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Comprehensive Assessment of Energy Systems (GaBE)

Sustainability of Electricity Supply Technologies under German Conditions: A Comparative Evaluation

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Sustainability of Electricity Supply Technologies under German Conditions: A Comparative Evaluation

This document essentially reproduces the report prepared in November 2003 by the Paul Scherrer Institut (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 the current report based on most recent sources. These modifications have no significant influence on the results and do not affect the original conclusions.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

On behalf of the International Committee on Nuclear Technology (ILK) the Paul Scherrer Institut carried out a comparative study addressing the sustainability of electricity supply technologies operating under German-specific conditions. The general objective of this analysis was to provide a support for the formulation of ILK position on the sustainability of various electricity supply technologies, with special emphasis on nuclear energy. The evaluation covers selected current fossil, nuclear and renewable technologies, which are representative for the average conditions in Germany.

As a starting point existing, representative evaluation criteria and indicators, recently proposed by competent international organisations were reviewed. Based on this survey and PSI's experience from various evaluation studies, a set of criteria and indicators for use in the present project was established. The main effort went into generation of quantitative technology-specific economic, environmental and social indicators. A number of methods were employed for this purpose including Life Cycle Assessment (LCA), Risk Assessment (RA) and Impact Pathway Approach (IPA). Some new methodological advancements were implemented, in particular improved link between LCA and impact estimation, and enhanced treatment of site-dependent effects in the estimation of impacts and corresponding external costs.

Two methods of indicator aggregation were employed, i.e. estimation of total (internal and external) costs and Multi-criteria Decision Analysis (MCDA). Use of MCDA is motivated by acknowledgement of the role of value judgements in decision-making. Both total costs and MCDA-based technology-specific total scores are useful comparative indicators of sustainability. Sustainability perspective implies a balanced (equal) importance assignment to economic, ecological and social aspects.

Coal and oil chains exhibit the highest environmental external costs. The external costs associated with natural gas are the lowest among the fossil chains, i.e. of the same order as for solar photovoltaic. The nuclear chain exhibits the lowest quantifiable external costs, followed by wind and hydropower. In terms of total costs nuclear power shows again top performance, under German conditions superior to other currently implemented technologies.

Evaluations employing a variety of sustainability criteria result in a differentiated picture of the merits and drawbacks of the currently available electricity supply options. No single system exhibits a superior performance on all criteria. MCDA ranking based on all three pillars of sustainability is 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 on societal aspects nuclear.

In summary, this study provides a framework for systematic evaluation of sustainability of energy systems. Refinements of the methodology and specific indicators are feasible. Options for future applications include direct involvement of stakeholders, and evaluations of future technologies and of supply scenarios combining the various candidate technologies. Tools supporting such analyses have been developed by PSI and can be adjusted to the needs of country-specific applications.

1. INTRODUCTION

The electric utility sector is of central importance for the economic growth and social development. While numerous societal and economic benefits arise from electricity production, it can also have impacts, which may not be fully and unanimously reconciled with the concept of sustainability. Moving the electricity sector towards sustainable development calls for the integration of environmental, social and economic aspects in the decision-making process. As an input to such a process, one needs to assess how the different options perform with respect to specific sustainability criteria.

On behalf of the International Committee on Nuclear Technology (ILK) the Paul Scherrer Institut carried out a comparative study addressing the sustainability of electricity supply technologies operating under German-specific conditions. The general objective of this analysis was to provide a support for the formulation of ILK position on the sustainability of various electricity supply technologies, with special emphasis on nuclear energy. It was agreed on that the evaluation would cover selected current technologies, representative for the average conditions in Germany.

From the modelling point of view a number of issues deserve special attention when addressing sustainability. These are:

- Systematic consideration of burdens associated with stages of energy chains other than power plant as well as impacts of “grey” emissions;
- Consistent treatment of the underlying burdens when assessing environmental and health impacts associated with full energy chains;
- Treatment of accidents, particularly severe ones;
- Treatment of resource and availability aspects;
- Adequate analysis resolution that allows for appropriate differentiation between the overall performance of various technologies under country-specific conditions;
- Integration of the various dimensions of sustainability of energy supply including social aspects.

This report deals with the above issues and builds on the experiences from modelling and applications within PSI’s *GaBE Project* on “Comprehensive Assessment of Energy Systems” (Hirschberg and Dones, 2000). The *GaBE Project* provides answers to many issues in the Swiss as well as in the international energy arena. A systematic, multi-disciplinary, bottom-up methodology for the assessment of energy systems, has been established, implemented and frequently applied. It includes environmental analysis, risk assessment and economic studies, which are supported by the extensive databases developed in this work. One of the analysis products is aggregated indicators associated with the various sustainability criteria, thus allowing a practical operationalisation of the sustainability concept. Apart from technical and economic aspects the integrated approach also considers social preferences; this is done in the framework of multi-criteria analysis.

Apart from using previous experience the present work provides some new contributions to the resolution of the issues above.

The work performed consisted of:

1. Short survey of representative sets of criteria and indicators proposed by competent international organizations.
2. Establishment of criteria and associated indicator sets to be used in the evaluation.
3. Establishment of quantitative indicators mostly based on existing information.
4. Generation of aggregated results and associated sensitivity mapping.
5. Interpretation of the results, thus providing the basis for ILK position.

The report is structured as follows:

- Short review of the sustainability concept (Chapter 2);
- Framework and methods for comparative assessment of energy systems (Chapter 3);
- Multi-criteria Decision Analysis (MCDA) framework and application basis, including survey of criteria and indicators (Chapter 4);
- Quantitative indicators obtained for energy chains operating under German conditions (Chapter 5);
- Aggregation of indicators (Chapter 6);
- Conclusions (Chapter 7);
- References (Chapter 8).

2. SUSTAINABILITY CONCEPT

The concept of sustainable development 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). Sustainable Development, as defined in this report, is the capacity to meet the needs of the present without compromising the ability of future generations to meet their own needs. In a broad sense, sustainable development incorporates equity within and across countries as well as generations, and integrates economic growth, environmental protection and social welfare. A key challenge of sustainable development policies is to address these three dimensions in a balanced way, considering their interactions and whenever necessary making relevant trade-offs.

In the meantime a wide spectrum of definitions of sustainable development has been proposed, with varying emphasis on the major attributes of sustainability[1]. The Brundtland definition is subject to various interpretations, which are highly essential for the implementation and practical applications. On the conceptual level there is a quite distinct division line between those advocating “strong” sustainability versus proponents of “weak” sustainability. The differences between these basic concepts stem from different assumptions about substitutability between natural and man-made capital, about compensating damage, and about discounting future events.

Some rules or principles for sustainability conditions were proposed in the past (e.g. Hirschberg and Voss, 1999):

- The use of renewable resources should not exceed their regeneration rate.
- Non-renewable energy carriers and raw materials should be consumed at most at a rate, which corresponds to physically and functionally equivalent substitution by economically useful renewable resources, increased efficiency in utilizing the available resources or discovery of new reserves.
- Pollution and waste flows into the environment should not exceed the absorption capacity of the natural environment.
- Non-tolerable risks for the human health due to man-made impacts should be minimised or, if feasible, eliminated.

The above discussion on sustainable development constitutes an essential background. However, the definitions and principles as such do not allow for a straightforward operationalisation of the sustainability concept if the objective is to differentiate between the performances of 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 electric sector calls for the integration of economic, ecologic and social dimensions 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; the set may also serve for communication purposes as it allows presenting complex information in a relatively simple way. Generation of consistent quantitative indicators calls for an analytical framework and application of appropriate methods. This is described in the next chapter.

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[1] This work focuses on the degree of sustainability of specific energy carriers and current energy technologies, i.e. the scope of assessment is more limited than when addressing sustainable development in general.

3. OVERVIEW OF METHODS FOR COMPARATIVE ASSESSMENT AND SUSTAINABILITY EVALUATION

3.1 Overall Framework

Figure 1 shows the analysis framework developed for the comprehensive analysis of energy systems and used for applications in Switzerland. It employs a number of methods for technology assessment, supported by the associated databases. The overall approach is process-oriented, i.e. the technologies of interest and their features are explicitly represented, thus enabling a straightforward accounting for technical improvements.

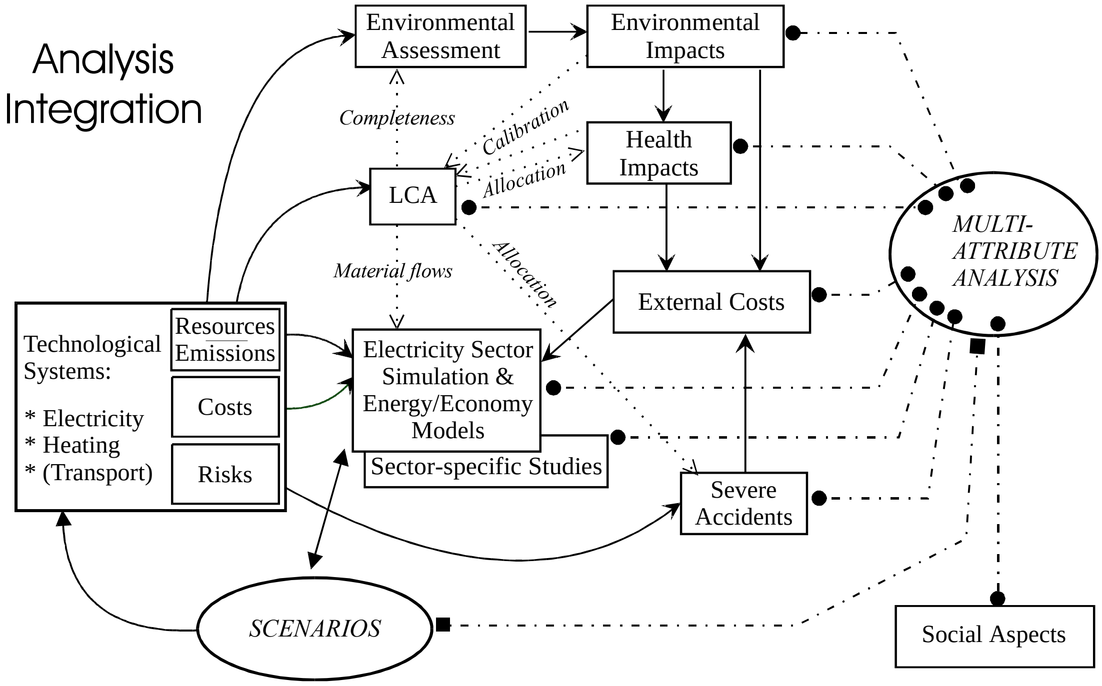

Fig. 1 Analysis framework for comprehensive assessment of energy systems.

Within the recently finalized China Energy Technology Program (CETP), sponsored and coordinated by ABB, and in conjunction with the Alliance for Global Sustainability (AGS), PSI, together with American (MIT), numerous Chinese, Japanese (Tokyo University) and Swiss (ETHZ and EPFL) partners, has investigated how the future electricity supply in China could be made more sustainable (Eliasson and Lee, 2003). Representatives of the major Chinese stakeholders participated in this program. The framework for the CETP analyses (Fig. 2) has been inspired by the approaches established within the GaBE Project at PSI. At the same time, the contrasts between China and Switzerland are enormous in terms of dimensions, standard of living, energy consumed per capita, structure and efficiency of energy systems, pollution levels, and economic growth.

The parallels with the framework shown in Fig. 1 are apparent. The CETP framework is, however, somewhat broader as it also includes Energy Transportation Modelling (ETM) as well as Electric Sector Simulation (ESS) only recently incorporated within GaBE. At the core of the ESS methodology is a model that simulates electrical system dispatch, and is based on the marginal cost of generation from individual units. Thousands of different scenarios can be designed, generated, modelled, analysed and presented, along with such attributes as costs, emissions, risks, and use of resources. Scenarios are created by combining multi-option strategies with future uncertainties. It should be noted that the stakeholder component and the associated interactions with the analytical tasks are explicitly shown in Fig. 2.

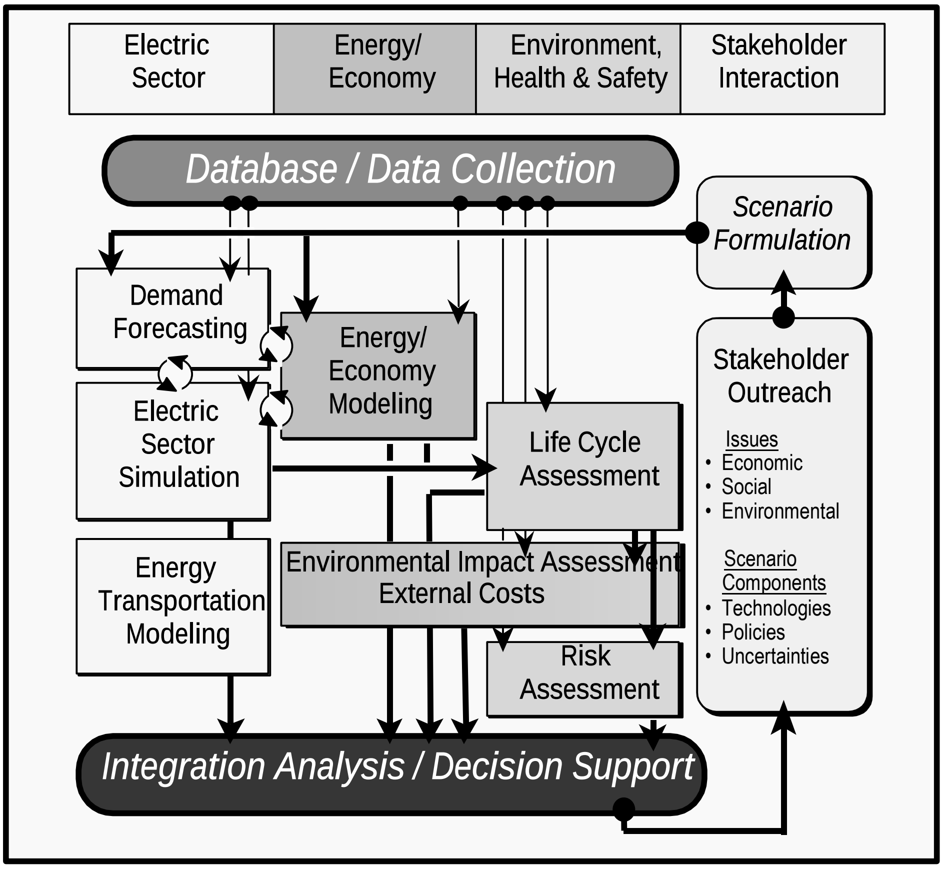

Fig. 2 Analysis framework used in the China Energy Technology Program.

3.2 Methods Used in Comparative Assessment

3.2.1 Life Cycle Assessment

Detailed environmental inventories for current and future energy systems during normal operation have been established (Frischknecht et al., 1996; Dones et al., 1996; Dones et al., 2003,2004), using Life Cycle Assessment (LCA).

Life Cycle Assessment (LCA) is a systematic method for the establishment of energy and material balances of the various energy chains. LCA considers not only direct emissions from power plant construction, operation and decommissioning but also the environmental burdens associated with the entire lifetime of all relevant processes upstream and downstream within the energy chain. This includes exploration, extraction, processing, transport, as well as waste treatment and storage. The direct emissions include releases from the operation of power plants, mines and processing factories, transport systems and building machines. In addition, indirect emissions originating from materials manufacturing, from energy inputs to all steps of the chain and from infrastructure, are covered. Fig. 3 shows a general presentation of an energy chain and Fig. 4 illustrates the basic principles of LCA, using one step in an energy chain as an example.

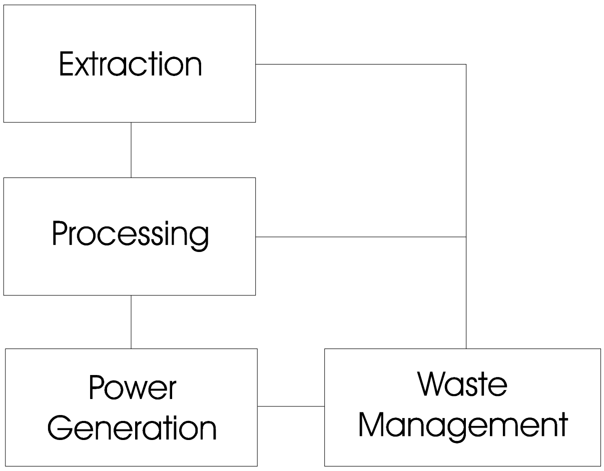

Fig. 3 Structure of an energy chain.

