Der Beitrag bietet die zusammenge-
fasste Darstellung eines Rahmens zur
systematischen vergleichenden Bewer-
tung der Nachhaltigkeit von Energiesys-
temen, darunter auch eine umfassende
Anwendung dieses Rahmens auf die
wichtigsten Stromerzeugungstechniken
und die damit zusammenhängenden
Brennstoffkreisläufe in Deutschland. Das
Schwergewicht liegt auf der Herausbil-
dung quantitativer, technikspezifischer,
wirtschaftlicher, umweltbezogener und
gesellschaftlicher Indikatoren. Eine Reihe
von Verfahren wurde dazu eingesetzt,
darunter die Lebensdauerbeurteilung, die
Risikobewertung und der die Auswirkun-
gen erfassende „Impact Pathway Ap-
proach". Zwei Verfahren zur Indikato-
renaggregation fanden Verwendung: die
Schätzung der Gesamtkosten (interne wie
externe Kosten) sowie die Mehrkriterien-
Entscheidungsanalyse. Die Anwendung
dieses letzten Verfahrens ist hauptsäch-
lich dem Eingeständnis zu verdanken,
dass Werturteile in Entscheidungsprozes-
sen eine Rolle spielen.

Strengths and Weaknesses of Current Energy Chains in a Sustainable Development Perspective

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1. Introduction

When addressing sustainability a num-
ber of issues deserve special attention from
the modelling point of view. These are:
- a systematic consideration of the burdens
associated with other stages in the energy
chain than just the power plant, and the im-
pact of "grey" (i.e. indirect) emissions;
- a consistent treatment of underlying bur-
dens in assessing environmental and health
impacts associated with full energy chains;
- treatment of accidents, particularly se-
vere ones;
- treatment of the resource and availability
aspects;
- an adequate analysis resolution, allowing
for appropriate differentiation between the
overall performance of the various technolo-
gies under country-specific conditions; and
- integration of the various dimensions of
sustainability of energy supply, including
the social aspects.

This paper builds on the experience
gained from the modelling and application
activities within the *GaBE Project* at *Paul
Scherrer Institute (PSI)* dealing with the
"Comprehensive Assessment of Energy Sys-
tems" [1]. The methodology has been ap-
plied in a variety of projects for countries as
different as Switzerland and China. In a re-
cent comprehensive application on behalf of
the *International Committee on Nuclear
Technology (ILK: Internationale Länder-
kommission Kerntechnik)*, PSI has carried
out a comparative study addressing the
sustainability of various electricity supply
technologies operating under German-spe-
cific conditions [2]. The overall objective of
this analysis was to provide a basis for the
formulation of an official *ILK* position on
the sustainability of the different electricity
supply technologies, with special emphasis
on nuclear energy [3]. The evaluation cov-
ered selected current fossil, nuclear and re-
newable technologies, representative of av-
erage conditions in Germany.

2. The Sustainability Concept

The concept of sustainable develop-
ment first emerged, or rather was reborn, in
1987 with the publication of the report *Our
Common Future* by the *World Commission
on Environment and Development (the
Brundtland Commission)* [4]. *Sustainable
Development*, as defined in this report, is the
capacity to meet present needs without com-
promising the ability of future generations to
meet their own needs. In a broad sense, sus-
tainable development incorporates equality
within and across countries, across genera-
tions, and integrates economic growth, envi-
ronmental protection and social welfare. A
key challenge of the sustainable develop-
ment policies is to address these 3 demands
in a balanced way, considering their mutual
interaction, and, whenever necessary, mak-
ing relevant trade-offs.

In the meantime, a wide spectrum of
definitions of sustainable development has
emerged, with varying emphasis on the ma-
jor attributes of sustainability. The
Brundtland definition is subject to various
interpretations, which are crucial to imple-
mentation and practical application. On the
conceptual level, there is a distinct division

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line between those advocating "strong" sustainability and those advocating "weak" sustainability. The differences between these basic concepts stem from the different assumptions made concerning substitutability between natural and man-made capital, compensating for damage, and discounting future events.

Some rules, or principles for sustainability conditions, have already been proposed in the past (e.g. [5]).
– The use of renewable resources should not exceed their regeneration rate.
– Non-renewable energy carriers and raw materials should be consumed primarily at a rate corresponding to their physical and functional substitution by equivalent, economically useful, renewable resources, and by increased efficiency in utilizing the available resources, or by the discovery of new reserves.
– The flow of pollution and waste into the environment should not exceed the absorption capacity of the natural environment.
– Intolerable risks to human health incurred as a consequence of man-made activities should be minimized, or, if possible, eliminated.

The above discussion on sustainable development constitutes an essential background to the evaluation. However, the definitions and principles as such do not allow for a straightforward implementation of the sustainability concept, if the objective is to differentiate between the performances of the various energy technologies of interest. Independently of which sustainability concept is chosen, there seems to be a general consensus that promotion of sustainable development within the electricity-generation sector calls for the integration of the economic, ecologic and social aspects in the decision-making process.

The evaluation of alternatives can (and should) be done on the basis of an agreed set of criteria and indicators covering these three dimensions (they may also serve for communication purposes, since they allow the presentation of complex information in a relatively simple way). The generation of consistent, quantitative indicators necessitates an appropriate analytical framework, and the application of suitable methods. This issue is briefly described in the next chapter.

3. Methodology Overview

The quantitative indicators used in this study are based on a systematic, multi-disciplinary, bottom-up methodology, specifically tailored to the assessment of energy systems [2]. The overall approach is process-oriented, meaning that the technologies of interest, and their features, are ex-

plicitly represented. The implementation and application of the various assessment methods is inspired by principles adopted from Life Cycle Assessment (LCA). The following summary of the methods used is limited to approaches which are needed for the derivation of a number of disaggregated indicators. The methods described here focus on environmental and related social indicators; most economic and social indicators are either directly available, based on straightforward assessment, or based on the use of expert judgment. Detailed *environmental inventories* (i.e. burdens such as emissions or wastes) for current and future energy systems during normal operation have been established for the *Union for the Coordination of Transmission of Electricity* (*UCTE*) countries, with the highest level of detail coming from Switzerland [6]. Full energy chains are covered, including fuel extraction and conversion, energy production and waste management. All systems are described on a "cradle to grave" basis, with each step in the chain being decomposed into construction, operation and dismantling phases. Material input and transportation needs are accounted for in all energy-chain stages.

The approach includes the coverage of: (a) the direct emissions and other burdens over the entire lifetimes of the power plants, together with all relevant upstream and downstream processes, within each energy chain; and (b) the indirect emissions and other burdens associated with the various material and energy inputs.

Severe accident risks are addressed based on the examination of historical experience world-wide, and by employing Probabilistic Safety Assessment (PSA) techniques. In this context, a highly comprehensive database ENSAD (Energy-Related Severe Accident Database) has been established [7, 8]. The full energy chains are also covered in this case. In the evaluations, particular attention is paid to the applicability of historical data to the cases being analyzed. A broad spectrum of damage categories is addressed, including fatalities, serious injuries, evacuations, land/water contamination, as well as economic considerations.

The *environmental impact* analysis enables estimations to be made of pollutant concentrations, and depositions resulting from emissions of the major pollutants. Estimation of the *environmental external costs*, i.e. health and environmental damage currently not included in energy prices, is based on the "impact pathway" approach [9, 10].

The steps involved in this approach are: technology and site characterization, prioritization of impacts, quantification of burdens (emissions and others), description of the affected environment, quantification of impacts (using, whenever applicable, dispersion models for atmospheric pollut-

ants and dose-response functions), and economic valuation.

