lignite** | Pulverised Fuel Firing | 800 MW | 40.1 % | 35 a |
| **Gas Combined-cycle** | Combined-cycle | 777.5 MW | 57.6 % | 35 a |
| **Nuclear (PWR)** | actual PWR | 1375 MW | 34.0 % | 40 a |
| **PV (poly)**<br>**PV (amorphous)** | poly-crystalline<br>amorphous | 5 kW<br>5 kW | 9.5 % 1)<br>4.5 % 1) | 25 a<br>25 a |
| **Wind** | 5.5 m/s 2) | 1.5 MW | - | 20 a |
| **Hydro** | Run-of-River | 3.1 MW | 90 % 3) | 60 a |

1) System-efficiency
2) Average windspeed p.a.
3) Efficiency of turbines

### *Cumulative energy requirements*

The generation of electricity is associated with partly quite intensive energy consumption by power plant construction, and – in the case of fossil and nuclear energy sources – also by fuel supply and waste treatment. The cumulative energy requirement as shown in Table 2 for different power generation systems includes the primary energy demand for the construction and decommissioning of the power plant as well as for the production and supply of the respective fuel. The energy content of the fuel input is not included in the figures.

**Table 2: Cumulative energy requirements (CER) and energy payback periods (EPP)**

| | **CER** (without fuel) **[$kWh_{Prim}$ / $kWh_{el.}$]** | **EPP** **[months]** |
|---|---|---|
| **Coal** (43 %) | 0.3 | 3.6 |
| **Lignite** (40 %) | 0.17 | 2.7 |
| **Gas CC** (57.6 %) | 0.17 | 0.8 |
| **Nuclear** (PWR) | 0.07 | 2.9 |
| **PV** (poly)<br>**PV** (amorph) | 1.24<br>0.67 | 141<br>76 |
| **Wind** (5.5 m/s) | 0.07 | 6.4 |
| **Hydro** (3.1 MW) | 0.04 | 10.9 |

The indirect primary energy input per produced kWh of electricity for hydro, wind and nuclear systems is in the range of 0.04 to 0.07 kWh. For natural gas and coal the necessary energy input per produced unit of electricity is in the range of 0.17 to 0.30 kWh which is basically determined by the energy required for the extraction, transport and processing of the fuel. The corresponding figures for today's photovoltaic systems are 0.67 to 1.24 kWh. This is also reflected in the energy amortisation time which is approximately 6 to 12 years in the case of photovoltaic systems using today's technology and is by far the longest compared to any of the other systems.

### *Raw material requirements*

Electricity production involves consumption of non-energetic raw materials such as iron, copper or bauxite. Sustainability also means the efficient use of such resources. Table 3 shows the cumulated resource requirements of the power generation systems considered here for selected materials. It covers the raw material requirements for power plant construction, fuel supply, and for the supply of other raw materials. The table only includes a small part of the various raw materials required and is therefore not a complete material balance. However, results indicate that the relatively small energy density of solar radiation and of the wind leads to a comparatively high material demand. This high material intensity for wind and solar energy is an important aspect with regard to the generation costs.

**Table 3: Total life cycle raw material requirements**

| | **Iron** [kg / GWh$_{el.}$] | **Copper** [kg / GWh$_{el.}$] | **Bauxite** [kg / GWh$_{el.}$] |
|---|---|---|---|
| **Coal** (43 %) | 2310 | 2 | 20 |
| **Lignite** (40 %) | 2100 | 8 | 19 |
| **Gas CC** (57.6 %) | 1207 | 3 | 28 |
| **Nuclear** (PWR) | 420 - 445 | 6 | 27 |
| **PV** (poly) / **PV** (amorph) | 5350 – 7300 | 240 - 330 | 2040 - 2750 |
| **Wind** (5.5 m/s) | 3700 | 50 | 32 |
| **Hydro** (3.1 MW) | 2400 | 5 | 4 |