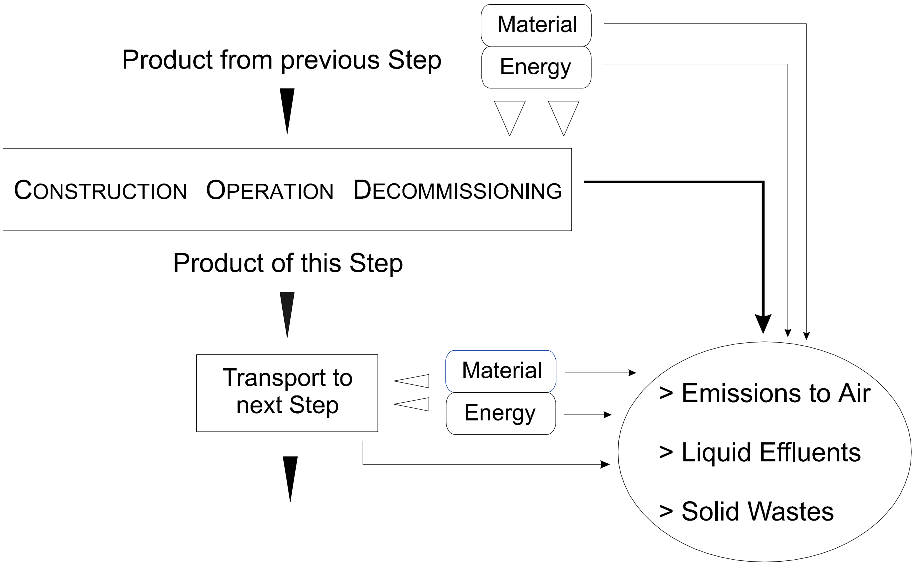

Fig. 4 Basic principles of LCA, shown for one step in an energy chain.

Some additional basic features of the LCA methodology as applied in the Swiss e*coinvent2000* database (Dones at al., 2003, 2004), extensively employed in the present study, are:

- Energy systems, transport systems, material manufacturing, production of chemicals, waste treatment and disposal, as well as agricultural products, have been assessed using detailed process analysis developed under consistently defined common rules.
- Electricity inputs were modelled using production technology or supply mix as close as feasible to the actual situation. In case of lack of specification, the UCTE mix was used as a reasonable approximation.
- Allocation criteria were developed for multi-purpose processes.

The basic LCA approach focuses on the estimation of the inventories of energy chains, including the associated resource consumption. It is possible to use LCA as a tool for simplified impact assessment. Pollutants can be aggregated into, for example, 13 environmental impact classes such as: greenhouse effect, ozone depletion, acidification, photo smog, nitrification, and radioactivity. Impact analysis based on LCA is, however, subject to considerable simplifications and the results exhibit the corresponding limitations. The LCA approach does not distinguish between the physical characteristics of the emissions (e.g. rate, duration, and location), meteorological conditions, complex pollutant interactions and transformations. Consequently, for some categories such as photo smog the results may not be always meaningful due to the dependencies and non-linearities involved. For some other impact classes, LCA-based impact estimation may represent a valid and resource-saving approach. Thus, in the case of the greenhouse effect, which represents a global impact, the place and time characteristics of the emission are practically of no importance. Furthermore, the estimates of the real impact of global warming are associated with enormous and partially uncontrolled uncertainties. For these reasons the aggregated greenhouse gas emissions are frequently considered as a relevant surrogate impact indicator. For other pollutants and impacts the LCA-based emissions should be regarded as an indicator of possible impacts and in no way as a measure of expected impacts. In order to generate best estimate impacts other approaches are necessary.

3.2.2 Impact Pathway Approach

The environmental impact analysis allows the estimation of pollutant concentrations and depositions resulting from emissions of the major pollutants. The estimation of environmental external costs, i.e. health and environmental damages currently not included in energy prices, is based on the “impact pathway” approach. The elements involved in this approach are: technology and site characterization, prioritisation of impacts, quantification of burdens (emissions and other), description of the receiving environment, quantification of impacts (using whenever applicable dispersion models for atmospheric pollutants and dose-response functions), and economic valuation. Thus, the pathways of pollutants are followed from the point of release to where damage takes place. The estimation of external costs is supported by the EcoSense software (European Commission, 1999; Krewitt et al., 2001).

External costs estimates represent a highly aggregated indicator of environmental performance. The total (“true”) costs of electricity production by different means are established by combining internal costs with the external ones. It has even been proposed that the total system-specific cost of energy production could serve as an integrated indicator of sustainability since it reflects the economic and environmental efficiency of energy systems (Voss, 2000).

The assessment of health and environmental impacts of energy production has undergone a major evolution in recent years, reflecting progress in the underlying scientific domains. To allow comparison between the various electricity generation systems a comprehensive, consistent and transparent methodology for the assessment of the impacts and the associated damages was recently established within the European Commission, initially in cooperation with the US Department of Energy. The full scope methodology for impact assessment is based on the impact pathway, or damage function, approach. The basic principles of this methodology encompass accounting for all relevant stages in each energy chain (extraction, processing, transports, power generation, waste treatment and storage). The impact pathway approach is a bottom-up method that traces the passage of the pollutant from the place where it is emitted to the final impacts on the receptors affected by it (Fig. 5).

The principal steps of this methodology include (European Commission, 1999)[2]:

1. Emissions: characterisation of the relevant technologies and the environmental burdens they impose (e.g. tons of NO_x per GWh_e emitted by power plant).
2. Dispersion: calculation of increased pollutant concentrations in all affected regions (e.g. incremental $\mu g/m^3$ of O_3), using models for atmospheric dispersion and chemical reactions for O_3 formation due to NO_x);
3. Impact: calculation of the dose from the increased exposure and calculation of physical impacts from this dose, using a dose-response function (e.g. crops yield reduction due to increase in O_3 concentration).
4. Cost (optional): the economic valuation of impacts.

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[2] For the effects that originate from rare events (severe accidents) rather than from continuous releases of pollutants, the process necessarily involves the assessment of frequencies associated with consequences of different magnitude. This is further elaborated in the next section on risk assessment.

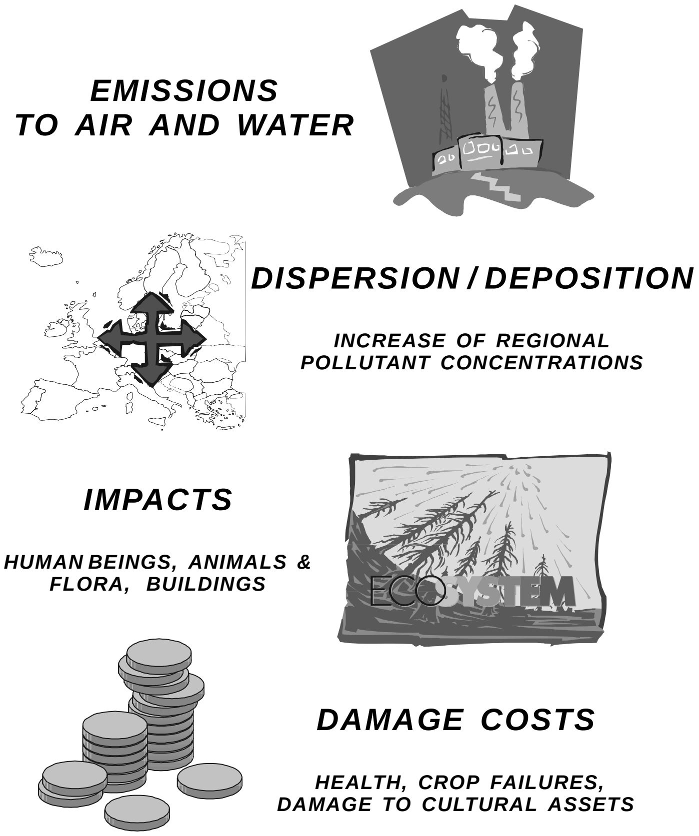

Fig. 5 Basic steps of the impact pathway approach.

The calculation process is site-dependent since the data and/or model used may be dependent on the location, and the aggregate impact is determined by the geographical distribution of receptors.

Apart from the public and occupational health effects (mortality, morbidity), environmental externalities that can be quantified using this approach include impacts on agriculture and forests, biodiversity effects, aquatic impacts (ground water, surface water), impacts on materials (such as buildings, cultural objects) and global impacts (greenhouse effect).

3.2.3 Severe Accidents Risk Assessment

In general terms by severe accidents we understand potential or actual accidents that represent a significant risk to people, property and the environment. A reasonably complete picture of the wide spectrum of health, environmental and economic effects associated with different energy systems can only be obtained by considering damages due to normal operation as well as due to severe accidents.

Of interest are accidents that might occur at fixed installations storing and processing hazardous materials, or when transporting such materials by road, rail, pipelines, open sea and inland waterways. Examples of hazards that need to be considered include fires, explosions, structural collapses and uncontrolled releases of toxic substances outside of the boundaries of the hazardous installations.

Here we address only the methods for the technical evaluation of risks associated with severe accidents. We recognize that public perception of risks, influenced by sociological and psychological aspects, had and continues to have a major impact on decisions. In the context of sustainability this aspect belongs to the social dimension.

Comparative analysis of severe accidents can be based on historical evidence, on Probabilistic Safety Assessment (PSA)[3], or on combinations of these. A full scope PSA consists of three levels of assessments. Level 1 deals with plant behaviour following a disturbance (accident initiator). Systems behaviour and interactions must be modelled, including operator interventions. This part of the study leads to an assessment of Core Damage Frequency (CDF) with associated uncertainties. The number of possible accident sequences can range into billions, but for each sequence the CDF is normally very small, so accident types are grouped by similarity in plant behaviour into a finite number of Plant Damage States (PDSs). These are further studied in the Level 2 PSA, which deals with post core damage response by the plant. Level 2 considers severe accident phenomena, and for each PDS, end states of the containment and possible releases of radioactivity to the environment are evaluated. These are normally reduced for the Level 3 assessment, which deals with offsite consequences, by considering the possible health effects of releases of radioactive substances within a manageable number of source terms. Figure 6 illustrates the framework of full scope PSA.

The need of introducing the probabilistic approach stems from some of the basic limitations of the retrospective analysis:

- In some cases there exists quite weak statistical evidence and very limited representation of the full spectrum of hypothetical accidents. A complicating factor is the heterogeneity of the available data in terms of technologies as well as with regard to the operational and physical environments in which they operate.
- Depending on the purpose (and object) of comparative analysis the experience-based data may not be applicable. Given large contrasts between the safety-related characteristics of the systems represented in the databases and systems being subject of the analysis, historical data may be questionable or even irrelevant.

As a result of recent efforts the basis for the technical comparison of severe accident risks associated with different energy chains has been significantly improved (Hirschberg et al., 1998, 2001 and 2003a; Burgherr et al., to be published). This applies in particular to the completeness of historical records, quality and consistency of the information, and coverage of various types of damages. Also applications of PSA are steadily growing, predominantly in the nuclear sector. For the purpose of comparative severe accident analysis the most comprehensive database ENSAD (Energy-related Severe Accident Database) has been established by PSI.

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[3] Probabilistic Safety Assessment provides a structured and logical approach to identify credible accident sequences, assess the corresponding likelihood, and delineate the associated consequences.

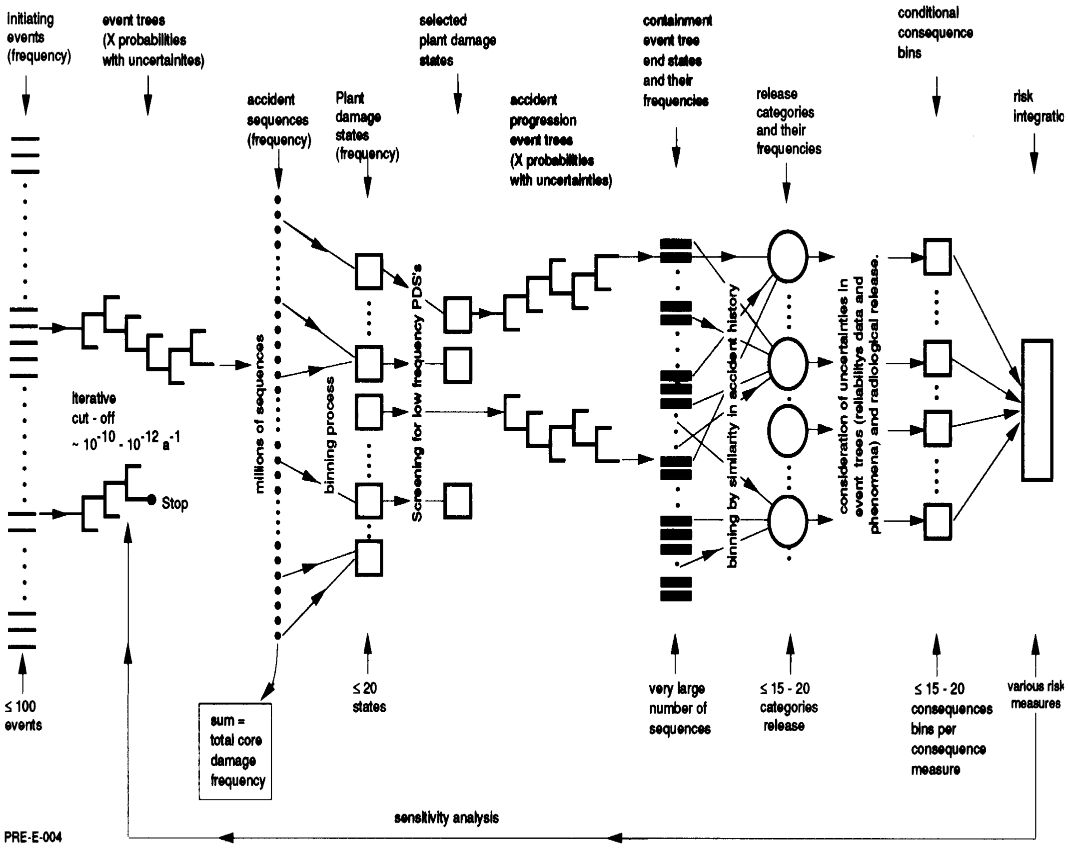

Fig. 6 Overview of a Probabilistic Safety Assessment (Cazzoli et al., 1993).

The scope of severe accident risk evaluation should cover all the relevant steps in full energy chains, as is the case with the impacts of normal operation. In fact, for some energy chains (applies to fossil cycles) these other steps may represent a much larger hazard than the power plant itself.

3.2.4 Energy-Economy Modelling

For energy economics the MARKAL models with the associated databases for the Swiss energy sector are used to study medium- to long-term structural changes on Swiss energy markets, to assess the importance of new energy technologies in meeting different policy goals, and to analyse the Swiss options to curb emissions of greenhouse gases as well as other air pollutants. MARKAL models minimize the cumulative costs of various energy policies while all candidate technologies of each energy market compete against each other for winning market shares. The energy-economy part is not focused on in the present report. However, the total costs of electricity production by different means, established by combining internal costs with the external ones (Hirschberg and Jakob, 1999), are one option that can be used as integrated measure of technology performance on economic and environmental criteria.

3.2.5 Dealing with the Future[4]

Particular attention is needed when dealing with the performance of concepts, systems or cycles to be implemented in the future. The LCA methodology has been originally developed and primarily applied for operating systems. Consequently, the input is normally based on experience and the standard approach is static. Therefore, applications to future systems require extensions, extrapolations and a number of additional assumptions based on literature, direct information from the industry and consultants, and on expert judgment.

For example, in (Dones et al., 1996) of particular importance was the input received from ABB on coal and gas power plant technologies, from BNFL and Cogema on some steps in the nuclear chain, and from a solar technology development company on photovoltaic. Availability of essential, LCA-specific process information and knowledge about the relative importance of the various sources of emissions made it possible to focus the analysis and economize the use of resources. The result driving parameters are: emissions, efficiencies, material intensities (for construction and operation), and transportation requirements. The relative importance of these parameters varies significantly between energy chains.

For nuclear technology, the most important expected changes towards improvements of ecological performance identified and evaluated were: reductions of long-term radon emissions from mine/mill tailings, reductions of electricity consumption in enrichment by replacement of diffusion by centrifuges or laser technologies, power plant improvements (particularly extended life time and increased burn-up), use of modern reprocessing facilities, reduced volume of conditioned radioactive solid wastes.

For electricity inputs needed for the LCA modules external to Switzerland, European mix for year 2010 was used, based on a forecast by the International Energy Agency. As compared to the current situation the mix reflects the expansion of gas, reduction of oil shares and a relatively small but significantly increased contribution of photovoltaic. Coal, hydro and nuclear remain at about the same level. Since the “new” systems generally show better performance and lower emissions than the “old” ones, assumptions needed to be made with respect to the specified market penetration of the “new” ones.

For impact and external cost analysis apart from new technologies also changes in number and distribution of receptors, in background emission patterns and in GNP per capita, need to be considered.

The future cost analysis also builds on literature studies and inputs from manufacturers. In addition, for systems currently having small market shares but large development potential, learning curves are used to account for improved economic performance given major increase in production volumes.

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[4] The present report only deals with current technologies. This sub-chapter is, however, provided here for the reasons of completeness and as guidance for possible future applications.

3.2.6 Rationale for Multi-criteria Decision Analysis

External costs estimates, if accepted by decision-makers, are highly attractive as directly comparative aggregated measures of environmental system performance. It has been proposed by some authors that the total (internal plus external) system-specific cost of energy production can serve as an integrated relative indicator of sustainability since it reflects the economic and environmental efficiency of energy systems (Voss, 2000). One objection to this proposition is that the social dimension, which plays a central role in the comparative assessment of energy systems, does not come to the surface when the systems ranking is purely based on the external costs. Taking the nuclear power as an example, issues like high-level long-lived radioactive wastes, hypothetical severe accidents or proliferation, contribute marginally or not at all to the estimated external costs. At the same time such issues remain controversial and, depending on the socio-political perspectives of those involved, can be of very high importance for the decision process. A number of criticisms of the cost-benefit analysis, including its extended version employing the so-called “contingent valuation” (used within the external cost accounting framework), were summarized in (Holland, 1997):

- Variety of ethical commitments regarding environment, not commensurable with each other or with individual and group interests;
- Environmental goods (and bads) are public goods (and bads), whose value cannot be adequately assessed on the individualistic basis;
- Market-based framework for eliciting values is incapable to recognise values of certain kinds and thus precludes their expression;
- Contingent valuation is an abstract and context-free instrument ill-suited for situated decision-making embedded in a special social context;
- Values are rarely “given” but need to be worked out and articulated in the decision-making process;
- Environmental values belong to the domain of citizen values rather than that of consumer preferences.