External cost estimates represent a highly aggregated indicator of environmental performance. The *total* (or *"true"*) *costs* of electricity production by different means are established by combining the internal and external costs. It has been proposed by some authors (e.g. [11]) that the total, system-specific cost of energy production could serve as an integrated relative indicator of sustainability, since it reflects the economic and environmental efficiency of the specific energy systems.

Another approach to aggregation is based on the application of *multi-criteria decision analysis* (MCDA). Use of a multi-criteria framework allows decision-makers to simultaneously address the often conflicting economic, ecological and social criteria. In comparison to the total cost assessment, MCDA brings the social dimension. The present application involves extensive use of the acquired detailed knowledge concerning systems performance in a process also open to accounting of values.

4. Selected Criteria and Indicators

There are many examples of the criteria and indicators relevant to sustainable development that have been established by international and national organizations. Examples include proposals made by the *United Nations Special Commission on Sustainable Development* [12], the *OECD* [13, 14], the *IAEA* [15], the *Enquête Commission* [16], and *PSI* [17, 18].

The following conclusions were drawn from the criteria and indicator survey carried out within this study.
1. The indicators have different scope and focus: sustainable development in general, sustainable development within the energy sector, and sustainable development within specific energy sources.
2. The sets of indicators originating from international organizations are not suitable for comparing the sustainability attributes of the major energy sources, in regard to appropriate differentiation between technologies.
3. In many cases, economic and environmental criteria/indicators are reasonably well developed; while social indicators are poorly developed and highly subjective.
4. Most of the sets are primarily based on directly available, simplistic indicators, and there are major consistency problems.
5. Little effort has been made towards aggregation of indicators to support decisions.
6. The sets of indicators originating from the *Enquête Commission* and *PSI* sets used in the past have both similarities and differences. The *Enquête Commission* does not

consider employment, proliferation, or specific accident and waste indicators, highly relevant for the social dimension. Furthermore, aspects such as land use or security of supply are not addressed. The *PSI* set of indicators employed in the aggregation avoids overlap but this is not the case with most other sets.

7. Earlier studies have not provided a harmonized, recognized set of technology-specific, application-specific numerical indicators. A broad knowledge base is a pre-requisite for the establishment of such indicators, and the analytical framework employed in the present study can serve as a basis for this.

Based on the results of the survey, the experience gained from the sustainability assessments (under radically different conditions) undertaken in Switzerland and China, together with the basic requirements on indicators and the discussions with *ILK*, a set of appropriate criteria and indicators has been defined. Three dimensions of sustainability have been considered: economy, environment and social. *Table 1* provides the indicators selected for the evaluation of electricity generation technologies operating in Germany.

Dimension	Impact Area	Indicator	Unit
Economy	Financial requirements	Production cost	¢kWh
		Fuel price increase sensitivity	Factor*
	Resources	Availability (load factor)	%
		Geo-political factors	Relative scale
		Long-term sustainability: energy-based	Years
		Long-term sustainability: non-energy-based	kg/GWh
		Peak load response	Relative scale
Environment	Global warming	CO₂-equivalent	Tons/GWh
	Regional environmental impact	Change in unprotected ecosystem area	km²/GWh
	Non-pollutant effects	Land use	m²/GWh
	Severe accidents	Fatalities	Fatalities/GWh
	Total waste	Weight	Tons/GWh
Social	Employment	Technology-specific job opportunities	Person-years/GWh
	Proliferation	Potential	Relative scale
	Impact on human health (normal operation)	Mortality (reduced life expectancy)	Years-of-life-lost/GWh
	Local disturbance	Noise, visual amenity	Relative scale
	Critical waste confinement	"Necessary" confinement time	Thousands of years
	Risk aversion	Maximum credible number of fatalities per accident	max fatalities/accident

* Increase of production costs due to doubling of fuel costs.

Tab. 1. Criteria and indicators employed in the present study [1].

It is important to note that the expected damage resulting from severe accidents, expressed in fatalities per unit energy, fall within the environmental dimension. This appears to be an inconsistency, and reflects the fact that it is difficult to quantify an accident-related environmental damage which could be applied to all the technologies in question. Consequently, mortality resulting from accidents serves here as a surrogate for the corresponding environmental effects.

5. Implementation: Reference Set of Indicators

This chapter addresses reference technologies, provides some more detailed information on indicators, and summarizes the indicator values employed in the quantification.

5.1 Reference technologies and adjustments to German conditions

The evaluation covers fossil energy carriers (lignite, hard coal, oil, natural gas), nuclear and renewables (hydro, onshore wind, solar photovoltaic). Wherever feasible, electricity generation technologies currently operating in Germany were selected as reference. The calculations carried out are representative of the average performance characteristics for these technologies. The same applies to the associated energy chains. In addition, representative load factors have been employed.

The set of indicators chosen for the evaluation reflects the fact that only current technologies have been considered. For example, expansion potential – a critical attribute when considering realistic options for the future – has not been considered within the present evaluation, which focuses on the current electricity supply in Germany.

German-specific data were used directly where available, and where considered consistent with the overall framework. In a few cases, Swiss data were considered relevant, as possible differences with the German data were judged not to be decisive.

Wherever necessary, suitable adjustments were made to the mostly Swiss or *UCTE* indicators to German conditions. Due to resource constraints, some of these adjustments were, of necessity, rather rough, though adequate for the purposes of the current study.

5.2 Economic indicators

5.2.1 Financial requirements

Production costs are here based on German sources. These are typical costs, and may not be representative of average conditions. It should be noted that the exceptionally low costs attributed to nuclear energy are due to the fact that the capital cost component has been amortized. In addition, no account has been taken of back-up costs for wind and solar photovoltaic (PV) technologies. *Sensitivity to fuel cost-increase* is represented by a factor corresponding to the increase of production costs resulting from a doubling of fuel costs.

5.2.2 Resources

Availability is based on typical load factors.

Geo-political factors refer to the security of energy carrier supply, taking into account the stability of the countries of origin. The indicators are based on judgment, and may need to be refined.

Long-term sustainability: energy-based is a measure of how long the resources of the particular energy carriers would be available, given that current consumption could stabilize, and that only resources which can be exploited without substantial increase of electricity production prices would be credited.

Long-term sustainability: non-energy-based uses copper as a reference material. Other materials could have been used instead, or in addition. Consumption of materials could also be viewed as an indirect measure of the efficiency of a system. The numerical values used, actually originate from *ecoinvent* [6].

Peak-load response reflects the technology-specific ability to respond swiftly to large temporal variations in demand. This capability is particularly attractive in view of market liberalization. Base-load technologies, and those renewables which strongly depend on climatic conditions, are not suitable in this context. In the case of hydropower, the fact that hydro reservoirs constitute a relatively small part of the hydro-based power supply in Germany was taken into account.