### *Pollutant Emissions*

Figure 1 compares the cumulative emissions of selected pollutants of the power generation systems considered. It is obvious that electricity generated from solid fossil fuels (hard coal and lignite) is characterised by the highest emissions of $SO_2$, $CO_2$ and $NO_x$ per unit of electricity, while emissions from the nuclear system, hydropower and wind are comparatively low. Electricity generation from natural gas causes emissions that are significantly lower than those from coal-fired systems. Although there are no direct emissions from the electricity generation stage, the high material requirements for the production of PV panels result in cumulative $CO_2$ and $NO_x$ emissions of the photovoltaic fuel chain that are close to those of the gas fuel chain and far higher as $SO_2$ and particulates are concerned.

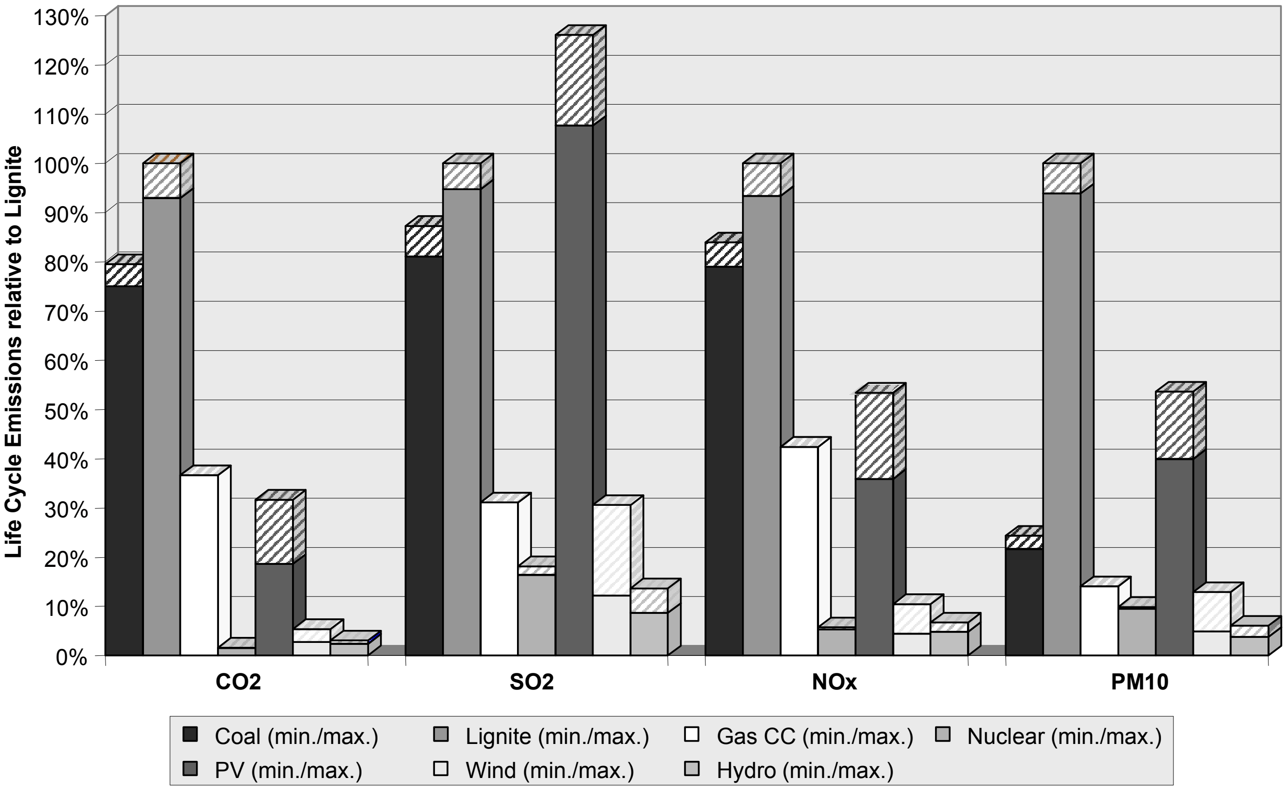


**Figure 1: Total life cycle emissions**

It might be mentioned that the indirect emissions from material supply and component manufacturing are determined to a great extent by the emissions of the respective energy mix. Due to the high proportion of fossil energy in the German electricity mix, results shown in Figure 1 are not directly applicable to other countries with a different energy mix.