The multi-criteria approach acknowledges that the questions to be answered are partially beyond the “analytical fix”. Simultaneously, the application of multi-criteria decision analysis allows extensive use of the acquired knowledge on systems performance in a process that is also open to accounting for values. Using such a procedure one can arrive at different best performing options under various socio-political perspectives (Sterling, 1997).

4. MCDA METHODOLOGY AND APPLICATION BASIS

4.1 MCDA Approach and Methods

Multi-criteria analysis provides a framework that allows the often conflicting evaluation criteria to be addressed simultaneously. Full-scale implementation of such analysis requires the establishment of a systematic and transparent process, with interactions between analysts and decision makers. The actors participating in the decision process frequently disagree upon objectives, and also about assumptions in the treatment of data and/or in analytical methods. Past experience shows that the technical input to the policy debate may be deadlocked and the political process operates in a less informed context.

The core of our problem is to present to the eventual decision makers the outcomes of the complex analytical endeavour in such a way that they can readily grasp the material in relation to their own problems. In this context there are some broad subdivisions as, for instance, those between certain and contingent, between possible and desirable, and between what we can influence and what not.

To begin with, there must be a certain realm of actions the decision makers can take, if they want to, and which will affect the situation in a sense they want. The choice between these actions - usually called *alternatives* - is the decision to be taken; this choice is free by definition, because if there are any constraints, either they are accounted for as penalties or costs in a different part of the method, or that action is excluded from being a possible alternative. Whether they actually like to opt for a particular alternative, and if they have the will to carry that action through, are different questions, which *a priori* must be left out. Thus, it may be said that identifying the alternatives means to organize the ensemble of what is feasible, regardless of the consequences.

On the other hand, there will also be a realm of possible *future states* of the system, which is being considered (“possible worlds”). As opposed to the alternatives, the decision makers cannot influence which of these will eventually occur - otherwise, one would account for the ability to do so within the alternatives. At best one can establish some likely probability distribution about their occurrence.

A third realm is constituted by the *criteria* according to which one intends to value the events. This is a hard task for the decision maker, who must clearly identify the aspects that he thinks matter, without expressing his preferences yet. To each criterion there corresponds a scale of values, and it is only by choosing one particular value out of its scale for each criterion that he expresses his preferences.

Thus, within the process employing the multi-criteria analysis alternatives and criteria need to be selected and the available immense amount of technical information organized, structured, simplified and reduced. There are various decision-making procedures that help to structure the problem and to perform the evaluation in a controlled manner. Two groups of “decision philosophies” can be distinguished:

- “Platonic” approach assumes that there is a best decision and presupposes that the decision maker has a well established system of values so that he can completely rank any set of events; it is assumed that a majority vote will settle any dispute.

- “Aristotelic” approach intends to eliminate the least satisfactory choices, does not require a complete ranking and looks for a solution for which there is ample support with minimally strong opposition. This approach aims at constructing a formal system, which can aid anyone taking part in a decision process to understand, specify and model his preferences to increase the coherence of the process itself.

Which philosophy is to be used depends essentially on the partners who are taking the decision. The material to be prepared is in any case fairly the same independently of which method is the preferred one. Commercial software is available to support both groups of approaches.

In reality, the division between the various approaches is not as clear-cut as suggested above. Belton (1990) emphasizes the following points:

- Multiple criteria approaches seek to take explicit account of multiple, conflicting criteria in aiding decision-making.
- The principal aim is to help decision makers learn about the problem situation, about their own and others values and judgments, and through organization, synthesis and appropriate presentation of information to guide them in identifying, often through extensive discussion, a preferred course of action.
- The most useful approaches are conceptually simple and transparent.
- There is a skill in making effective use of a simple tool in a potentially complex environment.
- The process leads to better considered, justifiable and explainable decisions.

The application of MCDA involves the following steps (Hobbs and Meier, 1994):

1. Selection and definition of attributes, selected to reflect important p1anning objectives and/or environmental concerns. System cost, reliability, impact on rates, air quality impacts, or impact on fisheries are examples: in this step we select which of these will be used in an application, and precisely how they should be defined. There are many issues to be considered here, including the need to avoid proliferation of attributes, and to avoid double counting.
2. Definition of the alternatives to be analysed. Very often this also involves definition of alternative futures that capture factors over which utility planner have little or no control (such as natural gas prices, or the price of SO_2 a1lowances).
3. Quantification of the levels of the i attributes estimated for each of the j alternatives; this generally requires the application of some model to predict the impacts. Uncertainty and risk in attribute levels is quantified at this time.
4. Preliminary screening of alternatives. However, it is important that the options that remain for further analysis reflect a sufficiently diverse set of attribute values so that trade-offs can be examined in a meaningful manner. If, say, all ten plans that survive a preliminary screening exhibit very small differences in environmental impacts, it is not likely that environmental groups would accept the end-result.

5. Construction and analysis of trade-off curves.
6. Dominance analysis, in which an alternative is screened out if it is dominated by another option. An alternative is dominated if there exists another plan that is just as good in all attributes, and strictly better in at least one.
7. Scaling of attributes, in which the level of an attribute is translated into a measure of value (also known as an attribute value function).
8. Selection of weights for each attribute. There are a large number of different techniques to elicit weights, each of which has advantages and disadvantages. How questions are asked about individuals' preferences proves to be very important.
9. Determination and application of an amalgamation rule. Such rules combine the weights and value functions into a single overall value or ranking of the available options, which reduces the number of options for further consideration to a smaller number of candidates.
10. Resolution of differences between methods, and between and among individuals.

Even though the elements are presented in the form of a sequential list, in any actual application a certain amount of iteration between these steps will be necessary.

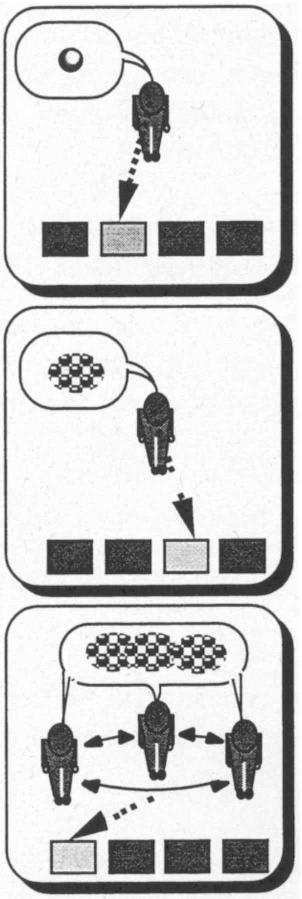
The two basic decision-aiding techniques are:

- **Multi-Attribute Utility Technique (MAUT).** The essence of this technique is to define a scoring scheme (or a multi-attribute utility function), measured on a scale between 0 and 1, with the property that if the score (or utility) is the same for two options there is no preference for one or the other. If however the utility for option i exceeds that for option j, then option i is preferred to option j. Such utility functions are established for each relevant factor (or attribute) and then aggregate in a total utility function representing the global interest for each option.
- **Multi-Criteria Outranking Technique (MCOT).** The aggregation techniques described above combine the evaluations according to a single figure of merit. Outranking techniques, instead of expressing the performances of each option in terms of a single overall figure of merit, compare each option i to every option j in order to evaluate whether option i outranks (or is preferable to) option j.

All methods, including outranking ones, seem to incorporate some method for obtaining a complete order. The drawbacks of MAUT include difficulties in exact specification of preferences of decision maker's, changes in the preferences, aggregation problems and the fact that decisions are seldom entrusted to a single procedure. The main merit of MAUT is its simplicity and transparency. Surveys of the methods come to the conclusion that no one method is consistently preferred by the users to others. Somewhat surprisingly, some of the popular outranking approaches perform quite badly in terms of the confidence of users in the results (e.g. Hobbs et al., 1992). There is a rather general agreement that careful tutoring and close collaboration between analysts and decision makers are more important to an application's success than which multi-criteria method is adopted. Furthermore, of critical importance is the quality and consistency of the indicators used for characterizing the performance of alternatives considered.

The case studies referred to in this report are based on the use of simple weighted sum approach. In all applications we emphasize the so called sensitivity mapping, i.e. understanding the sensitivity of ranking to specific patterns in users' preference profile and examination of the robustness of various options considered to variations in these profiles.

The methods described in the preceding section are straightforwardly applicable in multi-objective decision-making situations where the decision depends from only one, well-defined, "actor"[5] (see the general decision-making typology scheme of Fig. 7). In the case, very common in practice, where the decision-making takes place in both a multi-criteria and multi-stakeholder context, it is necessary to associate a negotiation component to these analytical approaches.



"One actor-one objective" model

One well-defined objective, one unique value system; problem easily detached from its context

Methodology: ***Expert Systems***

"One actor-multi-objective" model

One decision-maker only, at the top of the organisational hierarchy; the various "services" of this hierarchy may have different objectives, hut the stakes of the decision remain internal to the organisation

Methodology: ***Multi-criteria Analysis***

"Multi-actor-multi-objective" model

Different objectives, different value systems, different official "decision-makers", no hierarchical relationship between the opposing parties in a coexistence situation; problem cannot be detached from its context

Methodology: ***Multi-criteria analysis and negotiative process***

Fig. 7 Main decision-making contexts and typical associated approaches (adapted from (Simos, 1990)).

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[5] This could mean a unique physical person (enterprise responsible, administration responsible, etc.), but also, should the occasion arise, an homogeneous group sharing a unique value system (a group of individual persons can be considered as an unique "actor" if the rationality, value system, informational and relational systems of its various members have not to be differentiated).

4.2 Criteria and Indicators

4.2.1 Some Principles

Criteria and indicators are important to all statistical information systems. They serve as a mean for the description and communication and allow to present complex information in a relatively simple way.

An adequate set of evaluation criteria and indicators must itself fulfil a series of requirements and have certain characteristics:

To the extent possible, for *each criterion* there should be an *associated indicator*. This is quite straightforward, when considering criteria associated, for example, with economic performance of systems, but much more problematic – and controversial – in the context of social aspects.

Indicators should be *measurable and quantifia*ble (i.e. allowing interpretation) and logically independent (to avoid “double counting”). This requirement implies that a certain hierarchy (“decomposition”) of the criteria is necessary (and must be possible) to be able to distinguish between various effects and to quantify them.

The number of indicators must be *manageable*. Thus, a limit should be put to the aforementioned decomposition that should not become too fine. This is primarily driven by the necessity of simplifications for the interactions with users, stakeholders; from an analytical point of view, it would be possible to handle a much higher level of complexity.

Despite the limitation above, the selected criteria should be *inclusive,* i.e. no criteria should be excluded *a priori* only because in the eyes of individual evaluators they have low relevance; the stakeholders may have a totally different opinion. They should always have the option to drop certain criteria from the list or to disregard them by assigning a zero weight to them.

The *operationalisation* of the criteria calls not only for defining quantifiable indicators, but also for pragmatic definitions. *Simplifications* are necessary with view to currently available data, transparency and the nature of the specific application of the criteria list. If necessary, *complexity* can be increased at a later stage. This may be done by expanding the set of criteria or defining more representative indicators, or both.

It is not feasible to define a *unique set of criteria and indicators* that would be valid for all applications. Selection of a suitable set of sustainability criteria and indicators is highly dependent on the intended application (what question is to be answered). Given a clear definition of the goals many factors influence the choice. Evaluating various electricity supply options based on different fuels is a much different problem than trying to decide which alternative configurations of the nuclear fuel cycle are more economic, or sustainable. In the latter case, a more detailed distinction between the various nuclear-specific features becomes necessary.

The *structure* of the list of criteria may be dependent on the goals of the assessment, on particular issues that should be emphasized, on the tools used and on the way foreseen for interactions with the stakeholders (including the elicitation of preferences). It should be noted that the responses are not independent of the headings and the hierarchy used. Thus, the structure used for communication purposes has not to be identical with the one used in the assessment process.

Special difficulties associated with *non-quantifiable criteria* (e.g. those addressing social impact) must be recognized and spelled out. In several cases the scoring is subjective and may be not within the competence field of the analysts involved. The inclusion of such criteria and sub-criteria is also highly dependent on the goals and expected output of the evaluation. For most cases (unless for sensitivity purposes), it is not recommended to characterize “Social Acceptance” by a single (highly subjective) indicator. One could claim that for individuals such acceptance is binary (“go - no go”) and that political processes leading to decisions take full care of such criteria. Rather, one should attempt to introduce less subjective measures of social aspects, which can be quantified using transparent approaches.

4.2.2 Examples of Internationally Established Criteria and Indicator Sets

Energy has links with all three dimensions of sustainable development. Energy services are essential for economic and social development and improved quality of life. Energy demand will continue to grow, at the same time, energy production and use activities at present are responsible for major environmental degradation at all levels - local, regional and global. There are large disparities in the level of energy consumption among different countries; 1/3 of the world's population suffer from no access to electricity. While the depletion of the world's finite resources of energy is a long-term global concern, the continued uninterrupted availability of imported energy is an immediate concern for countries short of fossil fuel resources. Thus the provision of adequate energy at affordable costs and in a secure and environmentally congenial manner, in consonance with the social and economical developmental needs, is essential. The importance of these elements is quite obvious from the fact that, both, the energy sector and the energy related issues received particular emphasis in the programs for the further implementation of Agenda 21. This also explains the strong interest of international organizations to establish criteria and indicators for the energy sector.

There are many examples of criteria and indicators proposed by international organizations, particularly in the area of sustainable development. Here few representative examples are mentioned.

The United Nations (UN) created in 1992 a special Commission on Sustainable Development (CSD). The CSD established in 1995 the Work Programme on Indicators of Sustainable Development (WPISD) with the overall objective to provide decision-makers at the national level with indicators of sustainable development. The aim was to agree on a workable set of indicators by the year 2000 through a process of feed-back and revision. The WPISD produced a preliminary working list of 134 indicators, presented in a Driving Force- State- Response (DSR) framework. "Driving Force" indicators encompass human activities, processes and patterns that impact on sustainable development. "State" indicators refer to the status and "Response" indicators highlight policy options and other responses to foster sustainable development. Four different dimensions, namely the social, economic, environmental and institutional aspects, are covered. The indicators are arranged in a matrix that incorporates the three types of indicators horizontally and the four dimensions of sustainable development vertically. The indicators in the working list are intended as a core set to which other indicators, or sets of indicators covering particular aspects of sustainable development, e.g. to measure progress, may be added. The working list of indicators is currently being tested in 22 countries. Within the project work the 134 CSD indicators have been evaluated and finally 33 indicators have been selected to control the course of sustainable development. For this selection process international comparability, representative ness and availability of actual high quality data were taken as criteria.

The OECD three-year horizontal project on sustainable development was launched by OECD Ministers in April 1998. They called for the elaboration of the Organization’s strategy "in the areas of climate change, technological development, sustainability indicators and the environmental impact of subsidies". It aimed at making the sustainable development concept operational for public policies and at substantive outputs for the meeting of OECD Ministers in 2001, including a series of Background Reports, based on the work of various OECD Directorates and affiliates. The sustainable development framework referred to integration of economic, social and environmental factors in a way that will meet society's concerns at the lowest cost, and will highlight the linkages and trade-offs between these areas. Table 1 includes the core list of environmental performance indicators.

Table 1 Core List of OECD Environmental Performance Indicators (OECD/NEA, 2000).

Pollution Issues	
Climate Change	♦ CO_2 emission intensities
Ozone Layer Depletion	♦ Ozone depleting substances
Air Quality	♦ Air emission intensities
Waste	♦ Waste generation intensities
Water Quality	♦ Waste water treatment connection rate
Resource Issues	
Water Resources	♦ Intensity of use of water resources
Forest Resources	♦ Intensity of use of forest resources
Land Resources	♦ Changes in land use and in key ecosystems
Energy Resources	♦ Intensity of use of energy resources
Mineral Resources	♦ Intensity of use of mineral resources
Biodiversity	♦ Protected areas

Attempts have been made by the IAEA:

- to identify the main components to be addressed in connection with sustainable development, particularly in the energy sector;
- to derive a set of appropriate indicators for measuring and monitoring sustainable energy development;
- to determine the relationship between identified indicators and those in the CSD-list.

The Nuclear Energy Agency (NEA) recently proposed a set of sustainable development indicators for the nuclear energy sector. Table 2 provides a summary of the eighteen proposed indicators. Most of them are readily available in pub1ished nationa1 or intemationa1 statistica1 series, a1though some consistency checking and harmonization in units and reporting procedures might be necessary in order to ensure comparabi1ity across countries. The report (OECD/NEA, 2002) states that in some areas, e.g., waste volumes, a flexible approach might be needed at the beginning until consensus can be obtained on an agreed reporting system. In other areas, e.g., marginal production costs and INES, issues related to data confidentia1ity might need to be addressed before undertaking collecting and pub1ishing indicators under the OECD/NEA umbrella.

