Energy and Sustainability – An Outlook

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1. Introduction

The adequate provision of energy services is of central importance for economic growth and societal development. While numerous societal and economic benefits arise from the use of energy, the supply of energy and electricity can also have negative impacts on the environment and climate systems.

These are the main reasons why energy is generally recognised as the core issue in the sustainable development debate. In recent decades, energy issues have been a fundamental and controversial component of the conceptual and strategic discussions on sustainable development world wide.

Despite the fact that sustainable development is featuring prominently on the political agenda, there is no common understanding of the concept of sustainable development. Sustainable development is therefore used by different people and interest groups to make very different propositions of what is to be sustained and what is to be developed, the energy debate being a prominent example.

Science and technology are increasingly recognised to be central to both the origins of sustainability challenges, and to the prospects for successfully dealing with them. A scientifically sound conceptual framework with respect to the sustainable provision of energy will be outlined and applied to assess the prospects of various energy options and technologies to implement sustainable energy development which supports the needs of the present generation without jeopardizing the ability of future generations to meet their own energy needs.

2. A conceptual framework for sustainable energy supply

The most frequently quoted general definition of sustainability is from the World Commission on Environment and Development (WCED), also known as the “Brundtland Commission”. The Commission has defined “Sustainable Development” as “…development that meets the needs of the present without compromising the ability of future generations to meet their own needs. … It’s a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional change are made consistent with future as well as present needs.” In a broad sense sustainable development must enhance the long-term productivity of the resource base and improve the long-term wealth and well-being derived from alternative resource-use systems with acceptable environmental impacts.

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 acquires particular significance. The fundamental content of the second law of thermodynamics is that life and the inherent need to satisfy needs is vitally connected with the consumption of workable energy and available material.

Thermodynamically speaking, life inevitably produces entropy by degrading workable energy and available material and requires a permanent input of these constituencies. But available energy and material only constitute a necessary but not sufficient condition for life-supporting states. In addition to this, information and knowledge are required to create states 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” that results in further technological development is of particular significance to sustainability because it allows for a more efficient use of natural resources and an expansion of the available resource base for generations to come.

When further defining the concept of sustainability, 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. First, the use of renewable energy, e.g. of solar energy, also always goes hand in hand with a need for non-renewable resources, e.g. of non-energetic resources and materials which are also in scarce supply. Second, 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 leave 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 today’s generation enjoys.

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 technically and economically usable. It should be recalled that in the past the proven reserves, i.e. energy quantities available technically and economically, have grown 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.

In addition to expanding the resource base available, the economic 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, labour and the environment. In addition efficient use of resources within the concept of sustainability also corresponds to the general economic efficiency principle. Both provide the basis 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 of scarce resources. Lower costs for the provision of the same energy service mean an economically more efficient solution which is also less demanding 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 combine the private costs with the external ones could serve as a suitable yardstick for measuring the utilisation of scarce resources.

Summarizing the above concretisation of the sustainability concept, an energy system is to be regarded as sustainable, if

- the potential for an economic provision of energy services increases or does not decrease for the next generation,
- the substance release due to energy use does not exceed the natural assimilation capacity of the natural environment,
- the energy related risk for human health is smaller than the avoided natural risks due to the provision of energy services,
- energy services are provided with the least resource input possible, including the environmental resource.

These general rules for a sustainable energy supply system are not directly applicable when it comes to the comparison and assessment of energy technologies and energy supply chains. Here the assessment has to be based on comparative measures of the various sustainability aspects on a functional unit basis, e.g. a kWh of electricity produced or a unit of energy service provided. The relative sustainability of energy technologies is basically determined by the overall consumption of resources including environmental resources on a functional unit basis. One useful measure for the overall resource consumption is the total social cost per unit of energy service. This includes the private as well as the external cost of an energy chain to provide an energy service.

3. A comparative assessment of electricity generation options

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 technologies, representing the state-of-the-art of these technologies being operated in Germany. Table 1 summarises the main technical characteristics of the selected reference technologies.

Table 1: Characterisation of the reference electricity production technologies

	Technology	**Power installed (netto) [MWe]**	**Efficiency el [%]**	**Life [Years]**
Hard Coal	Pulverised Combustion	700	45,5	35
Lignite	Pulverised Combustion	800	43	35
Gas CC	Combined-Cycle	777,5	57,5	35
Nuclear, PWR, once-through	actual PWR	1375	33	40
Wood CHP	Combined Heat and Power	20	24	35
PV-Modul poly 5 kW	polycristalline	0,005	12,5¹⁾	25
WEA 1500 kW (5,5)³⁾	horizontal	1,5	2450 h/a ²⁾	20
WEA 1500 kW (4,5)³⁾		1,5	1680 h/a ²⁾	20
Hydro 3,1 MW	Run-of-River	3,1	90	60