### *Human health risks*

Electricity generation from fossil fuels, nuclear energy or renewable energy sources leads to an increased level of air pollution, or to an increased exposure of the population to ionising radiation, which in turn might cause an increased risk to the health of the exposed population. Using the emissions from the life cycle assessment as a starting point, health risks resulting from the operation of the energy systems considered here are assessed following a detailed impact pathway approach. For the quantification of health effects from pollutants relevant for fossil energy systems (fine particles, $SO_2$, Ozone) dose-effect models have been derived from recent epidemiological literature. The risk factors recommended by the International Commission on Radiological Protection (ICRP) are used to estimate effects from ionising radiation. The application of the ICRP risk factors to the very small individual dose resulting from long term and global exposure is, however, a matter of particular uncertainty and might lead to an overestimation of effects. Results of the risk assessment are summarised in the next figure. The increased death risk is presented as the loss of life expectancy in Years of Life Lost (YOLL) per TWh.

Figure 2 shows that electricity generation from coal and lignite lead to the highest health risks of the power generation systems considered, while power generation from nuclear systems, wind and hydro energy is characterised by the lowest risk. Due to the high emissions from the material supply, risks from photovoltaic systems are higher than the risks from natural gas-fired power plant. Results for the nuclear fuel chain include the expected value of risk from beyond design nuclear accidents, which is small compared to the importance of major nuclear accidents in the public discussion. However, the expected value of risk is not necessarily the only parameter determining the acceptability of a technology. Different evaluation schemes that take into account risk aversion or a maximum tolerable impact might lead to a different ranking of technologies.