Table 2 Proposed list of indicators (OECD/NEA, 2002).

INDICATOR	**UNIT**
ECONOMIC	
Share of nuclear energy in total primary energy consumption	%
Total nuclear energy generation	TWh
Nuclear generation per capita	TWh/cap.
Average availability factor of nuclear units	%
Marginal production cost	USmill/kWh
ENVIRONMENTAL	
Natural uranium consumption	tU/year
Land requirements	km^2
Radioactivity released to the atmosphere by nuclear energy facilities	Bq/year
Radioactivity released to water by nuclear energy facilities	Bq/year
Volume of solid waste	m^3/year
Share of solid waste in interim storage	%
SOCIAL	
Employment in the sector	Person x year
Manpower cost in the sector	US$/year
Number of days of work lost by accidents on nuclear sites or professional illnesses	day/year
Work related fatalities in the nuclear energy sector	Number/year
Dose to workers	Sv/year
Fatalities in the public due to nuclear energy activities	Number/year
Number of accidents in nuclear facilities (INES)	Number/year

In summary, the national and international work on indicators for sustainable development is ongoing. The initiatives have been driven by global concerns about "the planet earth" and by demands of decision makers at countries' level being in charge of implementing the concept of sustainable development.

4.2.3 Criteria and Indicator Sets Proposed and Used by PSI and its Project Partners

As outlined before, whether a set of general or sector-specific indicators has to be chosen depends on the scope of the specific problem and the level of decision-making. As we want to support the assessment of policy choices in the energy sector and to follow and control technological developments, sector-specific rather than general indicators have been proposed.

The PSI approach started with a small set of basic principles resulting from a comprehensive definition of sustainable development that encompasses all three dimensions ("pillars"), i.e. economic, environmental and social aspects:

- "No" degradation of resources in the broadest sense,
- "No" production of "non-degradable" waste and
- High potential for robustness/long-term stability,

whereby "no/non" reflects the aim of being as small or as near to zero as possible. Each principle is related to a set of specific criteria and indicators, which aim at being representative rather than complete.

The following table contains a set of representative criteria and associated indicators selected to assess energy-related technologies under the constraints of sustainability. This set is the result of an iterative process, following discussions among scientists and taking problems experienced in quantifying the indicators into account The context is set to a large regional and global scale; the mid-term, i.e. the years 2020-2030 and beyond, are taken as orientation points. In applicable cases the indicators should be based on LCA and generally cover the full energy chain.

Table 3 Set of Principles, Criteria, Indicators and corresponding [Units] to evaluate energy-related technologies under the constraints of sustainability (Energie-Spiegel, 2000).

"No" degradation of resources

- Use of fuels: *depletion times* [*years*]
  Use of other materials: *amount (e.g. copper ore)*, [*kg/GWa*]
- Use of land: *surface to support normal operation*, [km^2/GWa]
- Effects on water: *Pollution (e.g. by zinc) or consumption*, [*kg/GWa*] or [m^3/GWa]
- Environmental impact through emissions:
  - *Amount of climate relevant gases*, [*t* CO_2 *equivalent/GWa*]
  - *Amount of gases damaging the ozone layer*, [*t CFC equivalent/GWa*]
- Impact on human health:
  - *Through normal operation,* [*years of life lost/GWa*]
  - *Through accidents / collective risk,* [*fatalities/GWa*]
- Impact on social aspects:
  - *Risk aversion: Land losses per accident,* [km^2]; *fatalities per accident* [-]
  - *Work opportunities,* [$\Delta py/a/GWa$]
  - *Proliferation threat,* [*qualitative*]
- Competitiveness: *internal and external costs,* [*currency unit/kWh*]

"No" production of non-degradable waste

- Produced amount, [m^3/GWa]
- Necessary confinement times, [*years*]

"No" high sensitiveness with respect to the environment

- Supply and disposal security:
  - *Foreign dependency,* [*qualitative*]
  - *Technology availability,* [*currency unit*]
- Robustness, i.e. no necessity for…
  - *...rapid external interventions,* [*hours*]
  - *...socio-political / financial stability,* [*qualitative*]

The criteria and indicators provided in Table 3 show to be useful for characterization of technologies and for communicating the results to decision- and opinion-makers. MCDA-based aggregation of indicators calls for modifications since some of the indicators used are overlapping (e.g. health effects and external costs).

The set of criteria and indicators used in the full analysis of the candidate technologies for the future electricity supply in Switzerland is shown in Table 4 along with the basic set of used weights.

Table 4 Structure of the Base Case: Criteria, indicators, evaluation basis for their quantification, units, and weights (Hirschberg et al., 2000).

1st level	W	2nd level (evaluation basis & unit)	W	3rd level (evaluation basis & unit)	W
Economy	1/3	Financial Requirements	70	Production Costs (Rp/kWh)	50
				Investment (power plant, SFr/kW)	25
				Fuel Price Increase Sensitivity (Increase of Production Costs due to Doubling of Fuel costs)	25
		Resources	30	Short-Medium Term Potential (Generation potential GWh/year)	40
				Availability (load factors)	15
				Geo-political Factors (estimation)	15
				Long-Term Sustainability (years)	10
				Peak Load Response (relative scale)	20
Health & Environment	1/3	Human Health Impacts	30	Mortality (EIA & LCA, Rp/kWh)	90
				Morbidity (EIA & LCA, Rp/kWh)	10
		Loss of Crop (EIA & LCA, Rp/kWh)	1		
		Impact on Materials (EIA & LCA, Rp/kWh)	4		
		Non Pollutants' Effects	5	Land Use (m^2/kWh)	
		Greenhouse Gases (LCA, gCO2-equiv/kWh)	30		
		Wastes	15	Volume (LCA, m^3/kWh)	
		Severe Accidents	15	Fatalities (RA, fatalities/kWh)	
Social Aspects	1/3	Employment (jobs per unit of energy)	20		
		Proliferation Risks (yes or not)	5		
		Local Disturbance (estimation per unit of energy)	25		
		Critical waste confinement time (years)	25		
		Risk aversion (maximum fatalities per accident)	25		

W = weight.

Finally, Table 5 provides the criteria used in the China Energy Technology Program (CETP) for the evaluation of electricity supply mixes in Province Shandong. These criteria were established with the project partners after interactions with major Chinese stakeholders.

Table 5A Criteria definition for CETP: Economy (Haldi and Pictet, 2003).

Nr	Name	Evaluation method	Definition	Unit	Preference direction	Data origin
1	Economy Class					
1.1	Average Cost of Electric Service	EGEAS	Inflation adjusted overall cost per unit of electricity produced by the mix of plants over the planning period	Yuan / kWh	Min	MIT
1.2	Total Electric Sector Investment	EGEAS	Total amount of Chinese money (inflation adjusted) that will have to be spent to implement the scenario (new plants, back-fitting of older plants, related infrastructures, etc.)	Yuan / GWh	Min	MIT
1.3	Fuel Transport Burden	EGEAS + expertise	Increase of fuel transportation burden over the planning period, expressed in: $[(\text{▯}tons \cdot km_{2024} - tons \cdot km_{2000}) / tons \cdot km_{2000}] \cdot 100$	%	Min	MIT

Table 5B Criteria definition for CETP: Health and Environment (Haldi and Pictet, 2003).

Nr	Name	Evaluation method	Definition	Unit	Preference direction	Data origin
2	Health and Environment Class					
2.1	Global Warming	LCA approach	Greenhouse gas emissions in terms of CO_2 equivalent (for 100 years time horizon)	kg CO_2 eq. / kWh	Min	PSI
2.2	Public Health Impact (Air Pollution)	Environ-mental impact assessment	Evaluation of the impacts of the major air pollutants on the public health; represented here by the resulting mortality [in years of life lost or, in short, YOLL]	YOLL / GWh	Min	PSI
2.3	Potential Health Impact due to Severe Accidents	Statistic & probabilistic approach	The evaluation on this criterion results of the combination of the two sub-criteria mentioned below	-	Min	PSI
2.4	Resource Consumption	LCA approach	Consumption by the technologies used of non renewable energetic resources related to their known recoverable resources world-wide, in tons (fast-breeders not considered)	%	Min	PSI
2.5	Wastes	LCA approach	The evaluation on this criterion results of the combination of the two sub-criteria mentioned below	-	Min	PSI
2.6	Land Use	LCA approach	Overall evaluation of the surfaces and types of land used (surface degraded from one type to a lower environmental quality one; not associated to wastes)	km^2 / GWh	Min	PSI

Table 5C Criteria definition for CETP: Sub-criteria for criteria 2.3 and 2.5 (Haldi and Pictet, 2003).

Nr	Name	Evaluation method	Definition	Unit	Preference direction	Data origin
Criterion 2.3 “Potential Health Impact due to Severe Accidents”.						
2.3.1	Potential Health Impact due to Severe Accidents: Expected Risk	Statistic & probabilistic approach	Expected fatalities that could result from potential severe accidents within considered energy chains	Expected number of fatalities / GWh	Min	PSI
2.3.2	Potential Health Impact due to Severe Accidents: Maximum Credible Consequences	Statistic & probabilistic approach	Maximum number of fatalities that could result from a credible accident in any part of a specific energy chain.	Maximum number of fatalities	Min	PSI
Criterion 2.5 “Wastes”						
2.5.1	Wastes: Amount of Wastes	LCA approach	Overall evaluation of the quantitative burden (total volume) of produced wastes	m^3	Min	PSI
2.5.2	Wastes: Confinement Time of Critical (hazardous) Wastes	LCA approach	Rough estimation (order of magnitude) of the necessary confinement time for critical wastes.	years	Min	PSI

Table 5D Criteria definition for CETP: Society and Technology (Haldi and Pictet, 2003).

Nr	Name	Evaluation method	Definition	Unit	Preference direction	Data origin
3	Society Class					
3.1	Impact on Employment	Expertise	(Net) number x time and quality (represented by the salary level) of domestic direct Chinese jobs created by the scenario implementation over the planning period	Yuan	Max	ABB
4	Technology Class					
4.1	Maturity of Technologies	Expertise	Electricity production weighted according to the maturity of the technology used, relative to the actual production	%	Max	MIT

The above criteria were applied only to electricity supply mixes. PSI constructed and used a separate set of criteria and indicators to be applied on the individual technology level. This set is reproduced in Table 6. It contains mostly similar elements as the set for mixes but exhibits also some differences. This set was used in the interactive tool Shandong Electricity Option Ranking (SEOR), developed within CETP by PSI as a part of the integrated CETP software supporting future decision-making. SEOR is based on MCDA.

Table 6 CETP Criteria for Technology Ranking (Hirschberg and Dones, 2003).

1. Cost of Electricity - Total cost, including capital, production, and overhead costs per unit of delivered electricity. *The higher the cost, the worse the performance.*
2. Resource Use - This criterion combines two aspects:
    - 2.1. use of non-renewable fuel resources, and
    - 2.2. competing uses of fuel besides electricity.

    This criterion is partially subjective, and therefore the scores of individual technologies can be modified by the users. The higher the score, the better the performance.
3. Greenhouse - Total greenhouse gas emissions from the full energy chain per unit of delivered electricity. It includes all major emissions using CO_2 equivalence factors. *The higher the emissions, the worse the performance*.
4. Health - Mortality from air pollution including SO_2, NO_x, and particulates. *The higher the effects, the worse the performance.*
5. Waste - Total mass of solid wastes (non radioactive and radioactive) per unit of delivered electricity. *The higher the amount, the worse the performance.*
6. Accidents – Expected fatalities from potential severe accidents per unit of delivered electricity. *The higher the number of fatalities, the worse the performance.*
7. Availability - This criterion accounts for three aspects:
    - 7.1. availability of power plant technology for domestic Chinese construction;
    - 7.2. availability of fuel in Shandong; and,
    - 7.3. power plant reliability.

    This criterion is partially subjective, and therefore the scores of individual technologies can be modified by the users. The higher the score, the better the performance.
8. Social - This criterion accounts for three aspects of social interest:
    - 8.1. aversion to risks from severe accidents measured by maximum fatalities of the potential largest credible severe accident;
    - 8.2. confinement time of critical waste; and,
    - 8.3. employment.

    This criterion is partially subjective, and therefore the scores of individual technologies can be modified by the users. The higher the score, the better the performance.

4.2.4 Criteria and Indicator Sets Used in the Present Study

For the purpose of the present study also some national sets of criteria and indicators were examined. Of particular interest is the set of Enquête Commission (Enquête Commission, 2002). It builds on the three dimensions of sustainability. The economic dimension includes internal, external and total costs; the ecologic dimension includes energetic and non-energetic resource consumption, acidification, eutrophication and global warming potential, and different types of wastes; the social dimension is covered by health effects (mortality).

The following conclusions were drawn from the criteria and indicator survey carried out for the purpose of the present study:

1. The indicators have different scope and focus: sustainable development in general, sustainable development of energy sector, sustainable development of specific energy carriers.
2. The sets of indicators originating from international organizations are not suitable for comparing sustainability attributes of major energy carriers, with appropriate differentiation between technologies.
3. Economic and environmental criteria/indicators are relatively well developed; social indicators are poor and highly subjective (in relevant cases).
4. Most of the sets are primarily based on directly available, simplistic indicators. There are major problems with consistency. Few efforts have been made towards aggregation of indicators to support decisions.

6. The sets of indicators originating from Enquête Commission and PSI sets used in the past exhibit a number of similarities but also 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. PSI’s set employed in the aggregation avoids use of overlapping indicators, which is not the case with most other sets.
7. A set of widely accepted, technology- and application-specific, harmonized numerical indicators is not available from earlier studies. A broad knowledge base is a prerequisite for the establishment of such indicators. The analytical framework that can serve as a basis for analyses leading to generating a relevant set of quantitative indicators has been employed in the present study.

Based on the survey results, experiences from sustainability assessments under radically different conditions encountered in Switzerland and in China, basic requirements on indicators, and discussions with ILK, a set of appropriate criteria and indicators was defined. Three dimensions of sustainability, i.e. Economy, Environment and Social, were considered. The table below provides the indicators selected for the evaluation of electricity generation technologies operating in Germany.

One comment is in place. Expected damages due to severe accidents, expressed in fatalities per unit of energy are under the environmental dimension. This seems to be an inconsistency. The reason is that a measure of accident-related environmental damage, which could be applied to all technologies in question, is hard to establish. Thus, mortality due to accidents serves here as a surrogate for the corresponding environmental effects.

Table 7 Criteria and indicators employed in the present study.

Dimension	**Impact Area**	**Indicator**	Unit
Economy	Financial Requirements	Production cost	*c/kWh*
		Fuel price increase sensitivity	*Factor**
	Resources	Availability (load factor)	*%*
		Geo-political factors	*Relative scale*
		Long-term sustainability: Energetic	*Years*
		Long-term sustainability: Non-energetic	*kg/GWh*
		Peak load response	*Relative scale*
Environment	Global Warming	CO_2-equivalents	*tons/GWh*
	Regional Environmental Impact	Change in Unprotected Ecosystem Area	km^2/GWh
	Non-Pollutant Effects	Land use	m^2/GWh
	Severe Accidents	Fatalities	*Fatalities/GWh*
	Total Waste	Total weight	*tons/GWh*
Social	Employment	Technology-specific job opportunities	*Person-years/ GWh*
	Proliferation	Potential	*Relative scale*
	Human Health Impacts (normal operation)	Mortality (reduced life-expectancy)	*Years of Life Lost/GWh*
	Local Disturbance	Noise, visual amenity	*Relative scale*
	Critical Waste Confinement	“Necessary” confinement time	*Thousand years*
	Risk Aversion	Maximum credible number of fatalities per accident	*max fatalities/ accident*

* Increase of production costs due to doubling of fuel costs

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

More details on the definitions and quantification methods will be provided in Chapter 5.

5. IMPLEMENTATION – REFERENCE SET OF INDICATORS

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, wind, solar photovoltaic). Whenever feasible, electricity generation technologies currently operating in Germany were selected as the reference. The calculations carried out are representative for the average performance characteristics for these technologies. The same applies to the associated energy chains. Also, representative load factors were employed. The set of indicators chosen for the evaluation reflects the fact that only current technologies are considered. For example, expansion potential, a critical attribute when considering realistic options for the future, has not been considered within the present evaluation, centred on the current electricity supply in Germany.

German-specific data were used directly when available and considered consistent with the overall framework. In few cases use of the Swiss data was relevant as the possible differences were judged not to be decisive. Whenever necessary, suitable adjustments of mostly the Swiss or UCTE indicators to the German conditions were made. Due to resource constraints some of these adjustments were by necessity relatively rough, which however is adequate for the purpose of the current study.

Technological features and special adjustments will be further commented in connection to the summaries of quantification of specific indicators, provided in the following. For more detailed descriptions of adopted indicators we refer to source references cited here. More details are provided for indicators, which have been subject of further developments in this work.

5.2 Economic Indicators

5.2.1 Financial Requirements

“Production costs” are based on German sources. These are typical costs and may not represent the exact average. It should be noted that the exceptionally low costs of nuclear energy are due to the fact that the capital cost component has been amortized. Back-up costs for wind and solar Photovoltaic (PV) are not accounted for. In the PV case its contribution to the overall supply is so small that there is no need for a dedicated back-up. For wind these costs are significant, i.e. depending on the local wind conditions range from 5 to 20% of the production cost (Voss, 2003). Current evaluation concerns technologies as such; would scenarios be analysed then the back-up costs would need to be automatically accounted for.