5.3 Environmental and health indicators

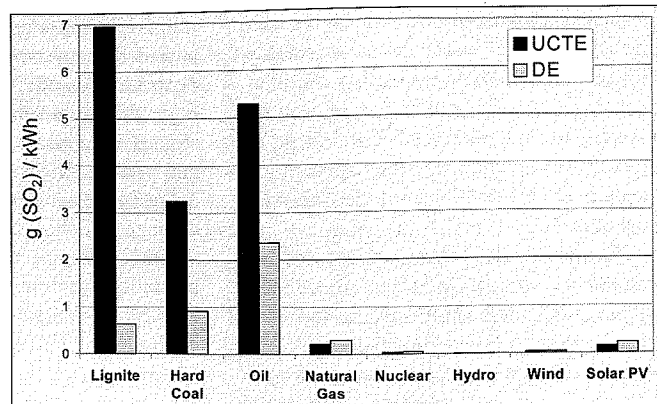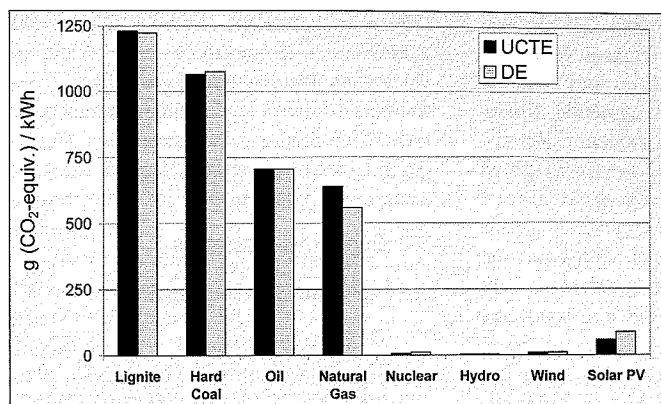All environmental indicators considered in this work are either LCA-based or have

Fig. 1a, 1b. LCA-based GHG and SO₂ emissions from German and UCTE energy chains during the year 2000 [2, 6].
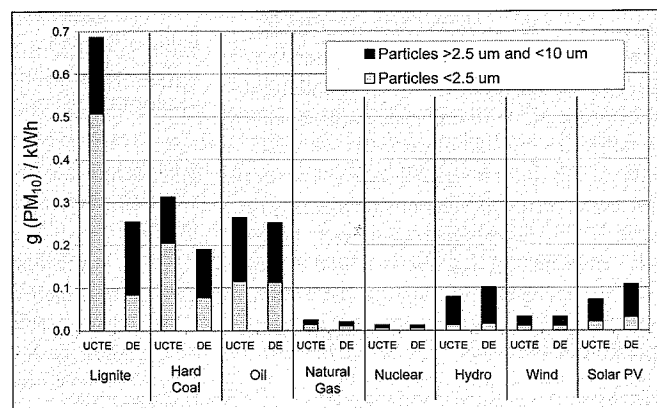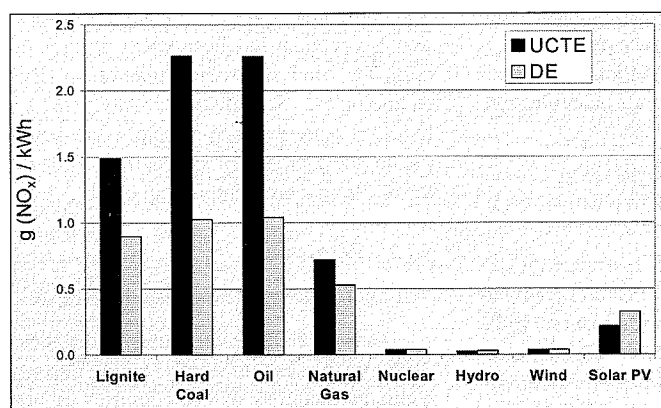

Fig. 2a, 2b. LCA-based NOₓ and particulate matter emissions from German and UCTE energy chains during the year 2000 [2,6].

followed an LCA-based philosophy: for example, full energy chains are also covered in the case of severe accidents. Further explanations of indicator features are given in [2].

5.3.1 Global warming

Global warming caused by *Greenhouse Gas (GHG)* emissions represents the global environmental effect, and is expressed in terms of *CO_2-equivalents* (for a 100-year time horizon). *Figure 1a* shows the *GHG* emissions for average German and *UCTE* technologies, and the associated stages in the energy chains, for the year 2000.

5.3.2 Selected pollutant emissions to air

Emissions of pollutants to air are not directly employed as indicators, but are included here because they are used for the estimation of regional environmental impact and their effect on health. *Figures 1a, 2a* and *2b* show SO₂, NOₓ, and particle emission (particulate matter of diameters less than 2.5 mm, and between 2.5 mm and 10 mm) for German and *UCTE*-averaged technologies, with associated energy chain stages, during the year 2000.

5.3.3 Solid wastes

The indicator *weight* refers to the total waste mass for each energy system, and is the sum of several single species, disposed within or pertaining to: hazardous waste, incineration, inert material landfill, land farming, municipal incineration, lignite ash, residual material landfill, sanitary landfill, underground deposits, final repository for low-level radioactive waste (assumed approximate density 2,500 kg/m³), final repository for spent fuel, high- and intermediate-level radioactive waste (of approximate density 2,300 kg/m³), uranium mill tailings (of approximate density 2,200 kg/m³), and low-active radioactive waste in superficial or shallow depositories (of approximate density 2,000 kg/m³).

No weighting factor has been applied here to account for the potential harm of each particular type of waste. Although the mass of waste may be misleading as an indicator if used in isolation, it is still a physically understandable item.

The *necessary confinement time* of the most hazardous waste has also been included among the social indicators. It can be regarded as a complementary attribute to mass, implicitly encompassing the potential harm from long-term waste management procedures.

Figure 3 shows the relative waste mass associated with each energy technology.

5.3.4 Land use

This indicator expresses the total land use for each energy chain, and corresponds
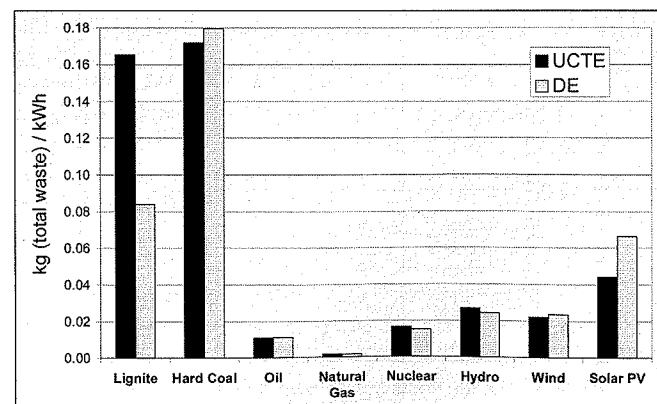

Fig. 3. LCA-based solid waste from German and UCTE energy chains for the year 2000 [2, 6].
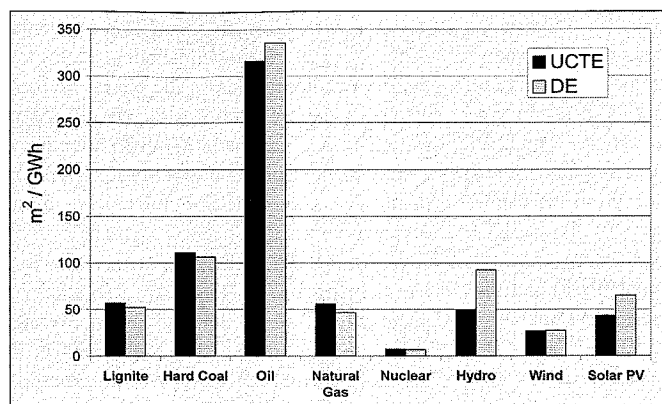
Fig. 4.   LCA-based land use for German and UCTE energy
           chains during the year 2000 [2,6].

to the sum of the different land types, as categorized in *ecoinvent* according to their transformation from one more-or-less natural status to one of the following:
- transformation to dump;
- transformation to industrial area;
- transformation to traffic area; and
- transformation to reservoir (for hydropower).

Ocean-based areas, relevant for gas/oil off-shore platforms and off-shore wind parks, have been excluded in this study, though they were accounted for in *ecoinvent*.

Figure 4 shows the land use for the various energy technologies.

5.3.5   Impact pathway-based indicators

We briefly describe here the methodology used for the estimation of the impact on human health resulting from normal plant operation. Impact here is quantified in terms of *mortality*, i.e. reduced life-expectancy, which in the present structure is regarded as one of the social indicators, and regional environmental impacts, as represented by change in unprotected ecosystem area.

