Sustainable Development in Energy: Comparative Assessment of Energy Options

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1. The Challenges

If the trends of the world's past history continue in the future, the prospects for the development of mankind include inconceivable catastrophes triggered off by hunger and poverty, by the destruction of the natural foundations of life or by man-made destabilisation of the earth's climate.

These challenges are all directly related to the energy supply system

- - since providing an increasing amount of energy services is a necessary pre-condition for eradicating hunger and poverty and even limiting the global population increase,
- since about three-quarters of anthropogenic emissions of CO_2 are released by the energy system;
- since today's energy system consumes the major share of finite fossil resources and is the single most important source of air pollution.
- since securing the economic productivity of developed countries will not be possible without a functioning energy infrastructure and competitive energy prices.

This is while energy issues featured prominently in the discussions of all earth summits from the United Nations conference on Environment and Development in Rio de Janeiro in 1992 to the World Summit on Sustainable Development in Johannesburg in 2002.

As far as these energy related challenges are concerned there is widespread agreement in society. But the degree of consensus dwindles with respect to the targets and models to be achieved and controversial, sometimes even contradictory opinions exist amongst important groups in society – at least in the industrialised countries – on the course to be taken. A lack of consensus prevails not so much on the end but on the means. Resolving the 'trilemma' among the economic aspirations of a rapidly expanding global population, the available resources, and the environment, is one of the most critical challenges of the twenty-first century.

The access to energy is of central importance to human welfare, economic and social development including poverty alleviation. Although global primary energy use grew in the past by about 2 per cent a year, on a per capita basis, however, the increase in total primary energy use has not resulted in any notable way in more equitable access to energy services between industrialized and developing countries. Slightly more than one million people in the industrialized countries (about 20 % of world's population) consume nearly 60 % of the total energy supply whereas the five billion people in developing countries consume the other 40 % of total energy supply. Affordable commercial energy is still beyond the reach of one-third of humanity.

Although the energy intensity of modern economies is decreasing, clearly more energy will be needed to fuel global economic development and to deliver opportunities to the billions and still increasing number of people in developing countries who do not have access to adequate energy services.

The rate of global commercial energy consumption is thousand of times smaller than the energy flows from the sun to the earth. Primary energy use is reliant on fossil fuels (oil, natural gas and coal), which represent nearly 80 percent of the total consumption. Nuclear power contributes about 7 percent, and hydro power and new renewable each contribute about 2 percent. Traditional, non commercial sources of energy, like firewood, are the dominant source in low-income developing countries, they account for about 10 percent of the total fuel mix.

Environmental impacts of energy use are not new. For centuries, wood burning has contributed to the deforestation of many areas. Just in the course of the past 100 years, during which world's populations more than tripled and the use of fossil fuels increased more than 20-fold, human environmental impact grew from local pertubations to global impacts. At every level (local, regional, global), the environmental consequences of current patterns of energy use make up a significant fraction of human impacts on the environment. Energy provision involves large volumes of material flows, and large-scale infrastructure to extract, process, store, transport and use it, and to handle the waste. Particulate matter, which is both emittend directly and formed in the air as a result of the emissions of gaseous precursors in the form of oxides of sulphur and nitrogen, and hydrocarbons impact human health, just as ozone, which is formed in the troposphere from interactions among hydrocarbons, nitrogen oxides, and the sunlight. Precursors of acid deposition can be transported over hundreds of kilometers and the resulting acidification is causing significant damage to natural systems, crops and human made structures and can effect ecosystems. Large hydropower projects often raise environmental issues related to flooding, whereas in the case of nuclear power, issues such as waste disposal raise concern. On the global scale, the possibility of significant climate change, largely caused by greenhouse gas emissions from fossil fuel burning presents a great challenges to the future of human civilisation. There is growing evidence that much of world's energy is currently produced and consumed in ways that could not be sustained if technology were to remain constant and if overall quantities were to increase substantially.