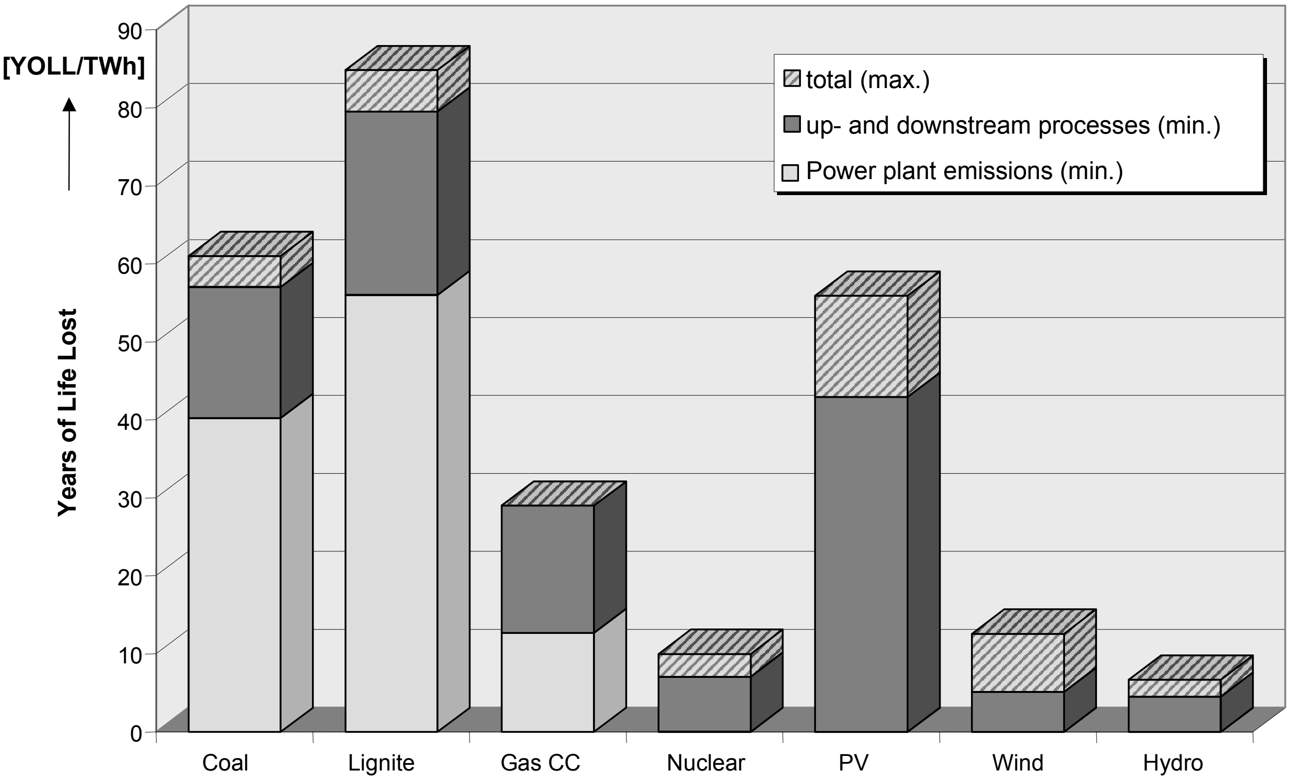


Figure 2: Health risks of energy systems

## *External costs*

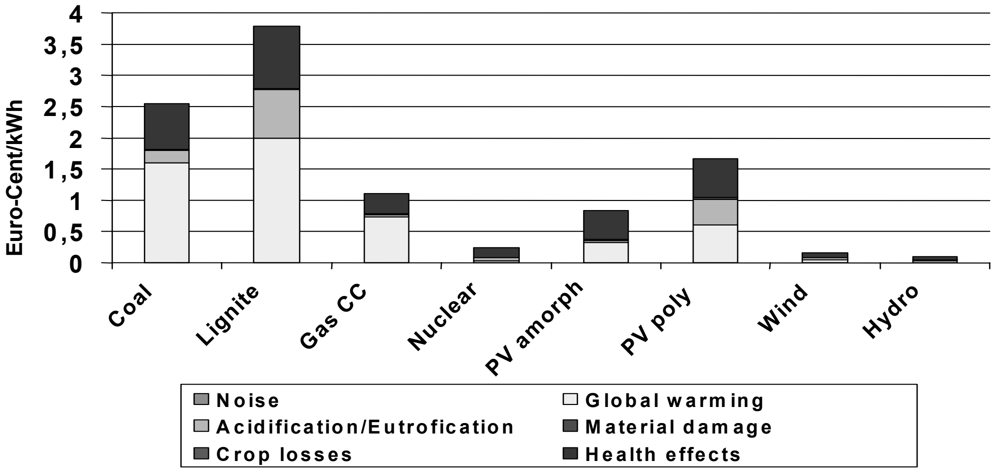
It is well accepted now that health impacts and environmental damage due to air pollution cause economic losses which are not accounted for in the electricity price (so called external costs). According to neo-classical welfare economics, external costs have to be internalised, i.e. added to the price of electricity, to achieve a full picture of the consumption of scarce resources.

External costs resulting from impacts on human health, agricultural crops and building materials are considered as quantifiable with a reasonable level of uncertainty, but impacts on ecosystems and in particular potential impacts from global climate change are hardly quantifiable based on current knowledge, so that an economic valuation of the potential impacts is very uncertain. In these cases, marginal abatement costs for achieving policy-based environmental targets (German $CO_2$-reduction targets in the case of global warming, and $SO_2$- and $NO_x$-targets derived from the European Commission's strategy to combat acidification for ecosystem protection) can be used to give a rough indication of the potential damage costs. Using the detailed Life Cycle Inventories as guiding input the marginal external cost estimates are based on applications of the "impact pathway approach", established in the EU ExternE Project. The "impact pathway approach" models the causal relationships from the release of pollutants through their interactions with the environment to a physical measure of impact determined through damage functions and, where possible, a monetary valuation of the resulting welfare losses. Based on the concept of welfare economies, monetary valuation follows the approach of "willingness-to-pay" for improved environmental quality. The valuation of increased mortality risks from air pollution is based on the concept of 'Value of Life Year Lost'.