The basis for environmental impact assessment (EIA) and external cost estimates was the methodology developed within the European ExternE project [9]. Updates of impact functions and valuation factors have been taken into account [19]. Moreover, environmental impact assessment has been combined with latest results of Life Cycle Assessment (LCA) from the *ecoinvent* project in order to include the full chain of electricity systems.

It has been shown elsewhere [9, 10] that environmental impact due to regional pollutants strongly depends on the location of the emission sources. Traditionally, Life Cycle Impact Assessment (LCIA) does not consider site-dependent effects. This deficiency has been adressed in the present study which aims to improve the relationship between EIA-based and LCA-based methodologies.

A problem with site-dependent LCIA approaches is to ensure consistent application of impact factors through the full energy chain. Site-specific factors should be used only where the locations of emissions are identifiable. Although all *ecoinvent* modules carry a location code, it is not always guaranteed that the location describes the emission site within a particular chain, because the module may have been used as an approximation for the corresponding process in another country. Usually, the *ecoinvent* location code refers to the technology, i.e. to emission factors typical for the technological state of the country. This is not necessarily the same as the real emission site if the specific technology is used in another country. Currently, there is no systematic way of tracing all such spatial mismatches between definition and application of a module in the *ecoinvent* database. Consequently, any mapping between site-specific impact factors and chain modules has to be constructed carefully.

For electricity, country-specific production and supply mixes have been modelled in *ecoinvent*. Therefore, the location code of electricity modules usually correctly reflects the country or region where the emissions occur. For these modules, country-specific factors are applicable. In contrast, most production and transport processes have been modelled only for Switzerland (and a few other countries) and/or for average European or global conditions. The application of, for example, a Swiss production module within the chain may not necessarily reflect the emission location, but might possibly serve as a substitute, since no module for another country or region is available. For such "sample" modules, the site-independent impact factors are applied.

For health effects due to primary particulate emissions, only fractions with diameters smaller than 10 μm (PM$_{10}$) have been considered effective. The impact factors for the larger fractions (which are calculated separately in *ecoinvent*) have been set to zero. No impact factors are available for emissions into the stratosphere; therefore, these emissions were also excluded. In total, the contributions of such emissions in the energy chains are very small. Following the recommendations in ExternE [9], the PM$_{10}$ functions have been applied to all primary PM$_{10}$ fractions without explicitly identifying

the included PM$_{2.5}$ fraction. This approach complies with the recommendations in ExternE [9] for power plants, but might lead to a slight underestimation in the chain of impacts due to transport. The error is considered small in the present context.

It was not possible within the limited framework of this project to include all site-dependent effects in the entire chain. This would have been equivalent to a full implementation of the method. The energy systems refer exclusively to German conditions. Thus, for the first application of the method, it has been considered most important to include site-dependent factors for Germany. The corresponding impact factors were included for the German electricity sector (for which *ecoinvent* provides country-specific data). The energy-chain emissions outside of Germany have been treated with standard impact factors for Europe. The present prototype implementation does not differentiate between high and low population density areas within the countries because, for the important secondary pollutants, there is no simple correlation between emissions from the 2 area-types and the extent of heir impact.

For all the electricity chains under consideration, mortality impacts have been calculated in terms of Years of Life Lost (YOLL). Mortality is the major contributor to the total external costs. Here, total external costs (including different morbidity effects, crops and material losses) have been estimated in a simplified way by multiplying the detailed YOLL calculation results by appropriate cost factors. For the given purpose, this is a sufficient approximation, because the total external costs are approximately proportional to the YOLL value. The damage factors used can be found in [20].

Figure 5 shows the resulting mortality, specific for the German energy chains considered in this study. The fossil systems other than natural gas exhibit much higher impacts than the other options. It should be noted that for nuclear a geometric mean based on maximum and minimum values was used.

The change of unprotected ecosystem area due to acidification and eutrophication is considered as the basic indicator for damage to ecosystems. Factors per unit emission of SO$_2$ and NO$_x$ for acidification and eutrophication have been calculated for the years 1990 and 2010 in [10]: SO$_x$ and NO$_x$ both contribute to acidification, NO$_x$ also causes eutrophication. Factors for ammonia have been neglected, because the energy systems considered here have almost no ammonia emissions. Calculations have been performed for emissions from different European countries, and for average EU-15. It is assumed that changes in unprotected areas due to acidification and due to
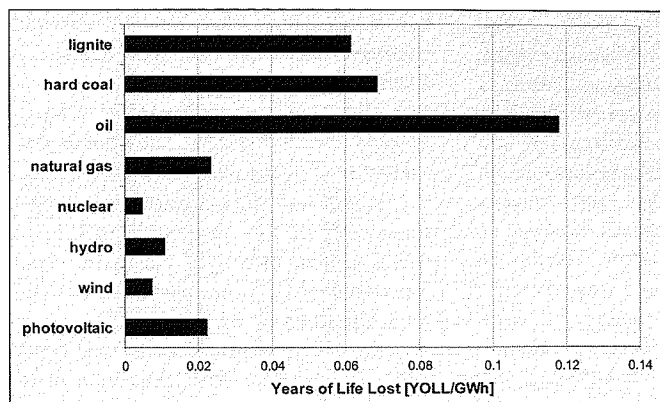
Fig. 5. Mortality associated with normal operation of German energy chains in the year 2000 [2].

eutrophication are approximately additive; a discussion of this assumption is given in [2]. The resulting indicator is the total change of unprotected ecosystem area per unit emission for each country. In contrast to conventional LCIA methods, the effects due to he different locations of the emission sources can be accounted for as far as the locations in the chain may be identified (site-dependent LCIA).

5.3.6 Severe Accidents

In principle, the approach used for the evaluation of severe accidents is consistent with the impact pathway method. Due to their special nature, however, accidents are treated separately.

The evaluation builds on other work carried out at *PSI* [7, 8, 21], and covers fossil energy sources (coal, oil and gas), nuclear power and hydropower. For details we refer to these publications. *Figure 6* shows frequency-consequence curves for coal, oil, natural gas and hydro chains, based on historical accidents world-wide in the period 1969-2000 as represented in *PSI's* database ENSAD (Energy-related Severe Acci-

dents Database). These curves show immediate fatalities. The results for a Swiss nuclear power plant originate from the plant-specific Probabilistic Safety Assessment (PSA) and reflect latent fatalities.

The *OECD*-specific results for fossil and hydro chains were considered representative for Germany. For nuclear energy, the risk measures obtained in Level III PSA for a Swiss nuclear power plant were employed as the starting point for the study, and then adjusted to reflect the higher power level and higher radioactive inventory more typical for the German plants. These adjustments, though quite rough, have practically no impact on the final results based on the aggregation methods applied in this work.