“Fuel price increase sensitivity” is represented by a factor corresponding to increase of production cost given 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 in view of the stability of countries of origin. The indicators are based on judgment and could be refined.

"Long-term sustainability: Energetic" is a measure of how long the resources of energy carriers will be available given that the current consumption would stabilize and only resources that can be exploited without substantial increase of electricity production prices are credited.

"Long-term sustainability: Non-Energetic" uses copper as a reference material. Other materials could have been used instead or in addition. Consumption of materials can also be viewed as an indirect measure of the efficiency of a system. The numerical values originate from *ecoinvent2000* (Dones et al., 2003, 2004).

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

5.3 Environmental and Health Indicators

All environmental indicators in this work are either LCA-based or LCA-philosophy has been followed (e.g. full energy chains are covered also in the case of severe accidents). Some comments on the specifics of the German conditions are in place.

All environmental inventories shown here for the average German and UCTE[6] solar photovoltaic have been recalculated from the available inventories for the current Swiss mix of 46% mono-crystalline and 54% poly-crystalline silicon slanted roof-top plants of 3 kW_{peak} capacity each, using a reference yield of 800 $kWh/kW_{peak}/a$ (Germany) and 1200 $kWh/kW_{peak}/a$ (UCTE), against 885 $kWh/kW_{peak}/a$ for Switzerland.

Average wind turbines in Germany are represented by 800 kW turbine with 20% capacity factor modelled in *ecoinvent* for average current European on-shore conditions, which closely reflects average conditions of wind turbines currently installed in Germany. The current (2002) mix of on-shore (98%) and off-shore (2%) electricity generation in Europe is considered for comparison.

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[6] Union for the Co-ordination of Transmission of Electricity. All figures shown herein refer to the Members Countries in year 2000, namely: Austria, Belgium, Bosnia-Herzegovina, Croatia, Denmark (associated member), France, Germany, Greece, Italy, Luxembourg, Macedonia, the Netherlands, Portugal, Slovenia, Spain, Switzerland, and Serbia and Montenegro. The CENTREL countries Czech Republic, Hungary, Poland, and Slovak Republic have officially joined UCTE in 2001. All figures for UCTE cover also German energy chains.

The hydro-mix for Germany has an 84% share of run-of-river and 16% share of reservoirs, whereas for UCTE it is 48% and 52%, respectively.

All environmental inventories calculated in the *ecoinvent* database for the German oil energy chain refer to old units operating for peak load supply. The average efficiency is therefore rather low (29%). In order to have a fair comparison with other fossil technologies all oil-specific environmental inventories have been corrected by a factor corresponding to the utilization of modern oil plants for base-load.

5.3.1 Global Warming

Global Warming caused by Greenhouse Gas (GHG) emissions represents the global environmental effects and is expressed in terms of *"CO_2-equivalents"* (for 100 years time horizon).

Figure 8 shows the GHG missions for average German and UCTE technologies and the associated stages of energy chains for year 2000.

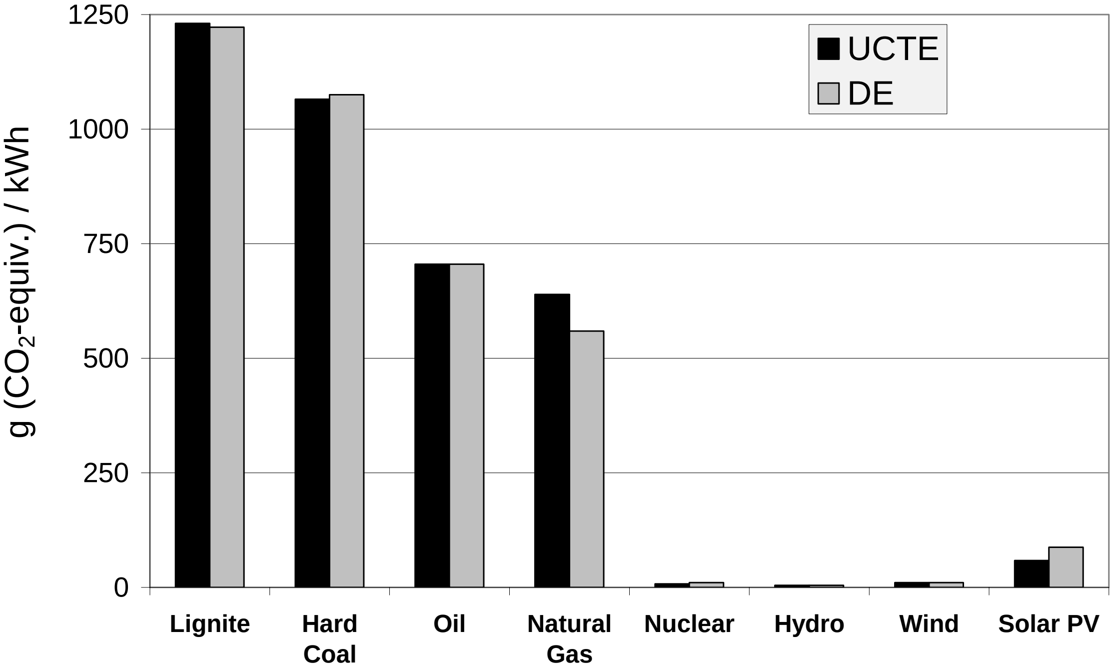

Fig. 8 LCA-based GHG emissions from German and UCTE energy chains in year 2000 (after Dones et al., 2004).

The differences for the natural gas chains are mostly due to the higher average efficiency of the recently constructed units in Germany. Besides, the differences in the composition of the origin of the gas for the two cases somewhat change the total methane leakage from long-range transmission pipelines.

5.3.2 Selected Pollutant Emissions to Air

Emissions of pollutants to air are not directly employed as indicators but are included here since they are used for the estimation of the regional environmental impacts and health effects. Figures 9 through 11 show SO_2, NO_x, and particle emission (particulate matter <2.5 µm and particulate matter >2.5 µm and <10 µm) for German as well as UCTE average technologies with associated energy chain stages in year 2000.

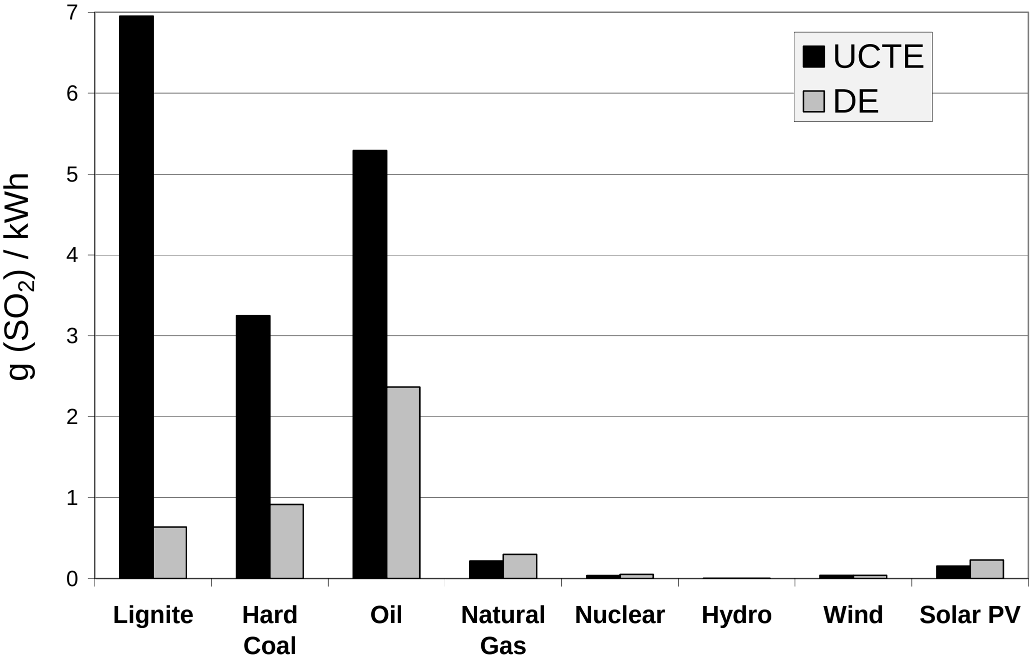

Fig. 9 LCA-based SO_2 emissions from German and UCTE energy chains in year 2000 (after Dones et al., 2004).

German hard coal power plants contribute approximately 75% to total emission of sulphur dioxide and approximately 60% to total nitrogen oxides from the coal energy chain. Fluidised gas desulphurisation is installed at all German coal power plants and de-NOx at almost all units. The average UCTE coal power plants show higher emissions of sulphur and nitrogen oxides, because not all units are yet equipped with appropriate pollution control systems. The average efficiency of electrostatic precipitators in German coal plants appears to be higher than for average UCTE coal plants.

German oil power plants contribute approximately 60% to total emission of sulphur dioxide and approximately 50% to total nitrogen oxides from the oil energy chain. Actual data for oil power plants show that specific emissions of sulphur and nitrogen oxides are smaller for German oil plants than for average UCTE plants.

German natural gas power plants contribute only 1% to total emissions of sulphur dioxide and approximately 60% to total nitrogen oxides emissions from the natural gas energy chain. NO_x emissions depend among other factors on the average efficiency of the natural gas plant, which is higher for the average German gas plant. Also the composition of the origin of the gas has an influence, because of the contribution of low efficiency turbines used for pumping the gas through long pipelines.

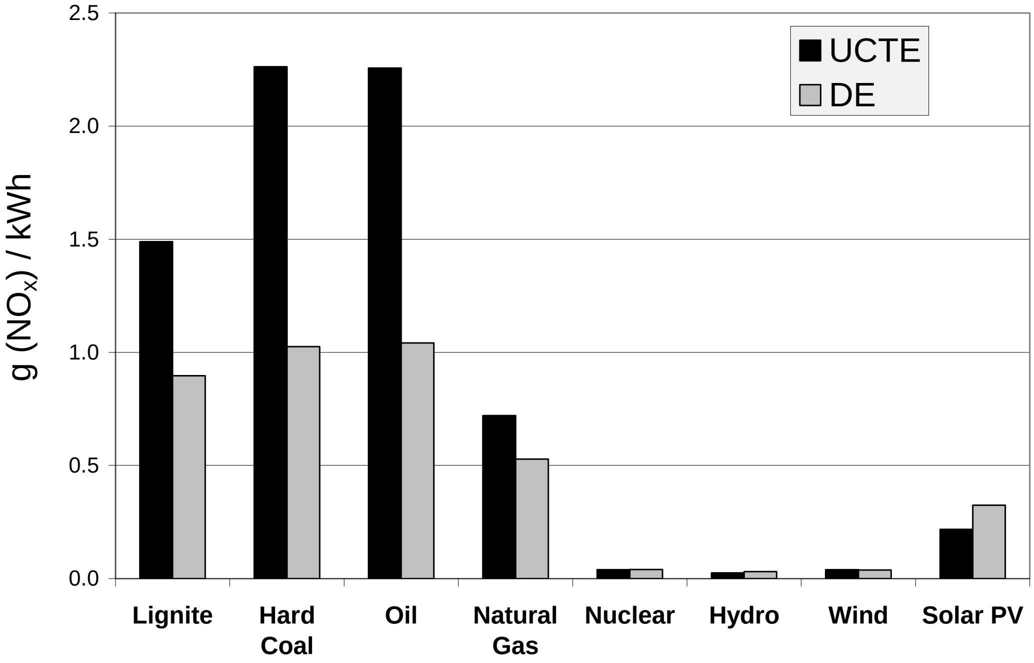

Fig. 10 LCA-based NO_x emissions from German and UCTE energy chains in year 2000 (after Dones et al., 2004).

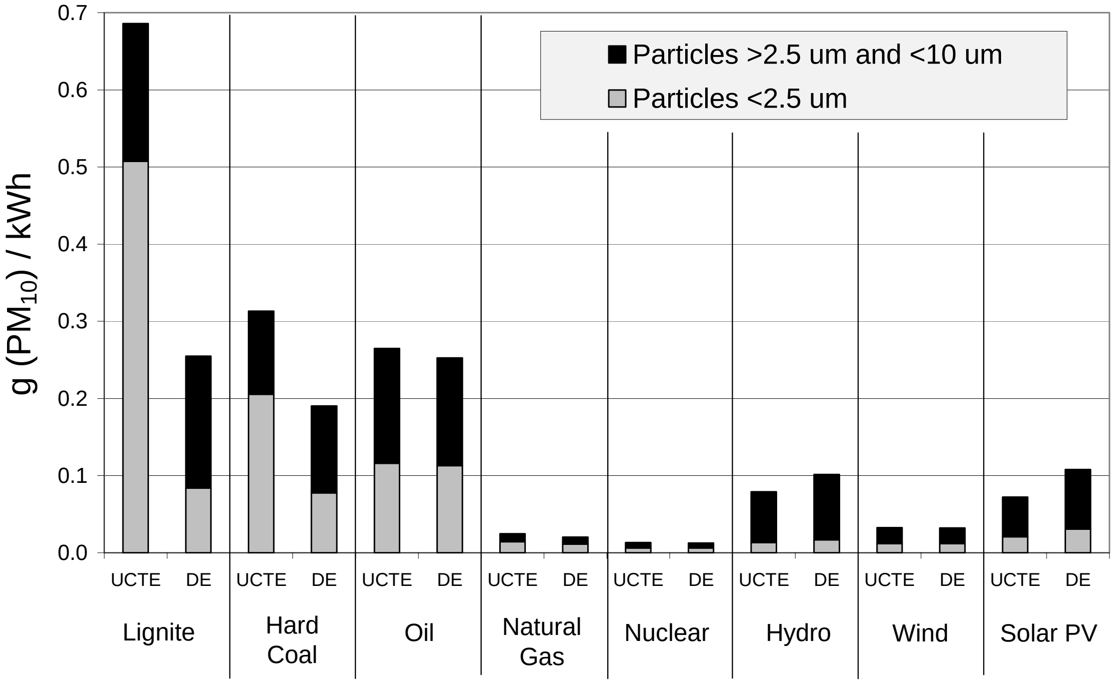

Fig. 11 LCA-based particulate matter emissions from German and UCTE energy chains in year 2000 (after Dones et al., 2004).

PM_{10} emissions from run-of-river plant construction are higher than for construction of dams.

Differences between the environmental inventories of the German and UCTE wind plants are negligible.

5.3.3 Solid Wastes

The indicator *"Weight"* refers to the total waste mass for each energy systems. This is the sum of several single species, disposed of as or in:

- 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 2500 kg/m^3)
- final repository for spent fuel, high and intermediate level radioactive waste (assumed approximate density 2300 kg/m^3)
- uranium mill tailings (assumed approximate density 2200 kg/m^3)
- low active radioactive waste in superficial or shallow depositories (assumed approximate density 2000 kg/m^3)

No weighting is applied here to account for the potential harm of each waste type.

The ecoinvent database considers emissions from depositories to groundwater but not for all species of wastes, due to lack of sufficient scientific information and highly uncertain modelling. Therefore, the long-term environmental flows to groundwater are not yet consistently treated for all industrial processes and cannot be considered as the ultimate indicators of harm. Although the weight of waste may be misleading as indicator when used in isolation, it is still a physically understandable item.

The *"necessary confinement time"* of the most hazardous waste, has been included among social indicators. It can be seen as a complementary attribute to the mass, implicitly encompassing the potential harm from waste management. If LCA studies in the future will address the long-term emissions to groundwater fully and consistently across all modelled industrial activities, the indicators used herein might be substituted by others, covering emissions to groundwater.

Figure 12 shows in graphical form the waste masses for the assessed energy technologies with associated chains for Germany. These are compared again with the average values for the corresponding UCTE chains for year 2000. Oil UCTE, which has not been modelled explicitly, is here approximated by the relevant modules for Italy.

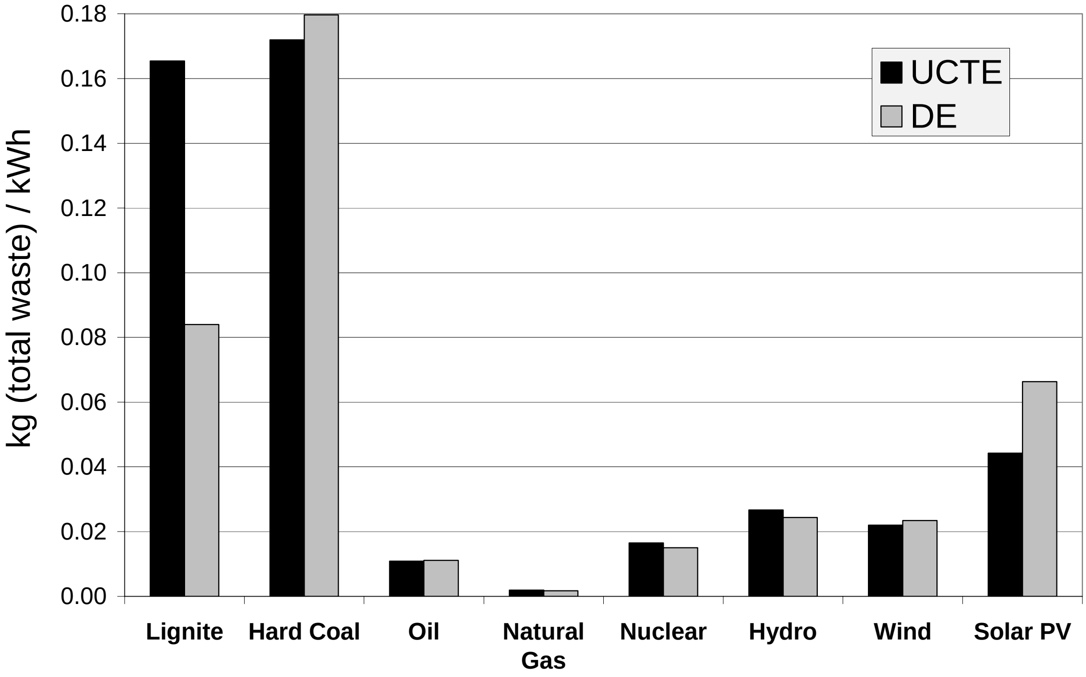

Fig. 12 LCA-based solid wastes from German and UCTE energy chains in year 2000 (after Dones et al., 2004).