External costs calculated for the reference technologies are summarized in Figure 3. For the fossil electricity systems, human health effects, acidification of ecosystems, and the potential global warming impacts are the major source of external costs. Although, the power plants analysed are equipped with efficient abatement technologies, the emission of $SO_2$ and $NO_x$ due to the subsequent formation of sulphate and nitrate aerosols leads to considerable health effects due to increased "chronic" mortality. A comparison between the fossil systems shows that health and environmental impacts from the natural gas combined cycle plant are much lower than from the coal and the lignite plant.

External costs arising from the nuclear fuel chain are significantly lower than those estimated for the fossil fuels. Most of the radiological impacts are calculated by integrating very small individual doses over 10 000 years. The application of the ICRP risk factors in this context is at least questionable, and most likely leads to an overestimation of effects. The impact resulting from emissions of 'conventional' (i.e. $SO_2$. $NO_x$, and particles) air pollutants from the nuclear fuel chain dominate the external costs. The external costs calculated from the expected value of risk from beyond design nuclear accidents are surprisingly small compared to the importance of major nuclear accidents in the public discussion.

External cost of photovoltaic, wind and hydropower mainly result from the use of fossil fuels for material supply and during the construction phase. External costs from current PV application in Germany are higher than those from the nuclear fuel chain and close to those from the gas fired power plant. Impacts from the full wind and hydropower life cycle are lower than those from all other systems, thus leading to the lowest external costs of all the reference technologies considered. While the uncertainties in the quantification of external costs are still relatively large, the ranking of the considered electricity options is quite robust.



Acidification/Eutrofication: Valuation based on marginal abatement costs required to achieve the EU "50%- Gap Closure" target to reduce acidification in Europe
Global warming: Valuation based on marginal $CO_2$-abatement costs required to reduce $CO_2$-emissions in Germany by 25% in 2010 (19 Euro/t$CO_2$) 16.1.2001

**Figure 3: External costs from different electricity generation technologies operated in Germany**

### *Power generation costs*

Costs in general might be considered as a helpful indicator for measuring the use of sparse resources. It is thus not surprising that a high raw material and energy intensity is reflected in high costs. The power generation costs shown in the next figure indicate that power generation from renewable energies is associated with higher costs – much higher in the case of solar energy – than those resulting from fossil-fired or nuclear power plants. However, as discussed above, the private costs alone do not fully reflect the use of scarce resources. To account for environmental externalities, external costs have to be internalised, i.e. added to the private generation costs. Figure 4 shows that the external costs resulting from the electricity generation of fossil fuels amount from 30 % (natural gas) to about 100 % (lignite) of the generation costs, while for the other technologies the external costs are only a small proportion of generation costs. The internalisation of external costs might lead to competitiveness of some wind and hydropower sites compared to fossil fuels, but do not affect the cost ratios between the renewable and the nuclear systems. On the other hand it is obvious, that the full internalisation of environmental externalities would improve the competitive advantage of nuclear energy to fossil electricity production.

The results of energy and raw material requirements, life cycle emissions, risks and both external and generation costs discussed so far are based on the characteristics of current technologies. It is expected that technical development will result in a further reduction in costs and in the environmental burdens of power generation. However, this applies to all the power generation technologies considered here. Preliminary results for future systems indicate that the ranking of technologies with respect to total costs is quite robust.