5.4 Social indicators

5.4.1 Employment

The aim of the technology chain labour assessment was to estimate the life-cycle labour content of 8 technology chains for electricity generation, including lignite pulverized coal, bituminous pulverized coal (hard coal), oil, natural gas, hydro, wind and solar PV generation. In order to do this, each chain was divided into four components: 1) Fuel Extraction & Processing; 2) Fuel Trans-portation; 3) Generation Plant Construction; and 4) Generation Plant Operation.
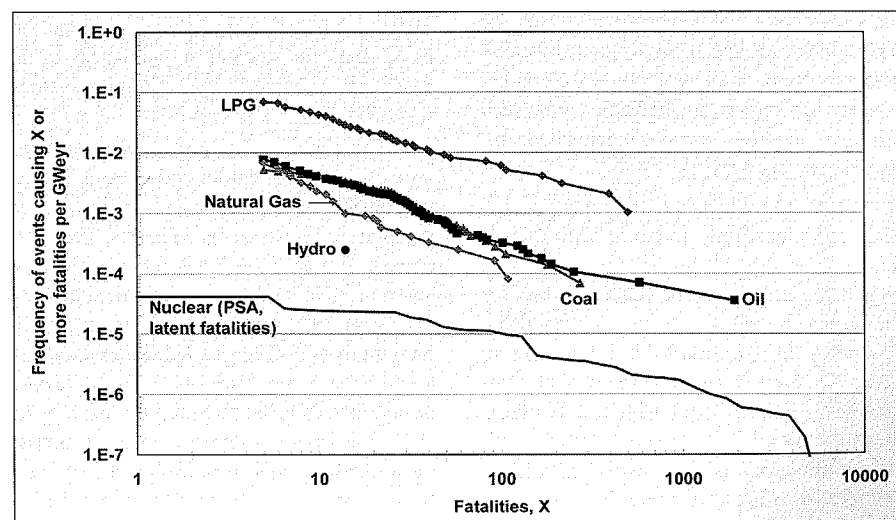
It is difficult to find hard data for establishing accurate, averaged labour statistics for these technologies across the entire German electricity sector. National electricity sector associations (*VDEW* and *VDN*) do not collect employment numbers by fuel-type or type of plant. The only official number from these organizations is the total employment level of 131,000 for the German electricity sector. Normalizing by the total net generation of about 520 TWh in 2002 gives an average employment of about 250 man-yr/TWh. If the more detailed US employment data ratios are applied, this would result in about 110 man-yr/TWh for generation, transmission and distribution (T&D), and about 240 man-yr/TWh for general and administrative jobs. These data can serve as an order of magnitude check against individual generation technologies, although they do include non-generation components, and do not include T&D employment.

Overall, the estimation of labour followed 3 possible methods. When national data (e.g. mining jobs) were available, they were used to obtain a national sector average. If industry sources were available for specific plant types (e.g. generation labour for combined-cycle plants), these were used next. Finally, order-of-magnitude estimates were made (e.g. for average hydro construction labour) when other sources failed. Total uncertainty depends upon both the relative sizes and uncertainties of the labour estimates for the individual technology chain components.

Two other factors also affect the uncertainty of labour estimates. First is the question of where the dividing boundary should be. For example, in the case of coal and nuclear generation, direct plant construction labour was estimated for on-site construction, and excluded the specific labour content of components. However, for the wind and solar technology chains, more indirect aggregate industry construction data were used, based on data availability, and the fact that more of the labour is devoted to component fabrication.

Secondly, labour results have been normalized in terms of generation; i.e. they were given in man-years per TWh. This means that variable labour (e.g. fuel) depends upon plant efficiency, and fixed labour (e.g. construction) depends upon plant generation.

Some electricity generation (e.g. by wind and solar) is fixed by natural availability, but most generation is based on cost-based dispatch. In this case, the generation was based on the German average generation for the technology in question. Finally, labour components for different technologies were compared and adjusted, based on our own estimates of the relative labour intensity required. It should be noted that all
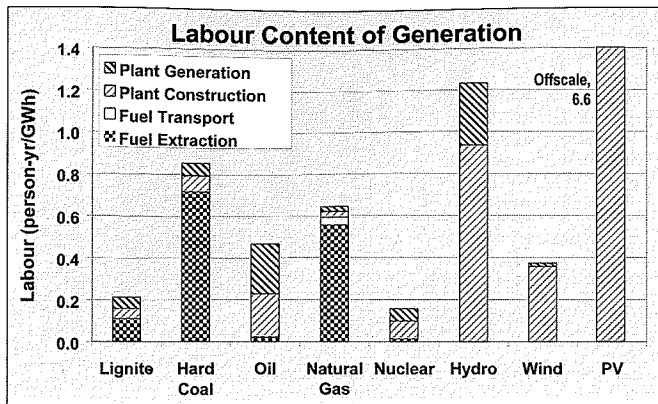

Fig. 6. Frequency-consequence curves for full energy chains in OECD with allocation and for the time period 1969 – 2000 [21].

Fig. 7. Energy-chain specific labour for Germany [2].

non-recurring labour (primarily construction labour) was amortized over the assumed life of the generation technology before adding the variable labour content for fuel, etc. This means that labour rates for the different labour components can be multiplied by the labour content to produce a total labour cost per kWh, if so desired. Finally, the relative sizes of the individual labour components and totals were compared for general consistency, and adjusted as deemed appropriate.

Figure 7 shows the results of the estimation: that is, the indicator *technology-specific job opportunities*.

5.4.2 Proliferation

Proliferation potential is a binary indicator, meaning that it either applies or not, given that only one type of nuclear generation and fuel cycle is considered.

5,4,3 Human health impacts due to normal operation

The "Mortality" indicator has been described in Section 5.3.5 (see also *Fig. 7*). It is worthwhile noting here, however, that mortality due to accidents is practically negligible compared to the corresponding effects of normal operation.

5.4.4 Local disturbances

This indicator concerns *noise and visual amenity,* and is rather vulnerable to subjective judgments. Some input from ExternE was used here to rank the energy chains. Nevertheless, the assigned indicator values may be disputable.

5.4.5 Critical waste confinement time

Necessary confinement time has already been discussed in Section 5.3.3. The indicator values should be regarded as order-of-magnitude estimates.

5.4.6 Risk aversion

Maximum credible number of fatalities per accident is used here as a surrogate for

risk aversion. Historical non-*OECD* results were employed for the fossil options, as opposed to expectation values based on historical experience within the *OECD*.

For hydro, however, *OECD* experience from all dam accidents (not only hydro dams) was used, since the enormous accidents in non-*OECD* countries are less credible in the German case: first, because German hydro is primarily run-of-river, and second, the reservoir capacities tend to be rather small. The extent of the consequences of hypothetical extreme accidents is thus largest in the case of nuclear, where appropriate adjustments were made to account for the larger radioactive inventories (the Swiss reference plant is rather small).

Valuation of this aspect depends on stakeholder preferences, can be addressed in multi-criteria analysis and, along with the issue of waste, affects in particular the ranking of nuclear power in the sustainability context [18].

5.5 Full indicator set used in the present study

Tables 2, 3 and *4* show the complete set of indicators used in the present application. Weights used in the base case of MCDA, described in Chapter 6, are indicated within parenthesis. Some of the numbers provided in the Tables originate from model-based assessments, and some are based on judgment. The associated uncertainties may be substantial. For this reason, the cited quantitative indicators are most appropriate to comparisons that aim to establish an internal technology ranking. However, they are adequate for the purpose of the present study, including MCDA-based aggregation. In applicable cases, the numbers have been rounded.

Impact Area/ (Weight)	Indicator/ (Weight)	Unit	Lignite	Hard Coal	Oil	Natural Gas	Nuclear	Hydro	Wind	PV
Financial Requirements/ (70)	Production cost/ (75)	c/kWh	3.3	3.0	3.1	3.6	2.1	7	9	60
	Fuel price increase sensitivity/(25)	Factor	1.6	1.5	1.8	1.8	1.3	1.0	1.03	1.1
	Availability (load factor)/(40)	%	80	80	80	80	80	40	20	9
	Geopolitical factors/ (15)	Relative scale	100	80	20	40	80	100	100	100
Resources (30)	Long-term sustainability: Energetic (15)	Years	400	2000	100	100	500	∞	∞	∞
	Long-term sustainability: Non-energetic (Cu) (10)	kg/GWh	13	11	12	4	5	1	38	230
	Peak load response (20)	Relative scale	20	50	100	100	10	30	0	0

Tab. 2. Set of economic indicators and weights used in the Base Case MCDA [2].