The bulk of the total solid waste mass for lignite energy chains is made of the ash from power plant operation, 93% for Germany and 97% for UCTE. Average lignite plants in UCTE show a much higher total mass of waste than for German plants, due to about the double amount of lignite ash disposed of in open cast refill, i.e. in UCTE there is no or much less partial recycling, extensively applied in Germany.

The specific (per unit of kWh) amount of waste from the energy chain associated with German hard coal power plants is dominated by the waste at coal mines (over 95% of total), because all ash from power plant operation is assumed to be recycled in the construction industry. For UCTE, the specific coal mining waste is lower due to the different contribution portfolio from the eight modelled supplying regions, which is somewhat compensated by the lower recycling rate of ash to give approximately the same total amount.

5.3.4 Land Use

This indicator expresses the total *"Land use"* for each energy chain. This corresponds to the sum of different land types, as they have been categorized in ecoinvent according to their transformation from one more or less natural status into one of the following:

- transformation to dump
- transformation to industrial area
- transformation to traffic area
- transformation to reservoir (for hydropower)

Areas at bottom of seas, relevant for the case of gas/oil offshore platforms or offshore wind parks, are here excluded. They were, however, accounted for in ecoinvent.

Figure 13 shows the land use for the assessed energy technologies with the associated chains for Germany. These are compared again with the average values for the equivalent UCTE chains for year 2000. Oil UCTE, which has not been modelled explicitly, is here approximated by the relevant modules for Italy.

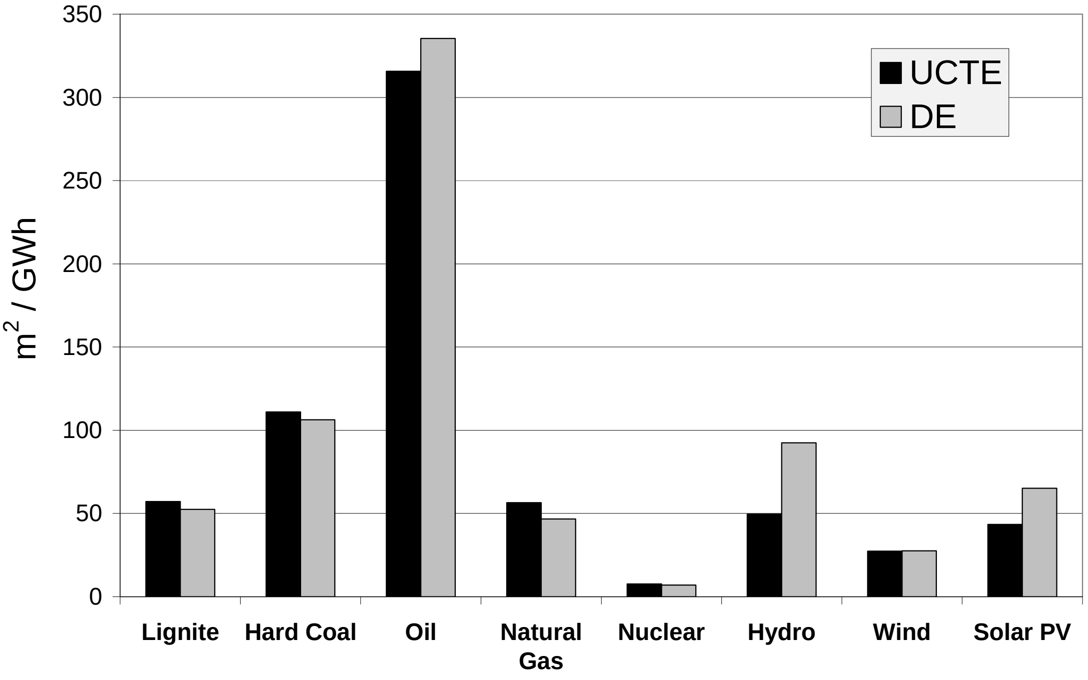

Fig. 13 LCA-based land use for German and UCTE energy chains in year 2000 (after Dones et al., 2004).

The differences between hard coal chains are mostly due to the different surfaces used for dump at coal mines in the various coal supply regions. The difference for hydropower depends on the shares of reservoir and run-of-river plants, where the specific (per unit of energy) land use is higher for the latter; this is due to several reasons including the assumed shorter lifetime of run-of-river plants. The roof-top areas taken by the solar PV panels are not accounted for as land use. The differences calculated for total land use for solar PV are due to the different electricity yields in the two considered cases.

5.3.5 Impact Pathway-based Indicators

This sub-section describes the methodology used here for the estimation of human health impacts due to normal operation (represented by *"Mortality"*, i.e. reduced life expectancy", which in the present structure belongs to the social indicators), and for the assessment of regional environmental impacts (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 (European Commission, 1999), shortly described in Chapter 3. Updates of impact functions and valuation factors have been taken into account (Friedrich and Bickel, 2001). 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 (European Commission, 1999, Krewitt et al., 2001) that environmental impacts due to regional pollutants strongly depend on the location of the emission sources. Traditionally, Life Cycle Impact Assessment (LCIA) does not consider site-dependent effects. A new method has been applied in this study in order to include site-dependent effects and to improve the combination of EIA and LCA.

A problem for site-dependent LCIA is the consistent application of impact factors through the full 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 chain because the module may be 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 to trace all such spatial mismatches between definition and application of a module in the *ecoinvent* database. Therefore, a mapping between site-specific impact factors and chain modules has to be made 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. By contrast, most production and transport processes have been modelled only for Switzerland (and few other countries), or/and RER (Europe) or GLO (Global). The application of e.g. a Swiss production module within the chain may not necessarily reflect the emission location but possibly might serve as a substitute because 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 diameter 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 excluded; in total the contributions of these emissions in the energy chains are very small. Following the recommendations in ExternE (European Commission, 1999), the PM_{10} functions have been applied to all primary PM_{10} without differentiating the included $PM_{2.5}$ fraction. This complies with the recommendations in ExternE (European Commission, 1999) for power plants but might lead to a slight underestimation of impacts due to transports in the chain. The error is considered small in the present context.

Simplifications: It was not possible within the limited framework of this project to include all site-dependent effects in the full chain. This would be equivalent to a full implementation of the method. The energy systems refer 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 where included for the German electricity sector (for which *ecoinvent* provides country-specific data), and applied within the full chain of all systems. The emissions outside of Germany have been treated with standard impact factors for Europe. The present prototype implementation does not differentiate between high population and low population density areas within the countries because for the important secondary pollutants there is no simple general correlation between emissions in high/low population density areas and extent of impact and thus the corresponding factors are not yet established.

For all electricity chains under consideration, mortality impacts have been calculated in terms of Years of Life Lost (YOLL). Mortality is the major contributor to total external costs. The 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.

Table 8 shows factors for the impact “mortality” in terms of Years of Life Lost for different countries and different locations within countries. It can be seen clearly that the specific YOLL factors depend strongly on the location of the emission source.

Figure 14 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.

Table 8 Comparison of different countries and locations – Mortality risk in terms of "Years of Life Lost" (YOLL) resulting from the emission of one kilo-ton of pollutant (Reference years 1990/1998) (Hirschberg and Heck, 2002).

		YOLL per kt of SO_2 due to exposure to SO_2	YOLL per kt of SO_2 due to formation of sulfate aerosols	YOLL per kt of NO_x due to formation of nitrate aerosols	YOLL per kt of PM_{10} due to exposure to PM_{10}
Zurich CH	(a)	3.3	53.0	77.0	87.0
Beznau CH	(a)	3.4	57.7	75.4	68.2
St.Gallen, CH, countryside	(a)	2.7	45.9	64.5	66.1
Austria	(b)	2.1	36.8	44.0	56.5
Belgium	(b)	3.2	39.2	32.4	92.7
Denmark	(b)	0.9	17.0	20.0	22.4
Finland	(b)	0.3	7.0	7.8	6.0
France	(b)	2.3	40.0	51.4	62.9
Germany	(b)	2.2	31.6	27.9	68.6
Greece	(b)	0.8	24.3	33.8	32.6
Italy	(b)	1.5	27.3	34.6	48.0
Ireland	(b)	0.7	12.7	17.8	17.1
Netherlands	(b)	2.8	34.9	27.4	61.0
Portugal	(b)	0.9	17.4	21.7	24.4
Spain	(b)	0.9	21.7	27.8	33.0
Sweden	(b)	0.4	9.6	11.5	7.3
UK	(b)	1.8	21.1	17.5	40.4
EU-15	(b)	1.7	27.0	28.5	56.7
China average	(c)	5.2	190.8	143.1	110.3
Shandong Province (China)	(c)	8.4	312.3	225.2	211.3
Shanxi Province (China)	(c)	8.3	305.3	161.0	185.9
South America average	(b)	0.34	4.9	6.8	16.3
Brazil	(b)	1.2	13.3	10.9	16.4
State of Sao Paulo	(b)	3.9	38.5	52.5	39.9
Colombia	(b)	0.33	3.6	6	5.5

(a) Hirschberg and Heck, 2002.
(b) Krewitt et al., 2001.
(c) Hirschberg et al., 2003b.

As basic indicator for damages of ecosystems, the change of unprotected ecosystem area due to acidification and eutrophication is considered. Factors per unit emission of SO_2 and NO_x for acidification and eutrophication have been calculated for the years 1990 and 2010 in (Krewitt et al. 2001). SO_x and NO_x both contribute to acidification, NO_x also causes eutrophication. Factors for ammonia are neglected here because 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 here that the changes of unprotected areas due to acidification and due to eutrophication are approximately additive. The resulting indicator is the total change of unprotected ecosystem area per unit emission for each country (Table 9). In contrast to conventional LCIA methods, the different effects due to different locations of the emission sources can be accounted for as far as the locations in the chain are identifiable (site-dependent LCIA). It is recommended to use the 1990 estimates in order to avoid additional uncertainties because of the projection to 2010.

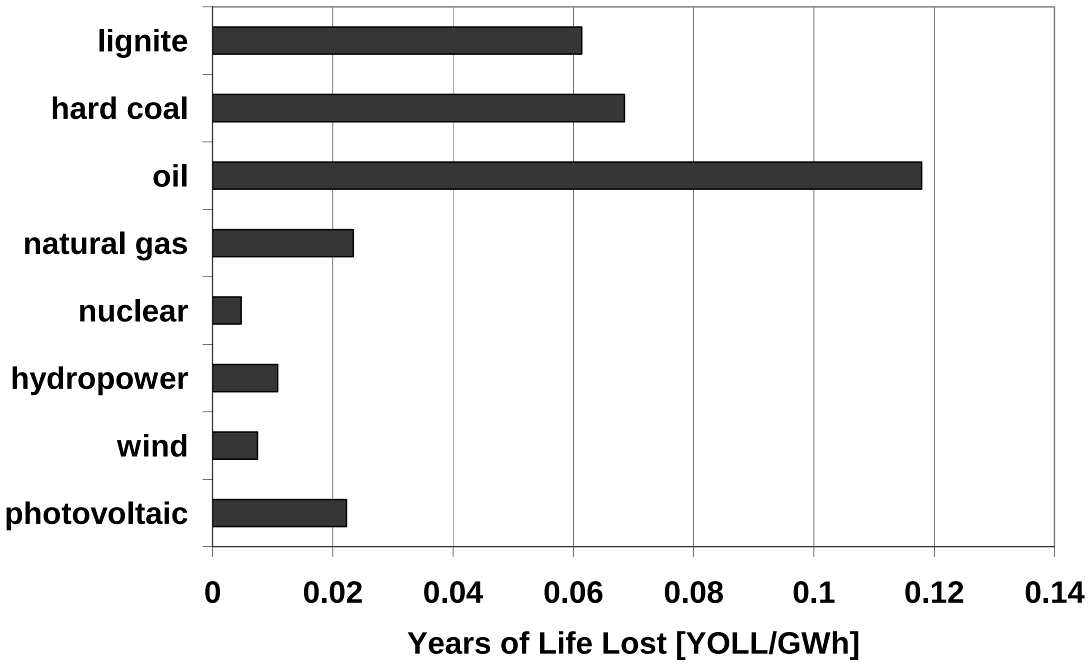

Fig. 14 Mortality associated with normal operation of German energy chains in the year 2000.

It could be objected that the assumption of additivity may lead to an overestimation of the unprotected area. But because eutrophication is caused by NO_x only (within emissions relevant here), a strong overestimation would result in a relatively high ratio of damages per ton NO_x compared to damages per ton SO_2. A comparison with damage factors in eco-indicator 99 (Pre, 2000) in Table 10 shows that this seems not to be the case. The sum of acidification and eutrophication for NO_x in (Krewitt et al. 2001) still yields a lower NO_x/SO_2 effect ratio for EU-15 average, for Germany and for most other countries than the estimate in eco-indicator 99 (Pre, 2000). (Pre 2000 gives only one global factor for all countries, as customary in traditional site-independent LCIA. The unit used in eco-indicator 99 for ecosystem damages is the PDF (Potentially Disappeared Fraction)[7] of plant species times area times year; acidification and eutrophication effects are summarized therein; values are derived from PDF for Netherlands). Therefore it seems justified to sum acidification and eutrophication factors in order to get a single site dependent indicator "change in unprotected area" as a pragmatic approximation. This also avoids the problem of weighting acidification against eutrophication in MCDA.

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[7] PDF = Potentially Disappeared Fraction (of plant species). "The probability that a plant species still occurs in an area can be determined. This is called the Probability of Occurrence or POO, which is translated for this project into Potentially Disappeared Fraction (PDF): PDF=1-POO" The unit for the damages to Ecosystem Quality is the PDF times area times year [m^2-yr] (Pre, 2000).

Table 9 Acidification and eutrophication - change in unprotected ecosystem area per unit emission (km2/kt) for emissions from different countries and EU-15 average, assuming that the effects are additive. Derived from (Krewitt et al., 2001).

	Change in unprotected ecosystem area (km^2/kt)			
	SO_2		NO_x	
	1990	2010	1990	2010
Austria	31.7	15.9	28.6	42.1
Belgium	8.8	12.1	13.4	23.4
Denmark	33.3	30.8	44.3	21.9
Finland	111.8	47.7	128.3	218.2
France	12	16.6	18.9	39.4
Germany	17	51.6	23.8	53.2
Greece	1.4	0	18.6	23.6
Ireland	9.4	5	23.7	16.6
Italy	12.8	7.3	24.7	38.9
Netherlands	10	12.9	22.3	26
Portugal	0.2	0.4	28.6	42.6
Spain	2.3	3.5	23.9	38.7
Sweden	60.5	53.7	63.7	51.6
UK	8.5	19.6	12.6	22.3
EU-15 average	13.1	18.8	26.1	49.6

Table 10 Ecosystem damage per unit emissions according to eco-indicator 99 (Pre, 2000).

	ecosystem damage in PDFm^{2}yr per kg		
	SO^2	NO^x	Ammonia
100% deposition in natural areas	1.73	9.52	25.94
60% deposition in natural areas	1.04	5.71	15.56

Another issue is the fact that the linear functions proposed above have been derived from threshold functions for acidification and eutrophication (critical loads and critical levels). In the original critical load concept, effects are assumed to occur only above a certain threshold. Below this threshold, the effect is assumed to be zero. This leads to discontinuous impact functions. By contrast, the simplified approach discussed above sticks to the concept of marginal change using equivalency factors which connect an arbitrarily small change of emissions proportionally to a small change of impact. The issue has been discussed in (Heijungs and Huijbregts, 1999) without an ultimately satisfactory solution as the authors admit. The position here is that a simple marginal approach is used because it suits the LCIA needs whereas a full threshold function approach has been considered impractical for LCIA (Heijungs and Huijbregts, 1999).

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 accidents are, however, treated separately.

This section builds on the work carried out by PSI (Hirschberg et al., 1998; 2000; 2003a; Burgherr et al., to be published). The assessments cover fossil energy sources (coal, oil and gas), nuclear power and hydropower.