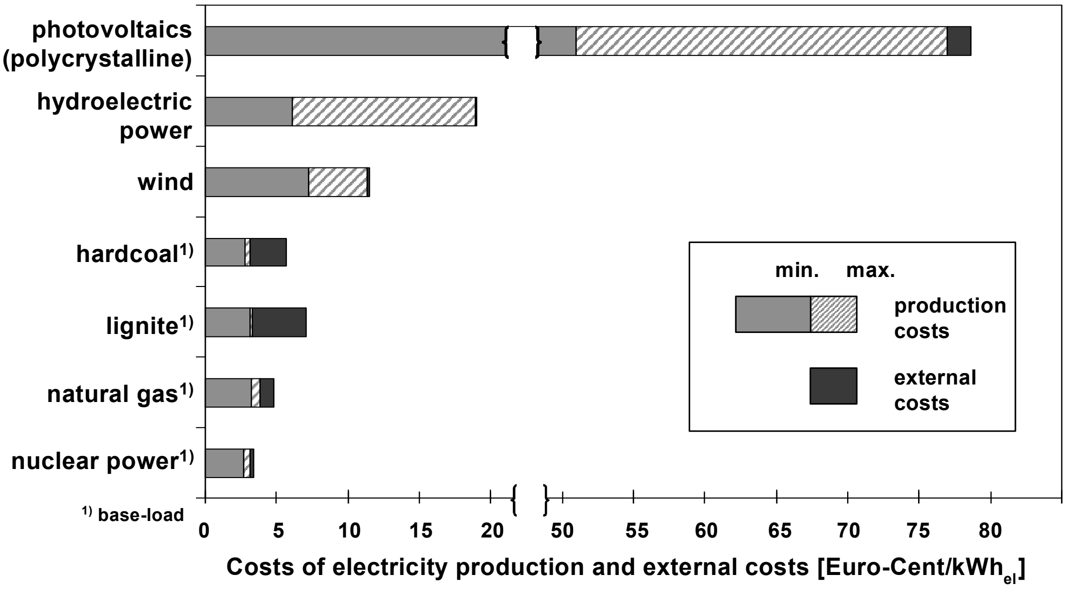


**Figure 4:** **Total costs of various electricity generation technologies operated in Germany**

## Uncertainties and open problems

In spite of considerable progress that has been made over the last years, especially with regard to the bottom up modelling of the full impact pathways and the monetary valuation of health effects, the life cycle inventory based quantification and valuation of environmental impacts is still linked to partly large uncertainties. Uncertainties related to impact assessment and valuation are certainly larger compared to those of the LCA inventory. Besides the data and model uncertainties the estimation of external cost is faced with systematic uncertainties arising from lack of knowledge, and value choices that influence the results.

Lack of knowledge is the single most important reason for the large uncertainties related to the quantification of climate change damage costs. This suggests to use abatement costs based on the standard-price approach to achieve a specific greenhouse gas reduction target as the second-best solution to make this impact visible in the external cost estimates. Large uncertainties are in the exposure-response functions for health impacts and the 'Value of Life Year Lost'. As in the past improved knowledge, e.g. of the influence of particle composition on the chronic mortality from fine particles could lead to different health related damage costs. But an assessment can always only reflect the current knowledge.
The estimates of external costs are influenced also by the discount rate chosen, to account for damage costs in the future as well as by valuation of damages in different parts of the world. The uncertainties stemming from these assumptions can be best dealt with by sensitivity analysis.

The application of the impact pathway approach and the monetary valuation methods suggest relatively low external costs for both beyond design accidents in a nuclear power plant and radioactive waste deposit. The impact from a single beyond design accident can be very large, but normalised to the electricity generation over the power plants lifetime, the expected value of risk (i.e. probability times consequences) is low, a fact which is even robust against uncertainties in the accident probability.

Some people argue that the use of the expected value of risk to estimate the external cost of a low probability events with large consequences is an open problem. They consider the maximum damage from a single incident as an important key criterion on its own, which has to be included in the impact valuation of technologies. Empirical evidence supporting this kind of reasoning is still missing.