Among other aspects, in particular the risks and uncertainties of the global warming problem have led to a resurgence of interest in sustainable development. Since the United Nations Conference on Environment and Development in Rio de

Janeiro in 1992 the concept of sustainable development as a model of environmentally compatible and socially acceptable development of human activities has gained widespread attention. Despite this growing interest, sustainable development is often broadly defined, so that the concept is used by different people to mean very different things. The energy debate being a prominent example.

To prevent the concept of sustainability from becoming a mere buss-word, there is a need to define what the concept of sustainable development means for the energy system in concrete terms and how it can provide guidance on the comparative assessment of energy supply options with regard to a sustainable provision of energy.

2. 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.

In a broad sense, sustainable development incorporates equity within and across countries as well as across generations, and integrates economic development, the conservation of the environment and the natural foundation of life as well as social welfare. A key challenge of sustainable development policies is to address those three dimensions in a balanced way, taking into account their interactions and making trade-offs whenever needed. Energy has direct links with the three dimensions of sustainable development. But this broadly accepted understanding of sustainability is not very specify about how to assess sustainability, for exemple with reference to the energy provision.

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.

Thermodynamically speaking, life necessarily produces entropy by degrading workable energy and available material and requires a permanent imput of these constituencies. But available energy and material only constitute a necessary but not sufficient condition for life supporting states of order. In addition to this, information and knowledge is required to create states of order serving life. Knowledge and information, which may be defined as “creative capacity” constitute a special resource. Although it is always limited, it is never consumed and can even be increased. Knowledge grows. Increasing “Creative capacity” resulting in further technological development is of partially significance to sustainability because it allows for a more efficient use of natural resources and an expanding of the available resource base for the generations to come.

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 due to the second law of thermodynamics the use of non-renewable resources is inevitable, 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 to 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 workable 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 uses 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 for the provision of the same energy service mean an economically more efficient solution which is also more considerate on resources. The argument that can be raised against using costs as a single aggregated indicator of sustainability with respect to resource usage performance is, that the external effects of environmental damage for instance are not currently incorporated in the cost figures. 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 provision of energy services an attempt is made to demonstrate, how energy supply options can be compared with regards to their relative sustainability. 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 total social costs as an integrated sustainability criterion.

3. Sustainability of energy option: A comparative assessment

The approach of Life Cycle Assessment (LCA) provides a conceptual framework for a detailed and comprehensive comparative evaluation of energy 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 today’s technologies to be operated in Germany. The following figures and tables will summarise results for some of the key impact categories. They should serve as an illustrative example how to assess energy-related technologies with regard to sustainability

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 1: Cumulative energy requirements (CER) and energy payback periods (EPP)

	CER (without fuel) **[kWh_{Prim} / kWh_{el}]**	**EPP** **[months]**
Coal	0,28 - 0,30	3,2 - 3,6
Lignite	0,16 - 0,17	2,7 - 3,3
Gas CC	0,17	0,8
Nuclear	0,07 - 0,08	2,9 - 3,4
PV	0,62 - 1,24	71 - 141
Wind	0,05 - 0,15	4,6 - 13,7
Hydro	0,03 - 0,05	8,2 - 13,7

The indirect primary energy input per produced kWh of electricity for hydro, wind and nuclear systems is in the range of 0,03 to 0,15 kWh. For natural gas and coal the necessary energy input per produced unit of electricity is in the range of 0,16 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 0,62 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 2 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 2: Total life cycle raw material requirements

	Iron [kg / GWh$_{el}$]	Copper [kg / GWh$_{el}$]	Bauxite [kg / GWh$_{el}$]
Coal	1.750 - 2.310	2	16 - 20
Lignite	2.100 - 2.170	7 - 8	18 - 19
Gas CC	1.207	3	28
Nuclear	420 - 490	6 - 7	27 - 30
PV	3.690 - 24.250	210 - 510	240 - 4.620
Wind	3.700 - 11.140	47 - 140	32 - 95
Hydro	1.560 - 2.680	5 - 14	4 - 11

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.