1) system efficiency; full load hours: 880h/a

2) full load hours

3) average wind speed (in 10 m height)

Cumulative energy requirements

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

Table 2: Cumulated Energy Demand (CED) and Energy Pay-Back Time (EPBT)

	Cumulated Energy Demand (CED) (without fuel) [kWh_{Prim} / kWh_{el}]	**Energy Pay-Back Time (EPBT) [months]**
Hard Coal	0,27	3,1
Lignite	0,16	3,2
Gas CC	0,17	0,8
Nuclear (PWR)	0,07	2,8
Wood CHP	0,08	13,2
PV-Modul poly 5 kW	0,61	66,3
WEA 1500 kW (5,5)	0,06	4,9
WEA 1500 kW (4,5)	0,08	7,2
Hydro 3,1 MW	0,04	11,0

The indirect primary energy input per produced kWh of electricity for hydro, wind and nuclear systems is in the range of 0,04 to 0,08 kWh. For natural gas and coal the necessary energy input per produced unit of electricity is in the range of 0,16 to 0,27 kWh which is basically determined by the energy required for the extraction, transport and processing of the fuel. The corresponding figure for today's photovoltaic systems is 0,61 kWh. This is also reflected in the energy pay-back time which is approximately 5 to 6 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 energy generation costs.

Table 3: Total life cycle raw material requirements

	Iron [kg/GWh$_{el}$]	**Copper [kg/GWh$_{el}$]**	**Bauxite [kg/GWh$_{el}$]**
Hard Coal	1.700	8	30
Lignite	2.134	8	19
Gas CC	1.239	1	2
Nuclear, PWR	457	6	27
Wood CHP	934	4	18
PV poly 5 kW	4.969	281	2.189
Wind 1500 kW (5,5)	3.066	52	35
Wind 1500 kW (4,5)	4.471	75	51
Hydro 3,1 MW	2.057	5	7

Pollutant Emissions

The cumulative emissions of selected pollutants of the power generation systems are compared in Figure 1. It is obvious that electricity generated from solid fossil fuels (hard coal and lignite) is characterised by high 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 quite high indirect emissions. Figure 1 shows that the total life cycle emissions of SO_2 and fine particulates of PV are in the range of coal fired systems (hard coal, lignite).

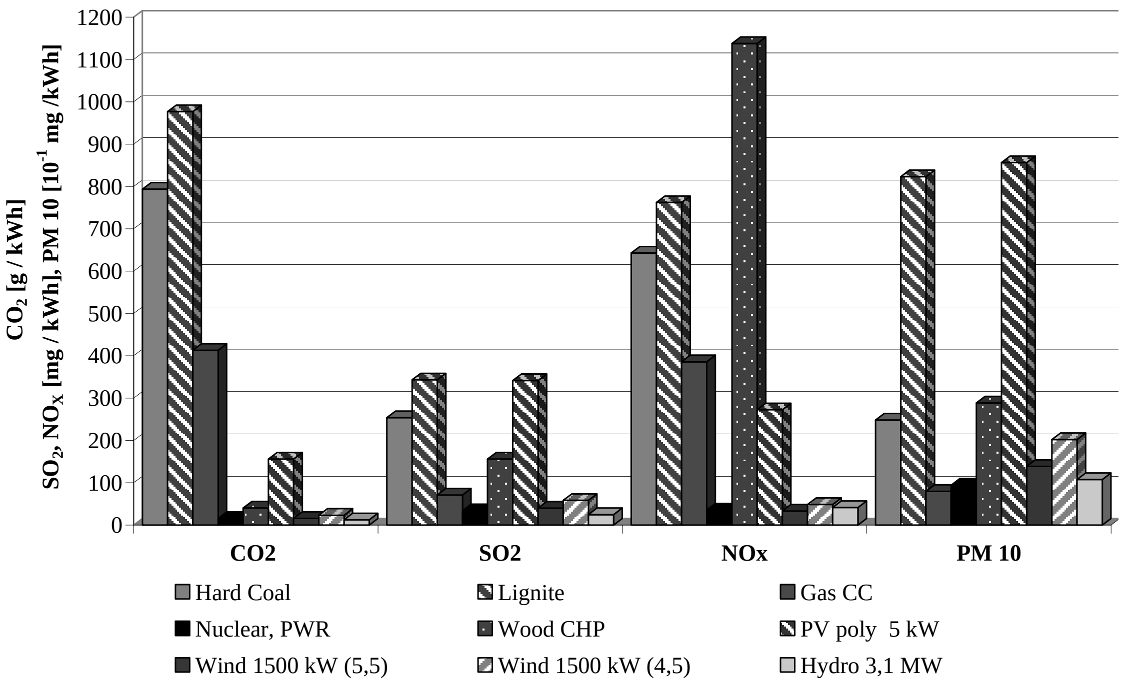

Figure 1: Total life cycle emissions

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 is connected to the emission of pollutants and the exposure to ionising radiation, which in turn might cause health risks to exposed members of the 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 Figure 2. The increased health 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, lignite and wood 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 connected to the up- and downstream processes of the solar cells, 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 smaller than the current concern about major nuclear accidents in the public discussion warrants. 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.