With respect to the uncertainties of external cost estimates it is important to notice, that these uncertainties are of relevance to any other valuation scheme. It is however remarkable, that in spite of these uncertainties and changing background assumptions, external cost estimates at least indicate a robust relative ranking for the key electricity production technologies. However, care has to be taken to acknowledge existing uncertainties and to not take external cost estimates out of the given context when using them in a policy context.

## LCA and external costs for policy support

Life Cycle Assessment and the external as well as the total cost approach can provide valuable decision support for a wide range of policy relevant issues:

- Assessment of technologies currently used to identify deficiencies and potentials for improvement and corresponding research issues.
- Comparison of current and future energy supply options with respect to their health and environmental impacts, resource requirements and with respect to their compliance with sustainability indicators.
- Cost-benefit-analysis of environmental policy measures.
- Extension of national green-accounting frameworks.

There are several examples of successful applications in these areas, for instance the use of the method for cost-benefit analysis of desulphurisation plants attached to large coal fired power plants in Europe. The comparison of the costs in € per tonne of $SO_2$ avoided and the avoided damage costs due to the reduced emissions shows that the benefit clearly outweighs the costs. This even remains valid, if the mortality impacts – the impact category considered to involve the highest uncertainty – would be neglected. So, even if the damage cost estimates are varied within the uncertainty range, the conclusion would not change.

In the context of the liberalisation of the European electricity market the concept of internalising external effects by means of technology-specific price adders has been discussed. The idea is to derive science based recommendations on the height of price adders for electricity production by different technologies from LCA and external cost research. This approach is expected to get the prices right in competitive markets and to ensure that the use of the environment is accounted for in the market mechanism.

But the use of simple price adders for each technology appears inappropriate, besides the still existing large uncertainties of the external cost estimates. This is due to the fact that health and environmental impacts depend heavily on the concrete technical design and the location of a specific power plant. For this reason the use of regionally differentiated pollutant-specific damage costs is recommended for the internalisation of external costs due to airborne pollutants.

These damage costs should at least be differentiated by country. Table 4 presents damage costs per tonne of pollutant emitted in Germany.

**Table 4: Specific damage costs in € per tonne of pollutant emitted in Germany (reference year 1998)**

| | € per tonne emitted |
|---|---|
| $SO_2$ | 5650 |
| $NO_x$ | 5030 |
| $PM_{10}$ | 8700 |
| NMVOC | 1770 |

The advantage of such a pollutant-oriented approach is that it gives a direct incentive for reducing the emissions. This is expected to outweigh the disadvantage of a higher effort for recording the emissions of every pollutant.

In the case of $CO_2$ and other greenhouse gases, due to the high uncertainties involved in estimating damage costs, it is recommended to base internalisation instruments (such as emission certificates or a greenhouse gas tax) on greenhouse gas reduction targets and the associated marginal abatement cost.

The risks of low probability accidents should be integrated into the monetary accounting system by introducing liability insurance obligations.

It can be concluded that LCA and quantification of environmental costs give valuable input to the assessment of the relative sustainability of different electricity production technologies in spite of the current knowledge gaps. These methods thus can contribute to a rational decision support. LCA inventories provide very useful information concerning the evaluation of resource requirements of different electricity production options. External cost estimates represent an aggregated indicator of environmental performance. Together with the private costs, total costs can serve as an integrated indicator for the overall resource consumption and in this respect for relative sustainability of the different energy options.

As far as applicable, the approach of monetary valuation can be considered to be the most appropriate way of weighting and aggregating different impact categories when assessing the environmental impact or the resource intensity of energy systems. Monetary values based on individual and social preferences for a wide range of health and environmental impacts have been derived from empirical work. The use of such values for aggregation has advantages compared to weighting schemes derived from expert or personal judgement, as the weighting is based on “measured” preferences. And last, but not least, monetary values have the advantage of being more illustrative than “utility points” or other artificial measures, although the results might be the same.

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