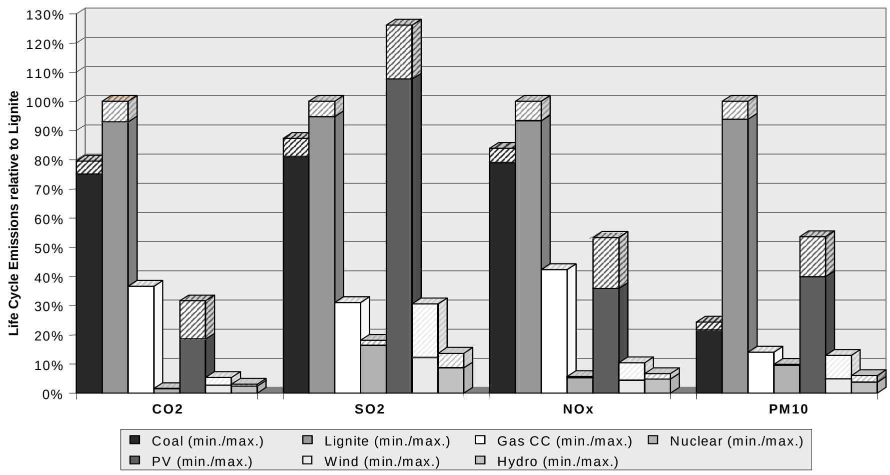


Figure 1: Total life cycle emissions

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.

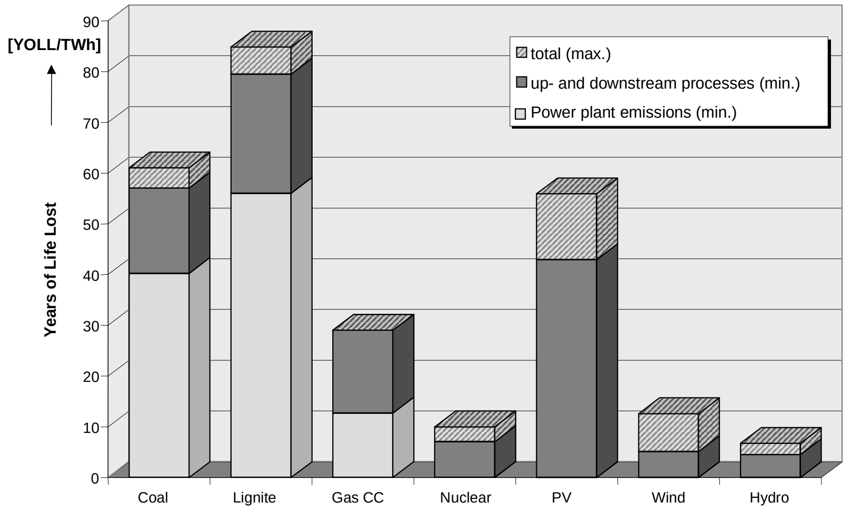


Figure 2: Health risks of energy systems

External costs

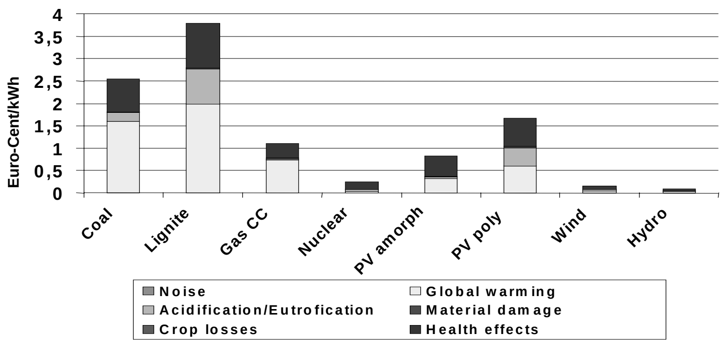
It is well accepted now that health impacts and environmental damage due to air pollution cause economic losses which are not accounted for in the electricity price (so called external costs). According to neo-classical welfare economics, external costs have to be internalised, i.e. added to the price 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/tCO_2)

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

Total cost of power generation

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 and has to be taken into account when accessing energy futures compatibly with sustainable development goals.