Impact Area	Indicator/ (Weight)	Units	Lignite	Hard Coal	Oil	Natural Gas	Nuclear	Hydro	Wind	PV
Global Warming	CO_2-equivalents/(40)	tons/GWh	1220	1080	884	559	10	4	10	86
Regional Environmental Impact	Change in unprotected ecosystem area/(25)	km²/GWh	0.032	0.039	0.061	0.016	0.0017	0.0009	0.0029	0.011
Non-Pollutant Effects	Land use/(5)	m²/GWh	52	106	335	47	7	92	28	65
Severe accidents	Fatalities/(15)	Fatalities/GWh	5.7E-7	2.1E-5	4.5E-5	1.0E-5	2.3E-6	3.4E-7	1.1E-8	1.1E-7
Total Waste	Weight/(15)	tons/GWh	84	180	11	2	15	24	23	66

Tab. 3. Set of environmental indicators and weights used in the Base Case MCDA [2].

Impact Area	Indicator/ (Weight)	Units	Lignite	Hard Coal	Oil	Natural Gas	Nuclear	Hydro	Wind	PV
Employment	Technology-specific job opportunities/ (10)	person-years/GWh	0.21	0.86	0.47	0.65	0.16	1.2	0.36	6.6
Proliferation	Potential/(5)	Relative scale	0	0	0	0	100	0	0	0
Human Health Impacts (normal operation)	Mortality (reduced life-expectancy)/(40)	YOLL/GWh	0.061	0.068	0.12	0.023	0.005	0.011	0.007	0.020
Local Disturbances	Noise, visual amenity/(15)	Relative scale	10	8	6	2	4	5	7	0
Critical Waste confinement	"Necessary" confinement time/(15)	Thousand years	50	50	0.1	0.01	1 000	0.01	1	50
Risk Aversion	Maximum credible number of fatalities per accident/(15)	max fatalities/ accident	10	500	4500	100	50000	2000	5	100

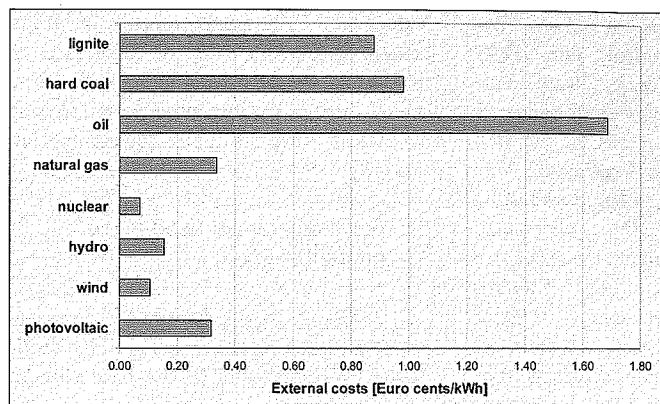*Tab 4. Set of social indicators and weights used in the Base Case MCDA [2].*

Fig. 8. *External costs of electricity generation in Germany; external costs of global warming are not included [2].*
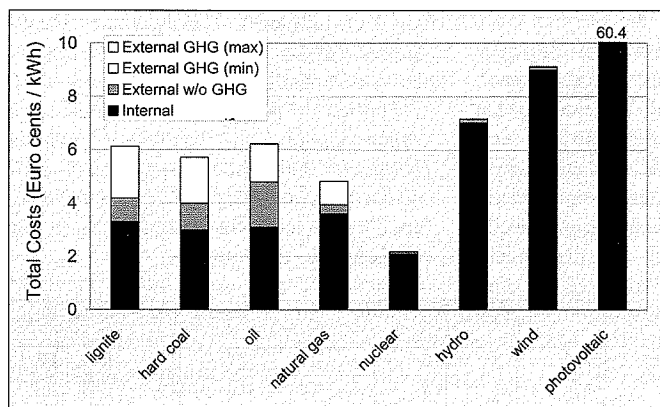

Fig. 10. *Multi-criteria sensitivity mapping for Germany: health and environmental criteria plus production costs. The higher the total score, the better is the overall system performance [2].*

Fig. 9. *Comparison of total costs of current technologies in Germany (GHG = Greenhouse Gases) [2].*

6. Aggregation

Aggregation of indicators enables the overall performance of technologies to be evaluated. Two aggregation approaches were used.

6.1 Aggregation based on total costs

The total costs are the sum of the internal and external costs; the latter are shown in *Fig. 8*. External costs are driven by public health effects, caused by increased levels of concentrations of pollutants in ambient air, or by an increased level of ionising radiation resulting from activities at the various process stages in the energy systems[1]. Generally, damages resulting from the emission of a unit of pollutant are high if the number of affected receptors is very large. The fossil systems (except for natural gas) exhibit much higher impacts than the other options.

The total costs, comprising internal and external German-specific costs, are shown in *Fig. 9*. External costs associated with global warming are highly uncertain, and much less robust, than those due to air pollutants.

According to a ranking based on total costs, nuclear energy is the best performer, followed by natural gas, hard coal, lignite and oil. Photovoltaic has by far the highest total costs.

6.2 Aggregation based on Multi-Criteria Decision Analysis

6.2.1 Base-case development

Multi-Criteria Decision Analysis (MCDA) used in this project allowed us to combine, on an aggregate level, the central results of the analyses performed for the economic and environmental sectors with the social preferences of the users. The technology-specific indicators constitute the analytical input to this evaluation.

The approach used for the evaluation is based on a simple-weighted, multiple-attribute function. Individual weights reflect the relative importance of the various evaluation criteria, and are combined with the normalized indicator values (scores). Normalization is carried out using a local scale, defined according to the set of alternatives under consideration. For example, the alternative which does best on a particular criterion is assigned a score of 100, and the one which does least well a score of 0.
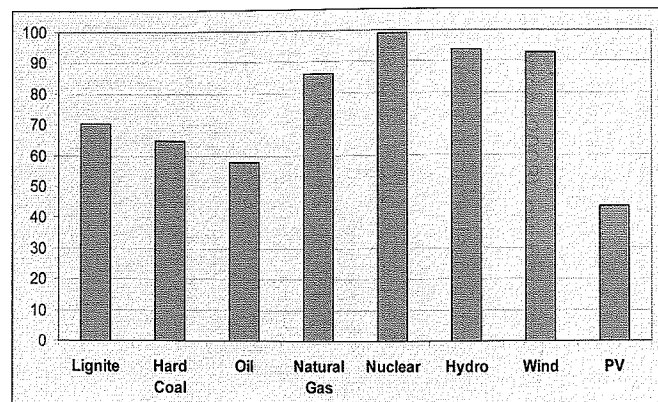
All other alternatives are given intermediate scores, based on linear interpolation between these two reference points. A single overall value is obtained for each alternative by summing the weighted scores for all criteria. Ranking of the available options is then established on the basis of these values.

The actual weights applied can be obtained from stakeholder considerations. Alternatively, various weighting schemes can be assigned to accommodate the range of perspectives expressed in the general energy debate. The sensitivity to these choices has also been investigated.

In one of the evaluation cases, only a subset of the criteria has been employed: namely, environmental criteria, together with health component in the social dimension and production costs (*Figure 10*). This case has some parallels to the evaluation of total cost. The rankings based on the 2 methods show certain similarities (though they are not identical), with nuclear being the top performer, and PV being the worst.

A different set of results is obtained (*Figure 11*) if the full set of criteria is used, and the weights are equally distributed between the 3 main components (economy, environment and social), thus postulating that sustainability ultimately calls for equal importance being given to each of them.

The case with equal top-level weights results in top performance being attributed to hydro and wind, followed by nuclear and natural gas. Nuclear is at a lower rank than in the "total cost" and "environmental criteria plus health plus production cost" cases as a result of the inclusion of social criteria.