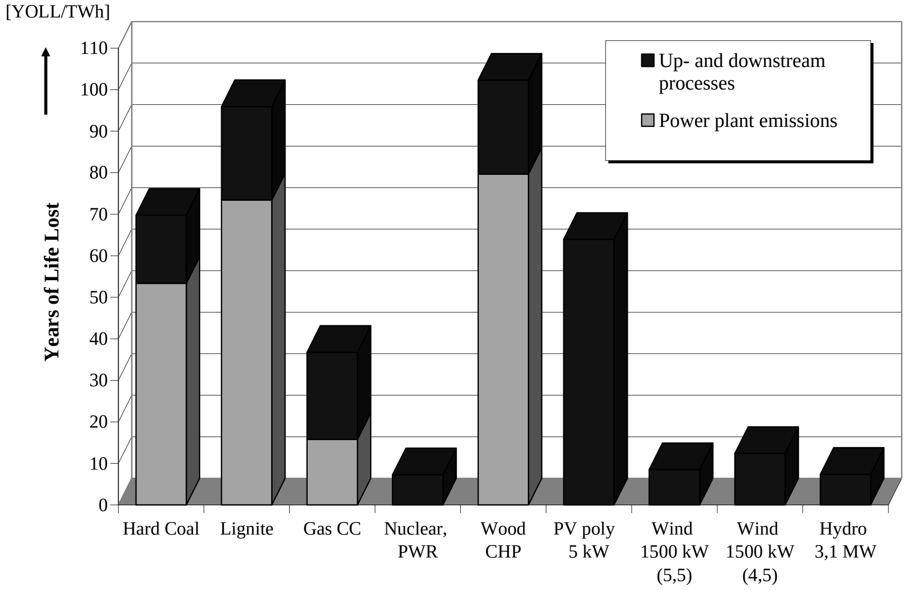

Figure 2: Health risks of energy systems

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, including the environment as a resource.

External costs resulting from impacts on human health, agricultural crops and building materials are considered quantifiable with a reasonable level of uncertainty, but impacts on ecosystems and in particular potential impacts from global climate change can not be readily quantified, based on current knowledge. As a result 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) can be used to give a rough indication of the potential damage costs. Using the detailed Life Cycle Inventories as reference input data, 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 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, NO_x and fine particulates lead 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, given the dominance of the potential for nuclear accidents in the public debate.

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 applications 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 cycles are lower than those from the other renewable systems, thus leading to low external costs. While the uncertainties in the quantification of external costs are still relatively large, the ranking of the electricity options considered is quite robust.