Significant effort has been directed towards the examination of the relevance of the worldwide accident records to the Swiss-specific conditions, particularly in the context of nuclear and hydropower. For example, a detailed investigation of large dam failures and their consequences was carried out. This includes a study of the dependency between the frequency of dam failures on the one hand, and the types of dams and their purposes on the other. Generally, while Swiss-specific aspects were emphasized, the major parts of the collected and analysed data, as well as the insights gained, are of general interest. In particular, three sets of the aggregated results of the evaluation of the past experience have been provided, i.e. one based on worldwide occurrence, one valid for OECD-countries, and one for non-OECD-countries. The generic results obtained for OECD are for the purpose of comparative assessment considered to be representative for Switzerland. For fossil fuels allocation schemes were developed, taking into account the flows of these carriers between OECD- and non-OECD-countries.

A comprehensive database on severe accidents, with main emphasis on the ones associated with the energy sector, has been established by the Paul Scherrer Institute (PSI). ENSAD (Energy-related Severe Accident Database), which covers all stages of the analysed energy chains, has been developed using a wide variety of sources. This includes among others: major commercial and non-commercial accident databases, journals, newspapers, technical reports, encyclopaedias, relevant books and conference proceedings, and inputs from numerous direct contacts with persons and organizations being in a position to provide crucial information on past accidents.

The base version of ENSAD was established in 1998 and has been recently much extended by implementing the recent results of PSI's work within the China Energy Technology Program (Hirschberg et al., 2003a) and within the ongoing EU Project NewExt (Burgherr et al., to be published). Of particular significance is that the unsatisfactory coverage of coal accidents in China has now been improved. Due to the use of a variety of information sources ENSAD exhibits in comparison with other databases a much more extensive coverage of the energy-related accidents. Furthermore, the coverage is well balanced with respect to countries and regions where the accidents took place.

The evaluations of severe accident frequencies and their consequences were first carried out for each energy carrier covered in this work. These results were then used for comparisons between the various energy sources. The comparisons concern the electricity sector, although within the gas chain also the Liquid Petroleum Gas (LPG) was included. The results were normalized on the basis of energy production by means of each of the sources covered.

As opposed to previous studies the ambition has been, whenever feasible, to cover a relatively broad spectrum of damage categories of interest. This includes apart from fatalities also serious injuries, evacuations, land or water contamination, and economic losses. It is, however, acknowledged that the completeness and consistency of the coverage of these categories varies significantly between the different sources. Here only the results concerning fatalities are reproduced as they are most complete and consistent, and have been used in the present study.

Significant differences exist between the aggregated, normalized damage rates assessed for the various energy carriers. One should, however, keep in mind that from the absolute point of view the fatality rates are in the case of fossil sources small when compared to the corresponding rates associated with the health impacts of normal operation. For this reason the evaluation focuses here on the relative differences between the various energy carriers.

Figure 15 shows the fatality rates for the various energy sources. The results presented in this paper distinguish between OECD and non-OECD countries.

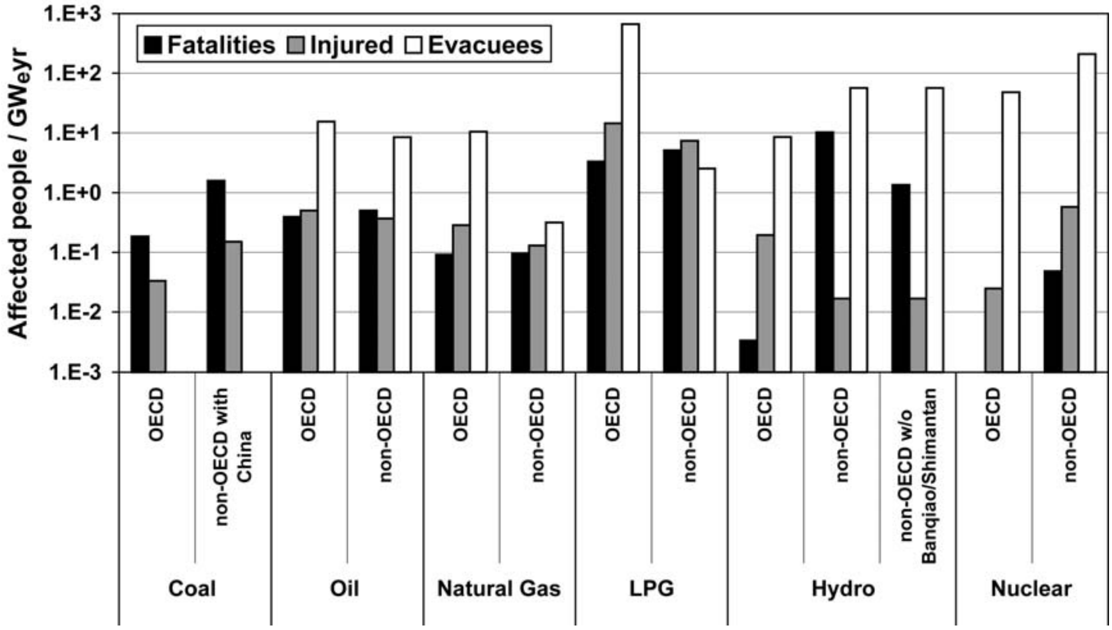

Fig. 15 Severe accident immediate fatality-, injury- and evacuee-rates for immediate fatalities in major energy chains for OECD and non-OECD countries), based on time period 1969 – 2000 (Burgherr et al., to be published).

Damage indicators per unit of energy were estimated employing reallocation of an appropriate share of damages in non-OECD countries to OECD countries, taking into account imports of fossil energy carriers from non-OECD countries. Note that only immediate fatalities were considered, but latent fatalities, of particular relevance for the nuclear chain, are commented in the text below.

It is important to emphasize the differences in the extent of the statistical material available for the different energy sources. While the historical experience with severe accidents is extensive in the case of fossil energy chains, the statistical evidence available for severe nuclear accidents resulting in fatalities is limited to one accident. Also for hydropower the statistical basis is relatively poor.

The broader picture obtained by coverage of full energy chains leads on the worldwide basis to aggregated immediate fatality rates being much higher for the fossil fuels than what one would expect if power plants only were considered.

Generally, the immediate fatality rates are for all considered energy carriers higher for the non-OECD countries than for OECD countries, though the differences for fossil fuels are smoothed by partial reallocation. In the case of hydro and nuclear the difference is in fact dramatic. For comparison, representative PSA-based results obtained for nuclear power plants in Switzerland and in USA show latent fatality rates typically of the order of 0.01 per GW_eyear. The corresponding immediate fatality rates are practically negligible. Due to the Chernobyl accident, nuclear compares, however, more unfavourably to other chains when the experience base is considered for non-OECD countries only. Chinese coal chain, exhibits severe accident fatality rates about 50 times higher than the corresponding rates in OECD.

In the particular case of accident indicators, 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 the Swiss nuclear power plant Mühleberg were employed as the starting point 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.

The presentation of results is not limited to the aggregated energy chain specific values. Also frequency-consequence curves are provided. They reflect implicitly the above ranking but provide also such information as the observed or predicted chain-specific maximum extents of damages. This perspective on severe accidents may lead to different system rankings, depending on the individual risk aversion.

Figure 16 shows the curves based on the historical experience as represented in ENSAD and on PSA for the Swiss nuclear power plant Mühleberg. The curves for coal, oil, natural gas and hydro chains are based on historical accidents world-wide in the period 1969-2000 and show immediate fatalities. The results for the Swiss nuclear power plant Mühleberg originate from the plant-specific Probabilistic Safety Assessment (PSA) and reflect latent fatalities.

Figure 17 shows the corresponding results for non-OECD. For the nuclear chain the immediate fatalities are represented by one point (Chernobyl); for the estimated Chernobyl-specific latent fatalities lower and upper bounds are given. The results shown in Fig. 17) were used in the present study to establish *“Maximum credible number of fatalities per accident”* as a measure of risk aversion.

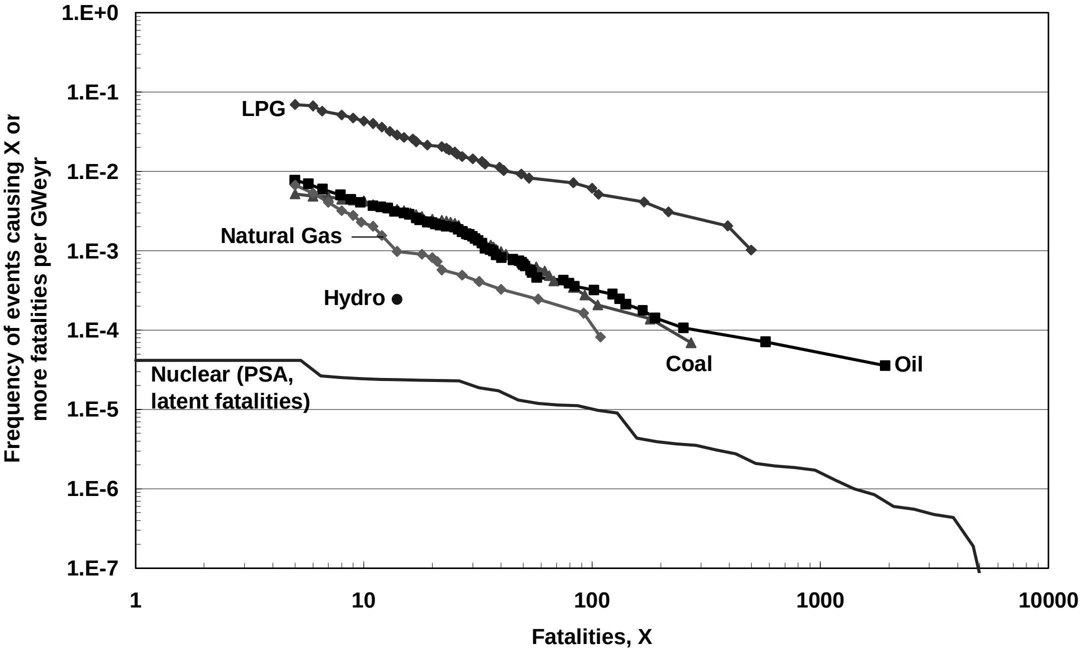

Fig. 16 Frequency-consequence curves for full energy chains in OECD with allocation and for the time period 1969 – 2000 (Burgherr et al., to be published).

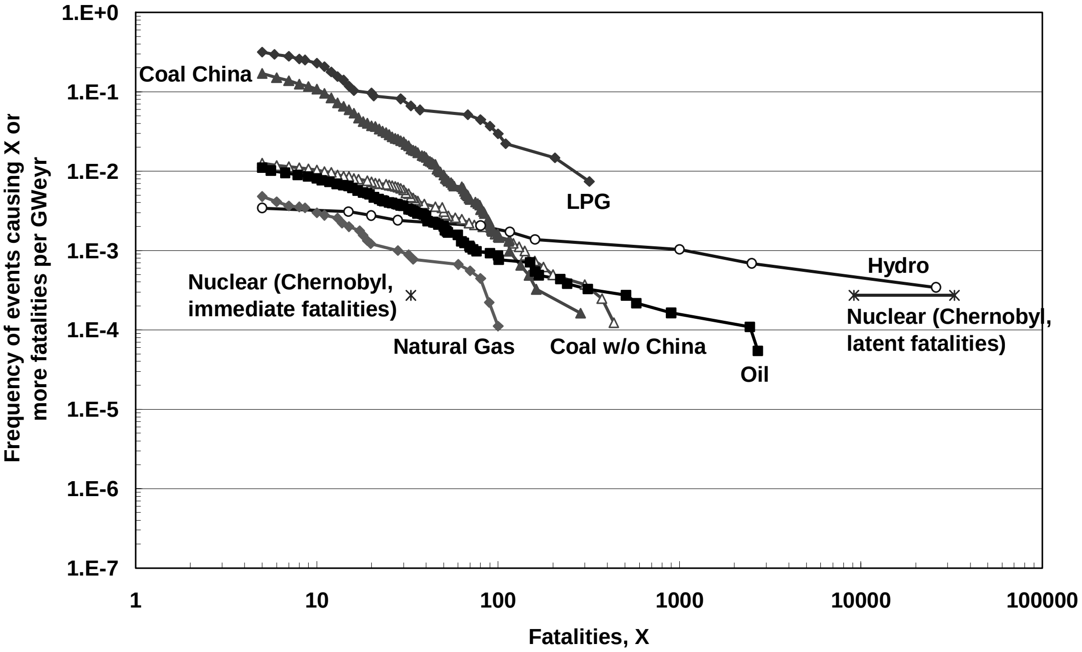

Fig. 17 Frequency-consequence curves for full energy chains in non-OECD with allocation and for the time period 1969 – 2000 (Burgherr et al., to be published).

The limitations of the approach used for the evaluation of severe accidents are related to the database (completeness and recording accuracy, quality, use of historical data), to uses of probabilistic techniques (intrinsic and practical limitations), and to the scope of the present approach (e.g. coverage of current technologies only, risk perception/aversion treated rather roughly).

5.4 Social Indicators

5.4.1 Employment

The purpose of the technology chain labour assessment was to estimate the life cycle labour content of eight technology chains for electricity generation, including lignite pulverized coal, bituminous pulverized coal (hard coal), oil-fired, natural gas-fired, hydro power, wind power and solar PV generation. In order to do this, each chain was divided into four components, including 1) Fuel Extraction and Processing, 2) Fuel Transportation, 3) Generation Plant Construction, and 4) Generation Plant Operation.

It is difficult to find hard data to establish accurate, average labour statistics for these technologies across the entire German electricity sector. National electric sector associations (VDEW and VDN) do not collect employment numbers by fuel or type of plant. The only official number from these organizations is the total employment of 131 000 for the German electric sector. Normalizing by total 2002 net generation of about 520 TWh gives an average employment of about 250 man-yr/TWh. If more detailed US employment data ratios are applied, this would mean about 110 man-yr/TWh for generation and T&D, and about 240 man-yr/TWh for general and administrative jobs. This can serve as an order of magnitude check against individual generation technologies, although these include non-generation components, and do not include T&D employment.

Overall, labour estimation followed three possible methods. When national data (e.g. mining jobs) was available, this was used to obtain a national sector average. If industry sources were available for specific plant types (e.g. generation labour for combined cycle plants), this was next used. 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 size and uncertainty 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 labour content of components. However for the wind and solar technology chains, more indirect aggregate industry construction data was used, based on the fact that more of the relative labour is component fabrication and also on data availability. Second, labour results were normalized by 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 plant generation (e.g. 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 estimates of the relative labour intensity required.

Specific Labour Assumptions by Generation Technology Chain:

- Coal Chains - The fuel extraction (mining) labour was based on national mining employment and production statistics. Domestic labour for bituminous coal was higher per ton, since it is from underground mines and German lignite is from pit mines. Significant bituminous imports have started in the last five to seven years, and a 30% higher labour content for this imported coal was assumed, based on lower labour costs and lack of specific data on national mining productivity for the import mix. Fuel transport labour was ignored, based on the low labour requirements for train and conveyor belt transport. Plant construction and operation labour were estimated based on a generic 500 MW plant size. Lignite plant operation labour was estimated to be somewhat higher, due to the much lower energy content, but the biggest difference in normalized labour per TWh was due to the assumed difference in generation. Based on national data, German lignite plants had a much higher capacity factor (about 90%) than bituminous plants (about 58%), so the labour is spread over more generation and the average labour content is much lower.
- Oil Chain – Labour for the fuel components of the oil-fired chain focused on refinery labour. Domestic German refinery labour was ratioed from U.S. refinery labour productivity and German refinery capacity and heavy oil production. Almost all German oil is imported, and the labour for production and transportation (primarily via tanker) were neglected as small in comparison. German oil-fired generation is a small fraction of national production (about 1%), and labour requirements for construction and production were based on a 300 MW generic oil-fired steam generation unit, rather than any oil-fired combustion turbines.
- Natural Gas Chain – Germany produces approximately 20% of its own natural gas consumption, and the combined labour force for its oil & gas exploration and production was allocated entirely to the much larger gas sector. Natural gas transportation was assumed to be entirely by pipeline over a distance of 1600 km, averaged over the mix of imported sources. Natural gas plant construction and operation was based on a generic 400 MW combined cycle unit, with a national average capacity factor of about 35%.
- Nuclear Chain – The nuclear fuel labour components were based on industry employment figures for a large fuel supplier for mining, conversion, enrichment and fabrication. The largest labour contribution comes from the enrichment component, and the total labour required was adjusted to include 40% reprocessing of spent fuel. Fuel transportation was neglected due to the high heat content of the fuel. Labour for plant construction and operation was based on a generic 1000 MW PWR and an average national capacity factor of 78%.
- Hydro Chain – The hydroelectric chain obviously has no labour contribution from fuel production and transportation. The majority of the labour comes from plant construction. Germany has approximately 7200 hydro plants totalling about 8.9 GW_e, which are mostly run-of-river plants. This means that the average plant size is only 1.2 MW_e, but the plant size distribution means that most generation will come from the small fraction of larger units.

Construction labour data varies widely, based on site-specific diversion and dam requirements, but an estimate of 50 man-years/MW_e of capacity was used for small to medium run-of-river plants. Operation was based on the assumption that 10% of the plants would employ 5 persons, and 90% of the plants would employ half a person on average. A national average capacity factor of about 30% reflects the run-of-river domination of the hydropower mix.