6.2.2 Sensitivity analysis

A number of sensitivity cases were run in order to investigate specific patterns in the ranking. Three cases, with, respectively,
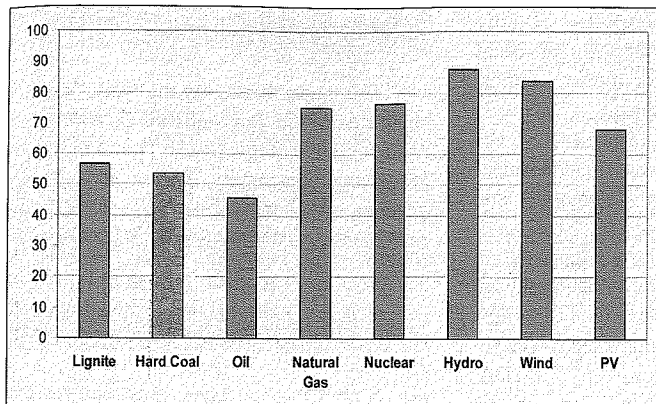
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1   Estimates of external costs also cover health impact from severe accidents within the various energy chains, though these contributions are practically negligible compared to the monetised health and environmental damages resulting from normal operation.

Fig. 11. *Multi-criteria sensitivity mapping for Germany: base case, employing the full set of criteria, and with equal weights assigned to the 3 dimensions of sustainability [2].*

economy-centred, environment-centred and social-centred weighting, are shown in *Figures 12–14*. The economy-centred case corresponds to the economic dimension being given a weighting of 80%, while the environmental and social dimensions each have a weighting of 10%; the other cases are defined in an analogous manner.

As can be seen, results are highly sensitive to the variation of weights. While the weights given to the lower levels of criteria

Fig. 12. *Multi-criteria sensitivity mapping for Germany: economy-centred case [2].*

Fig. 13. *Multi-criteria sensitivity mapping for Germany: environment-centred case [2].*

may, in most cases, be regarded as arbitrary, the ranking of systems remains quite stable for a moderate variation of these weights.

In addition to the sensitivity study, the impact of possible future, nuclear-specific technological improvements has also been examined. This includes a strong, design-based limitation of the consequences of hypothetical nuclear accidents, along with a radical reduction of necessary waste confinement times to a historical time scale (*Figure 15*). The beneficial effects on the ranking of nuclear in the MCDA-based sustainability evaluation are manifested by nuclear attaining the top rank, along with hydro and wind. This sensitivity case is mentioned primarily for the sake of illustrating the positive implications of the major developments in nuclear safety and waste research currently being pursued. Advancements are also feasible (and likely) for other technologies, though at this stage no specific developments of such a decisive character as those for nuclear have been identified. A systematic investigation of the impacts of evolutionary improvements of electricity generation technologies and associated energy chains on environmental burdens can be found in [22].
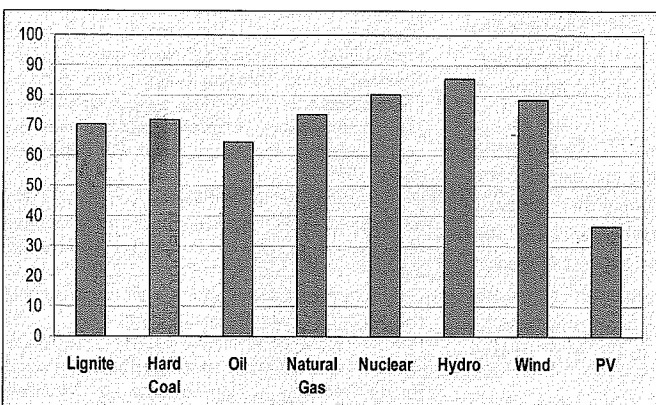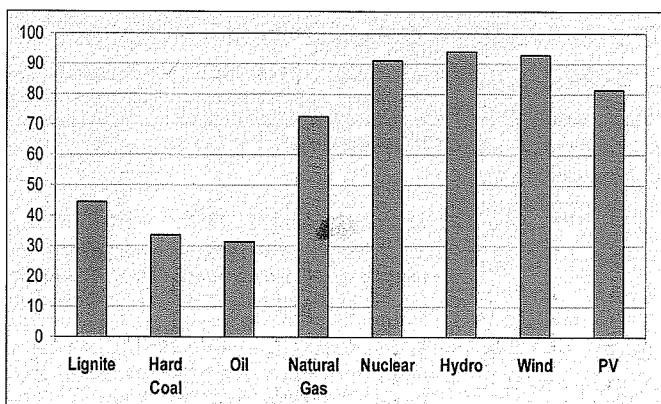
7. Conclusions

7.1 Role of the sustainability and assessment approach

It is suggested that sustainability considerations should guide political decisions involving energy supply options and associated technological developments. The evaluation process needs to be transparent and non-discriminative. The use of consistent, and (to the extent possible) objective, quantitative, technology-specific indicators is highly promising.

The present study has provided a suitable evaluation approach, which has been implemented and applied to the current major energy chains for electricity generation for Germany. As such, this proposal could be helpful to the energy policy discussion in that country.

7.2 Option-specific features

– Fossil systems are subject to limited energy resources, and display relatively unfavourable ecological and accident-risk features. Natural gas is by far the best performer among fossil energy carriers.

– In the case of nuclear energy, the economic, environmental and health indicators are highly favourable. Within the western world, nuclear energy also has an excellent safety record, reflected in the very low estimates of technical risks. The sensitive issues for nuclear energy include risk aversion, and the perceived problems associated with the necessity to assure safe storage of (relatively small volumes of) radioactive waste over extremely long periods.

– In most respects, the "new" renewables (solar and wind) may be considered environmentally superior to fossil sources, but use relatively large amounts of material resources. The overall performance of wind energy is favourable, while the economic competitiveness of solar photovoltaic
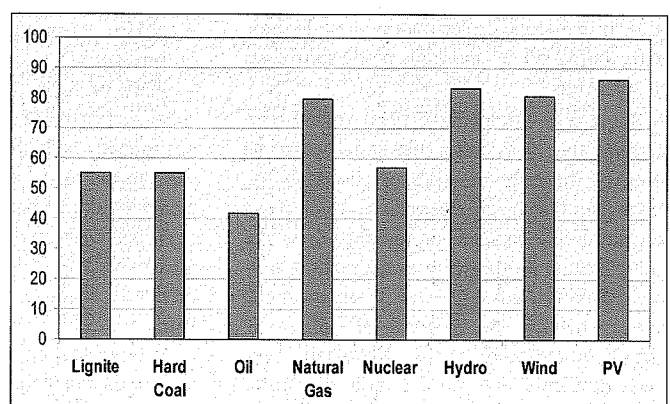

Fig. 14. *Multi-criteria sensitivity mapping for Germany: socially-centred case [2].*
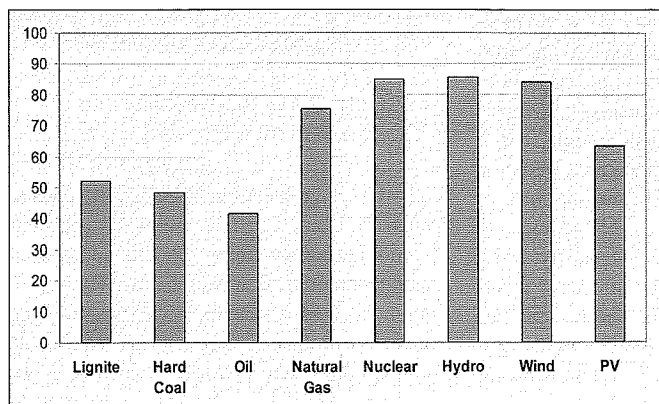
Fig. 15. Multi-criteria sensitivity mapping for Germany: full set of criteria, equal first-level weights, scoring credit for potential nuclear advancements [2].

systems is still extremely low, at least for German climatic conditions.