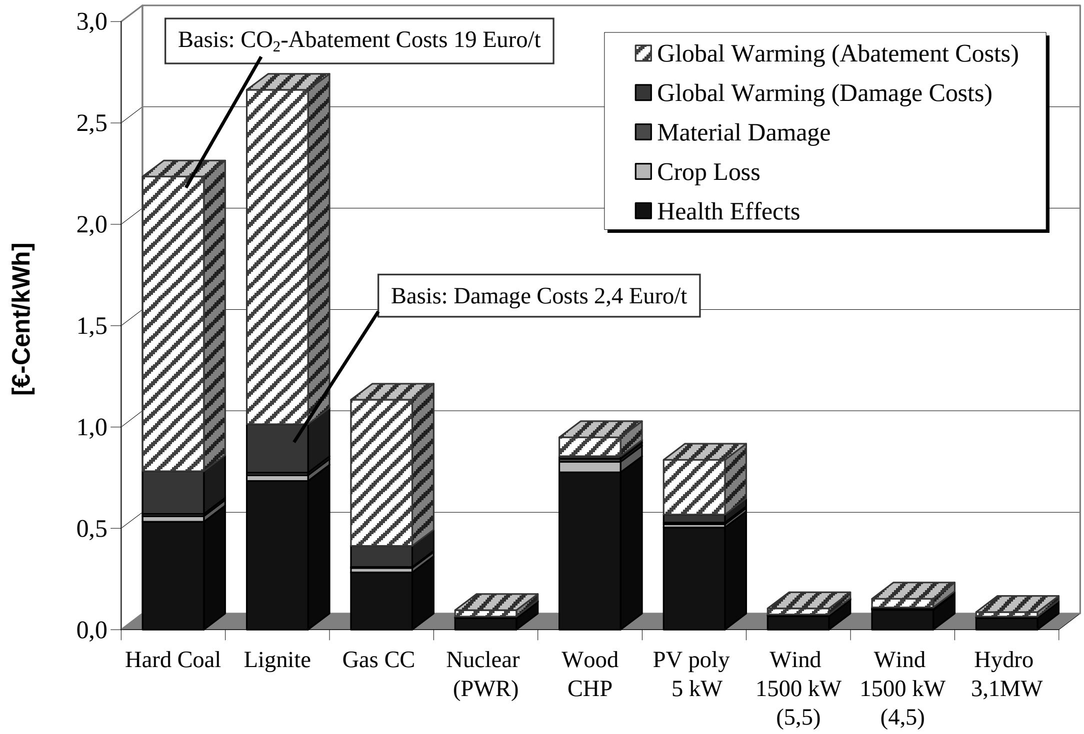

Figure 3: External costs from different electricity generation technologies operated in Germany

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 internalisation of external costs reduces the cost gap between the fossil and renewable electricity system to some extent, but does not affect the cost ratios between the renewable and the nuclear systems. The internalisation of external costs might lead to competitiveness of some wind and hydropower sites compared to fossil fuels, but does 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 assessing energy futures compatibly with sustainable development goals.

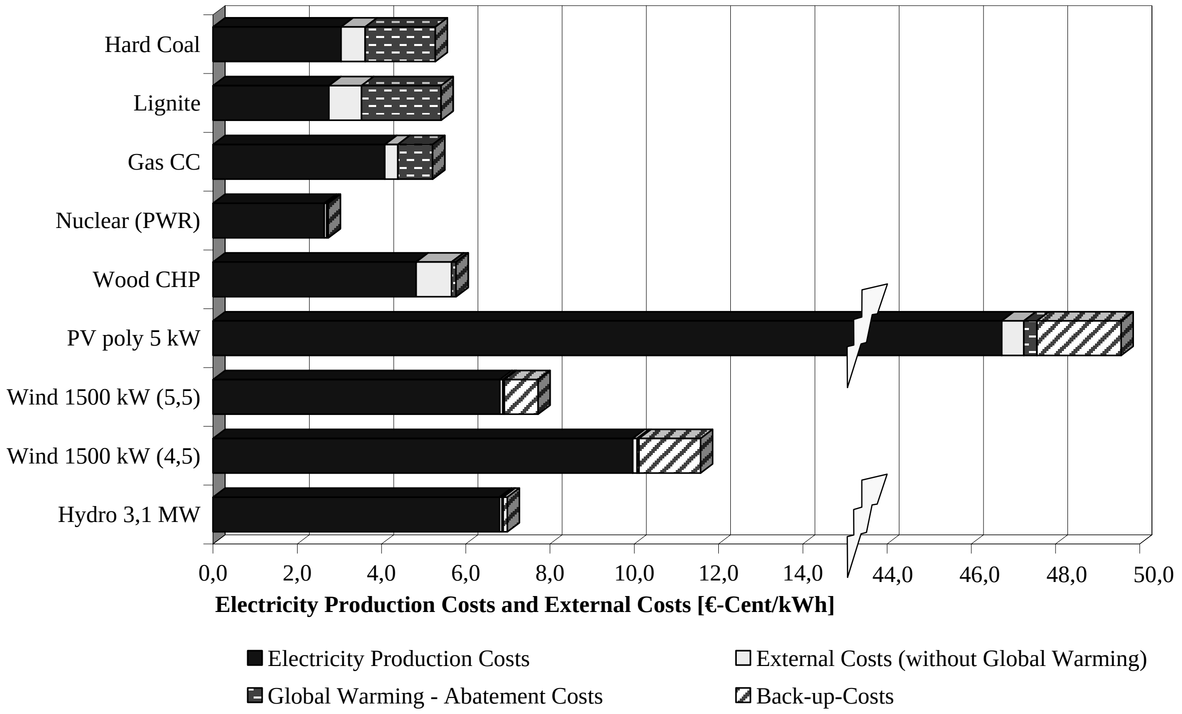

Figure 4: Total costs of various electricity generation technologies operated in Germany

4. Concluding remarks

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 – a process which will require concerted efforts by governments, businesses and members of civil society, based on a scientifically sound understanding of the concept of sustainable development. We have outlined a concept of sustainable energy development with the central goals to maintain or increase the technically-economically accessible resource base for the provision of energy services and not to exceed the assimilation capacity of the natural environment and have also shown how to assess the relative sustainability of the various energy options. Life cycle assessment (LCA) and total social cost valuation are useful tools to assist energy policy in a comprehensive comparative evaluation of energy supply options with regard to a sustainable energy provision. As liberalized electricity markets are becoming widespread, getting the prices right, i.e. internalizing the external cost of the various energy supply options, is a prerequisite for market mechanisms to work effectively towards sustainable development.

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