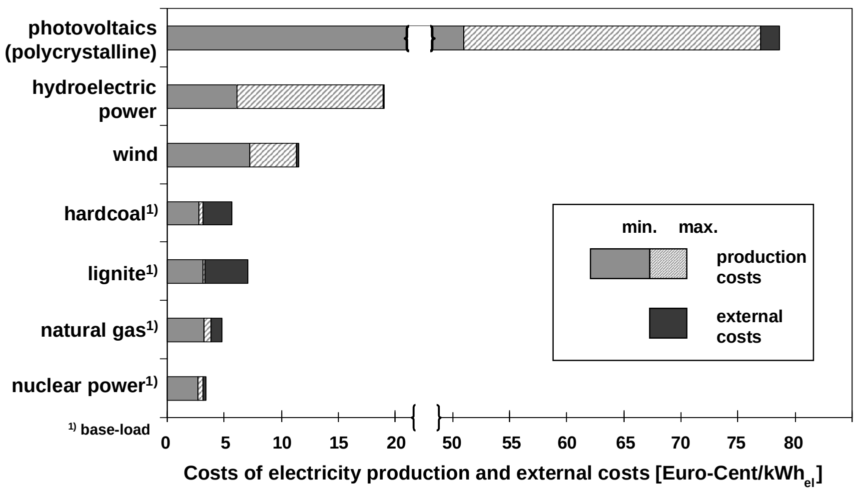


Figure 4: Total costs of various electricity generation technologies operated in Germany

In spite of considerable progress that has been made over the last years in live cycle assessment and external cost valuation, these are still some unresolved issues and partly large uncertainties. Lack of knowledge is the single most important reason for the large uncertainties related to the quantification of climate change damage costs and for the health-impacts of some pollutant. The question of discounting damage costs in the future and the appropriate discount rate as well as the question of riskaversion are issues of debate. There is clearly a need for further refinement and the incorporation of new scientific knowledge from epidemiological studies, global climate research and ecosystem analysis. There is also a need to take into account to continuous improvements of energy technologies as well as emerging new technologies, especially when using the analysis for a better informed policy making toward sustainability. Not-withstanding these caveats - and the consequent need for future work – the LCA method together with the total cost approach as an indicator for the overall resource consumption, does provide clear value-added in the decision-making process with respect to a sustainable energy future.

4. Are sustainable energy futures possible?

Energy is central to achieving the interrelated economic, social and environmental aims of sustainable human development. But if we are to realize this important goal the development of consensus what sustainable development means in concrete terms and how to make the concept of sustainable energy provision operational is a prerequisite. We have outlined a concept of sustainable energy development with the central goal to maintain or increase the overall accessible assets (natural and man-made) available to future generations and how to assess the relative sustainability of the various energy options.

Technical progress made possible by increasing knowledge will play a key role in achieving sustainable development. Research and development are the only systematic way to contribute to both the understanding of the earth system and the technological innovations that will be needed to meet sustainable development goals. It can extend the accessible resource base and create new categories of resources as well as increase the resource efficiency and productivity and reduce environmental impacts, thereby resulting in reduced total cost of energy service provision. Fossil, nuclear and renewable resources have considerable potential, but realising this potential will require encouraging technological innovation through intensified research and development, removing obstacles to wider diffusion and developing marked signals to reflect environmental costs. Than the future might be much more a matter of choice than destiny. This is not to suggest that a sustainable energy provision is to be expected, only that it seems achievable. Changing the energy system in the direction of sustainability is no simple matter. It is a great challenge and a complex and long term process, one that will require concerted efforts by governments, business and members of civil society, based on a scientifically sound understanding of the concept of sustainable development.

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