7.3 Overall evaluation of sustainability

– Evaluations employing a variety of sustainability criteria result in a fragmented picture of the merits and drawbacks of the currently available electricity supply options. No single system exhibits superior properties for all criteria. However, most indicators show nuclear energy in a favourable light.

– For the most part, relative statements on sustainability of the various electricity supply options are meaningful, and comparative sustainability evaluations can be based on the aggregation of indicators employing either the full-cost or Multi-Criteria Decision Analysis (MCDA) approach.

– Coal and oil chains have the highest external costs. Those associated with natural gas are the lowest among the fossil chains, and are of the same order as those for solar photovoltaic. The nuclear chain exhibits the lowest quantifiable external costs, followed by wind and hydro. In terms of total costs, nuclear power again shows top performance (under German conditions), and is superior to the other currently implemented technologies. In particular, solar photovoltaic is presently burdened by the high production costs of solar cells.

– Some reservations have been voiced concerning the proposition that total costs be used as the only measure of sustainability, since then the society dimension, which plays a central role in decision-making, does not come feature prominently in the ranking process. Taking nuclear power as an example, issues such as the disposal of high-level, long-lived radioactive waste, hypothetical severe accidents and proliferation contribute marginally, or not at all, to the external costs. At the same time, these issues remain controversial and, depending on the socio-political

perspective of those involved, can be of paramount importance.
– Trade-offs between environmental, economic and societal sustainability components are inevitable, and are sensitive to value judgements. The results of MCDA, based on criteria limited to the corresponding scope of the total cost assessment (i.e. with health and environmental impacts equally weighted to production costs), leads to technology rankings with a number of similarities. Rankings based on all three pillars of sustainability are relatively robust when these pillars are considered equally important, and the weighting of lower level criteria (e.g. financial requirements or employment effects) is subject to variation. Putting emphasis on economy penalizes renewables; emphasis on environment penalizes fossil systems; and emphasis on societal aspects penalizes nuclear.

– Developments towards a strong limitation of the consequences of hypothetical accidents, along with a radical reduction in waste confinement times may have a highly favourable impact on the MCDA-based ranking of the nuclear chain.

– Both total costs and MCDA-based, technology-specific total scores are useful comparative indicators of sustainability. Overall, a meaningful sustainability perspective implies a balanced (equal) assignment of importance to economic, ecological and social aspects. Unbalanced emphasis on any one of these 3 dimensions is not in the spirit of sustainable development.

7.4 Possible future applications

– Direct interactions with stakeholders would be an important continuation for the present study.
– Study of future systems is recommended, since sustainability in the longer term will be determined both by the technological advancements made, and the willingness to implement them within the present energy sector.
– Along with analyses of future technologies, scenario analyses are also recommended. These tend to be more realistic, since they have built-in representations of realistic, technology-specific potentials, and explicit accounting of back-up systems for those technologies exhibiting relatively low load factors as a result of strong dependence on climatic conditions.

References

[1] *S. Hirschberg, R. Dones:* Analytical decision support for sustainable electricity supply. In Energie und nachhaltige Entwicklung: Beiträge zur Zukunft der Energieversorgung, VDI, Düsseldorf, Germany, pp. 168-187, 2000.
[2] *S. Hirschberg, R. Dones, T. Heck, P. Burgherr, W. Schenler, C. Bauer:* Sustainability of electricity supply technologies under German conditions: a comparative evaluation. *PSI* Report No. 04-15, 2004.[2]
[3] *ILK:* Statement on sustainability evaluation of nuclear energy and other electricity supply technologies. Report No. *ILK*-16 E, Jan. 2004.
[4] *G. Brundtland* (Ed.): Our Common Future: The World Commission on Environment and Development. *Oxford University Press,* Oxford, 1987.
[5] *S. Hirschberg, A. Voss:* Nachhaltigkeit und Energie: Anforderungen der Umwelt. Proc. Fachtagung Nachhaltigkeit und Energie, 25-26 Nov. 1998, Zürich.
[6] *R. Dones, C. Bauer, R. Bolliger, B. Burger, M. Faist Emmenegger, R. Frischknecht, T. Heck, N. Jungbluth, A. Röder:* Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Final Report, *ecoinvent* 2000 No. 6, data v1.1, *Paul Scherrer Institut* Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland, 2004.
[7] *S. Hirschberg, G. Spiekerman, R. Dones:* Severe accidents in the energy sector. *PSI* Report No. 98-16, 1998.
[8] *P. Burgherr, S. Hirschberg, A. Hunt, R.A. Ortiz:* External costs from major accidents in non-nuclear fuel chains. NewExt Project WP5 (to be published).
[9] European Commission: ExternE – Externalities of Energy. ExternE Final Report, 1999.
[10] *W. Krewitt, A. Trukenmüller, T.M. Bachmann, T. Heck:* Country-Specific Damage Factors for Air Pollutants. A Step Towards Site Dependent Life Cycle Impact Assessment. *Int. J. LCA,* 6, 199-210 (2001).
[11] *A. Voss:* Nachhaltige Energieversorgung – Konkretisierung eines Leitbildes. In Energie und nachhaltige Entwicklung: Beiträge zur Zukunft der Energieversorgung, *VDI,* Düsseldorf, Germany, pp. 122-140, 2000.
[12] United Nations: Indicators of sustainable development: framework and methodologies. United Nations, Commission on Sustainable Development, New York, 2001.

2 This document essentially reproduces the report prepared in November 2003 by *PSI* for the *International Committee on Nuclear Technology (ILK),* which in turn formed the basis for *ILK* Statement *ILK*-16, January 2004. Compared to the original version, few basic data changes were implemented in this report as a result of more recent sources. The modifications which were made have no significant influence on the results, and do not affect the original conclusions.

[13] *OECD/NEA:* Nuclear energy in a sustainable development perspective. *OECD,* Paris, 2000.

[14] *OECD/NEA:* Indicators of sustainable development in the nuclear energy sector – a preliminary approach. *NEA*/NDC(2002) 5, Paris, April 2002.

[15] *IAEA:* Guidance for the evaluation of innovative nuclear reactors and fuel cycles. Report of Phase 1A of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), Technical Document, *IAEA*-TECDOC-1362, *International Atomic Energy Agency,* Vienna, June 2003.

[16] *Enquête Commission:* Nachhaltige Energieversorgung unter den Bedingungen der Globalisierung und der Liberalisiering. Abschlussbericht, Berlin, July 2002.

[17] *Energie-Spiegel:* Facts für die Energiepolitik von Morgen. *Energie Spiegel* Nr. 3, *PSI/ETHZ,* Sept. 2000.

[18] *S. Hirschberg, R. Dones, U. Gantner:* Use of external cost assessment and multi-criteria decision analysis for comparative evaluation of options for electricity. in *S. Kondo, K. Furuta* (Eds.), Proc. 5th Int. Conf. on Probabilistic Safety Assessment and Management (PSAM 5), Osaka, Japan, 27 Nov.-1 Dec., 2000, pp. 289-296.

[19] *R. Friedrich, P. Bickel* (Eds.): Environmental costs of transport, *Springer-Verlag,* Berlin, 2001.

[20] *S. Hirschberg, T. Heck:* Health risks of major energy chains. *SVA*-Vertiefungskurs Wirkung ionisierender Strahlung. Winterthur, 4-5 Dec., 2002 (5.2-1 to 5.2-15).

[21] *P. Burgherr, S. Hirschberg, A. Hunt, R.A. Ortiz:* Severe accidents in the energy sector: damage indicators and external costs. *PSI* Report (to be published).

[22] *R. Dones, U. Gantner, S. Hirschberg, G. Doka, I. Knoepfel:* Environmental inventories for future electricity supply systems for Switzerland. *PSI* Report No. 96-07, 1996.   □