- Wind Chain – German wind chain labour requirements were based on employment of about 5000 for the entire wind sector in 2002, assuming 98% of labour was for the construction of new capacity and 2% for operation and maintenance of existing capacity. Average labour content of electricity was based on a national average capacity factor of 15%.
- Solar Chain – Solar PV labour for fabrication was based on a large manufacturer, and installation labour was based on 2 man-weeks for a generic 3 kW roof-mounted installation, including inverter/charger, batteries, etc. The direct and indirect manufacturing labour assumed is almost seven times higher than installation labour, and is obviously an important part of the costs that the industry must reduce to become competitive. Solar generation for German conditions was assumed to have a capacity factor of 10%, and this relatively low electricity production is another reason for its high cost, since both cost and labour are spread across a relatively small production.

It should be noted that all 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 size of the individual labour components and totals were compared for general consistency, and adjusted as deemed appropriate.

Figure 18 shows the results of the estimation, i.e. indicator *“Technology-specific job opportunities”*.

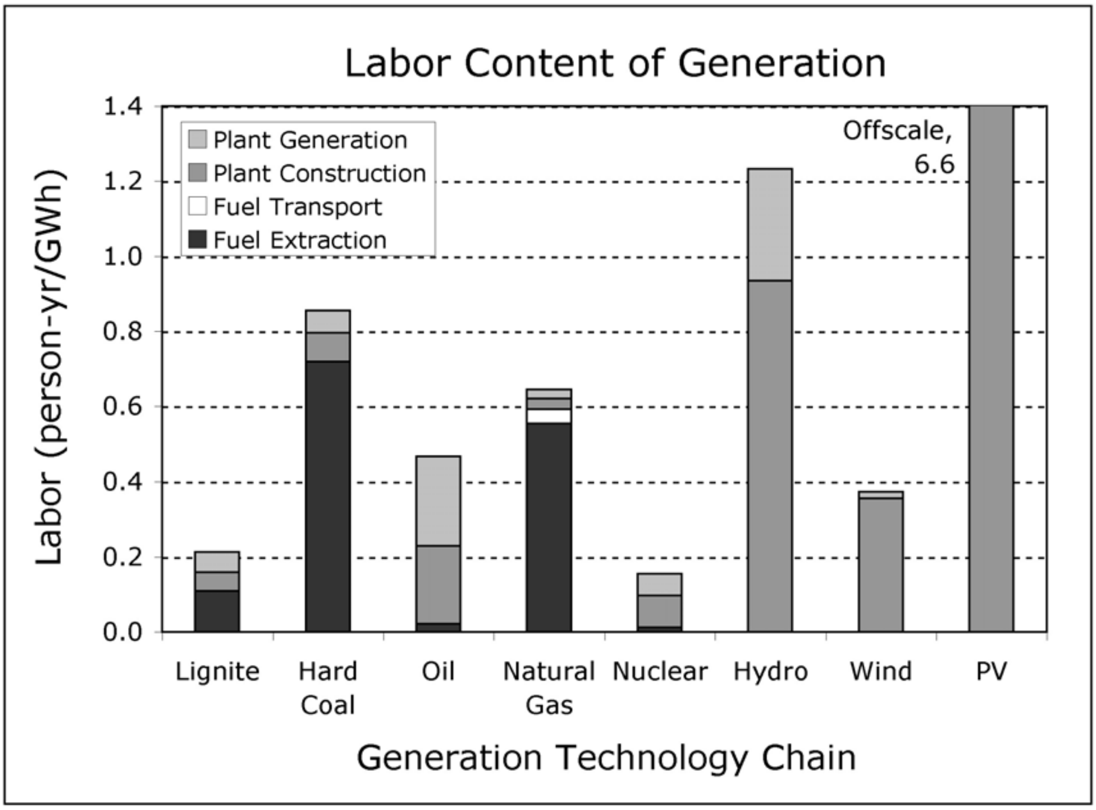

Fig. 18 Energy chain specific labour for Germany.

5.4.2 Proliferation

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

5.4.3 Human Health Impacts due to Normal Operation

The "Mortality" indicator has been elaborated in section 5.3.5 (see Fig. 14). It is worthwhile noting that mortality due to accidents is practically negligible compared to the corresponding effects of normal operation.

5.4.4 Local Disturbances

This concerns *"Noise and visual amenity"*. Thus, this indicator is partially subject to subjective judgments. Some inputs from ExternE were 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" was discussed in 5.2.3. The indicator values should be seen as orders of magnitude.

5.4.6 Risk Aversion

“Maximum credible number of fatalities per accident” is used here as a surrogate for risk aversion. The indicator values used are with two exceptions (hydro and nuclear) based on Fig. 17. Thus, historical non-OECD results were employed here as opposed to the expectation values that are based on the historical experience within OECD.

For hydro, however, OECD experience from all dam accidents (not only hydro dams) was used since the enormous dam accidents in non-OECD countries are less credible in the German case. First, German hydro is primarily run-of-river; second, the reservoir capacities tend to be rather small.

The extent of 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 wastes affects in particular the ranking of nuclear power in the sustainability context (Hirschberg et al., 2000).

5.5 Full Indicator Set Used in the Present Study

The following table shows the complete set of indicators used in the present application[8].

Weights used in the base case of MCDA, described in Chapter 6, are indicated within parenthesis.

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[8] Some of the numbers provided in the table originate from model-based assessments, some are based on judgement. The associated uncertainties may be substantial. For this reason the cited quantitative indicators are primarily suitable for comparisons aiming at the establishment of the internal technology ranking. They are adequate for the purpose of the present study, including MCDA-based aggregation. In applicable cases the numbers have been rounded.

Table 11 Full set of indicators and weights used in the Base Case MCDA.

Economic Indicators

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
Resources (30)	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
	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

Environmental Indicators

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)	*km^2/GWh*	0.032	0.039	0.061	0.016	0.0017	0.0009	0.0029	0.011
Non-Pollutant Effects	Land use/(5)	*m^2/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

Social Indicators

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

6. AGGREGATION

Aggregation of indicators allows the evaluation of the overall performance of technologies. Two aggregation approaches were used to support the ILK statement.

6.1 Aggregation Based on Total Costs

The total costs are comprised of internal and external ones. The latter are shown in Fig. 19; they are driven by public health effects caused by increased level of ambient air concentration of pollutants or an increased level of ionising radiation due to activities on the various process steps of the energy systems[9]. 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 other than natural gas exhibit much higher impacts than the other options.

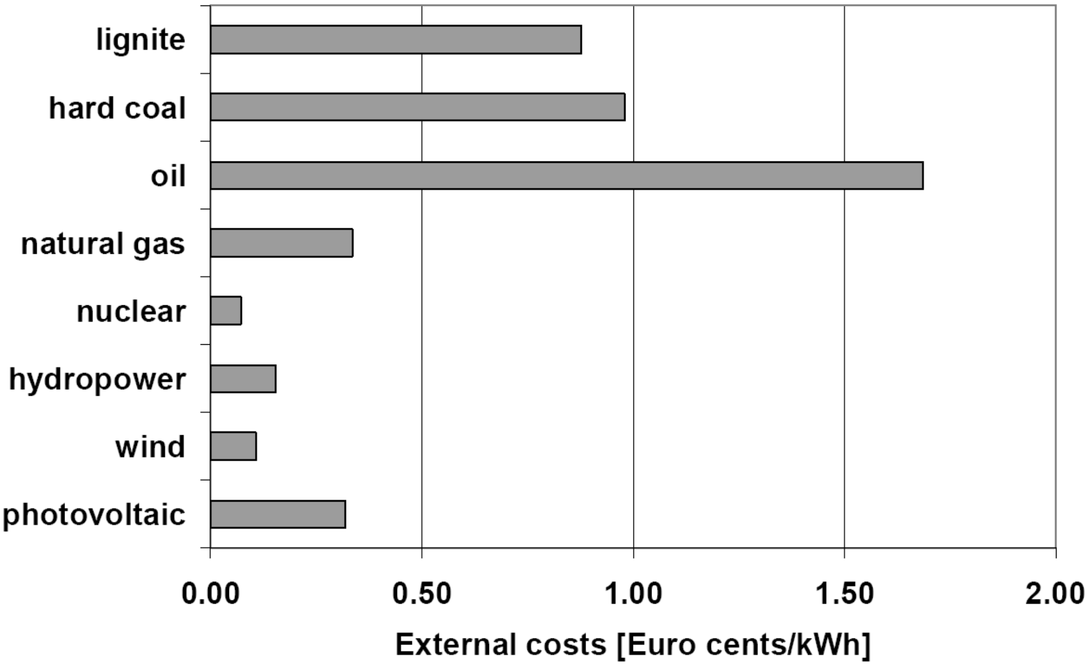

Fig. 19 External costs of electricity generation in Germany; external costs of global warming are not included.

The total costs, comprising internal and external German-specific costs, are shown in the figure below. External costs associated with global warming are highly uncertain and much lees robust that the ones due to air pollutants.

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[9] 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 damages from normal operation.

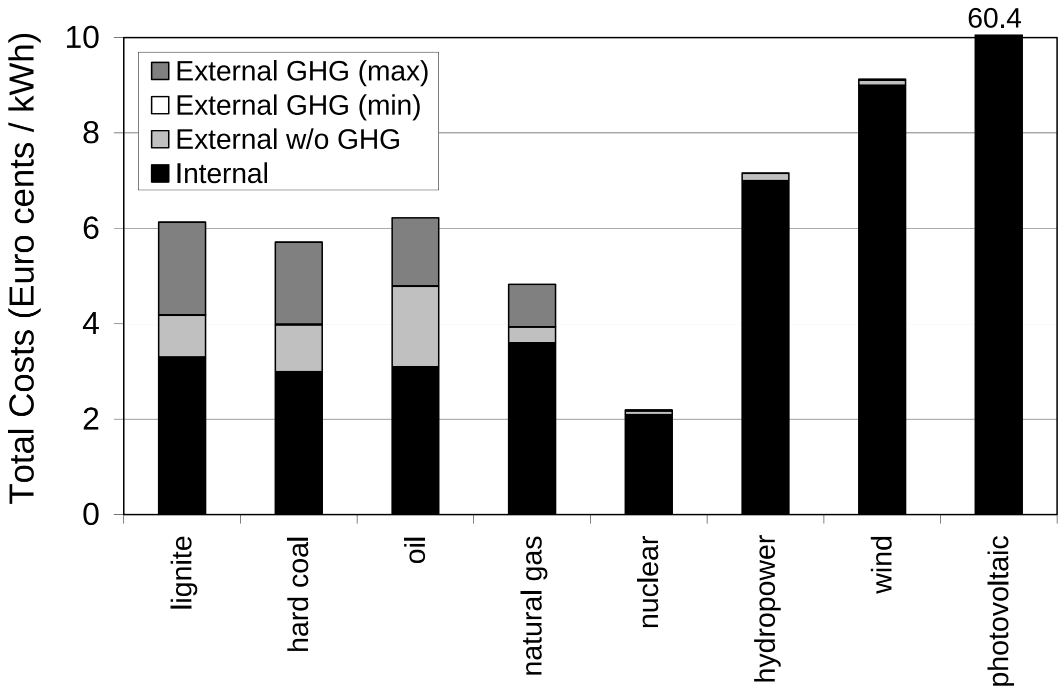

Fig. 20 Comparison of total costs of current technologies in Germany (GHG = Greenhouse Gases).

According to the ranking based on total costs nuclear energy is the best performer, followed by natural gas, hard coal, lignite and oil. Photovoltaic shows 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) as used in this project allowed to combine on an aggregated level the central results of the analyses within the economic and environmental sectors with the social preferences of the users. The technology-specific indicators constitute the analytical input to the evaluation.

The approach used for the evaluation is based on a simple weighted multiple attribute function. The 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 by 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; based on linear interpolation all other alternatives are given intermediate scores which reflect their performance relative to these two end 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 weights can be obtained from stakeholders. Alternatively, various weighting schemes can be assigned to accommodate a range of perspectives expressed in the energy debate. The sensitivity to these schemes has been investigated.

In one of the evaluation cases only a subset of criteria has been employed, i.e. environmental criteria plus health component included in the social dimension plus production costs (Fig. 21). This case has some parallels to the total costs evaluation. The rankings based on the two methods show certain similarities (though they are not identical), with nuclear being the top performer and PV being the worst.

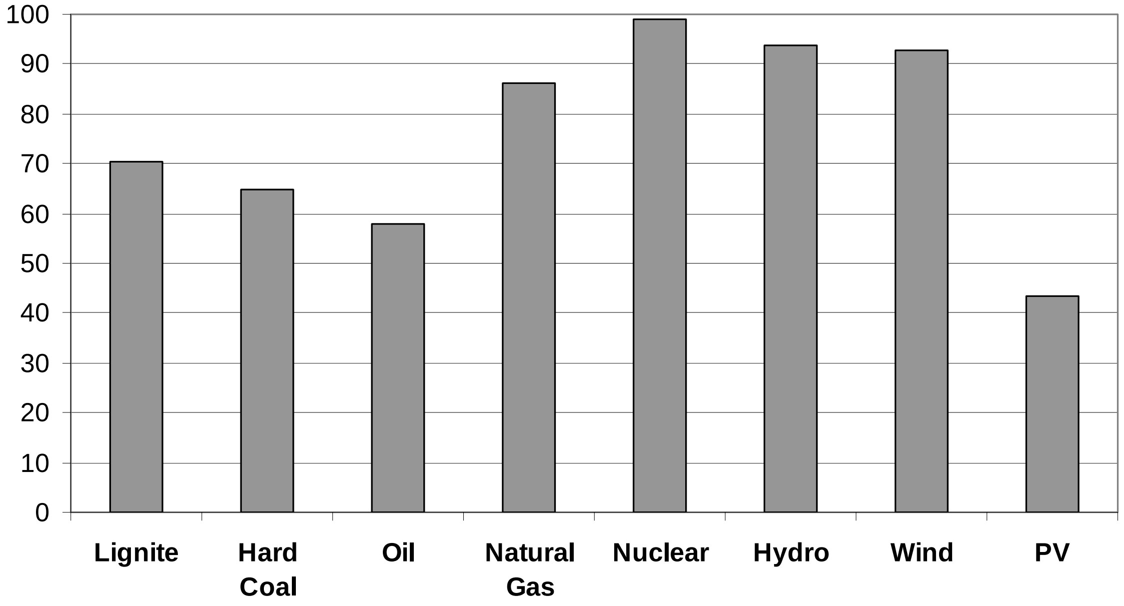

Fig. 21 Multi-criteria sensitivity mapping for Germany: Health and environmental criteria plus production costs; the higher the total score, the better the overall system performance.

If the full set of criteria is used along with weights equally distributed between the three main components (economy, health and environment, social), thus following the principle that sustainability ultimately calls for equal importance being given to all of them, a different set of results is obtained (Fig. 22).

The case with equal top-level weights exhibits a top performance of 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 the result of inclusion of social criteria.

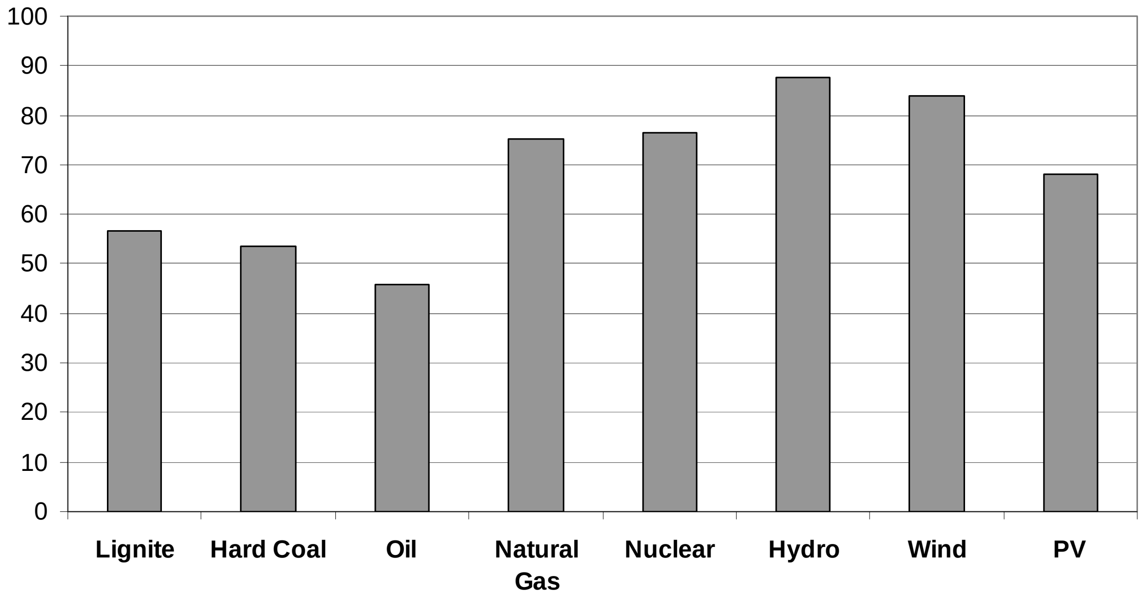

Fig. 22 Multi-criteria sensitivity mapping for Germany: Base case employing the full set of criteria with equal weights assigned to the three dimensions of sustainability.

6.2.2 Sensitivity Analysis

A number of sensitivity cases were run in order to investigate specific patterns in the ranking based on economically, environmentally respectively socially centred criteria. Here three cases with economy centred, environment centred and socially centred weighting are shown in Figures 23-25. The economy centred case means that economic dimension is given a weight of 80%, while environmental and social dimensions both have a weight of 10%; the other cases are defined in an analogous manner.

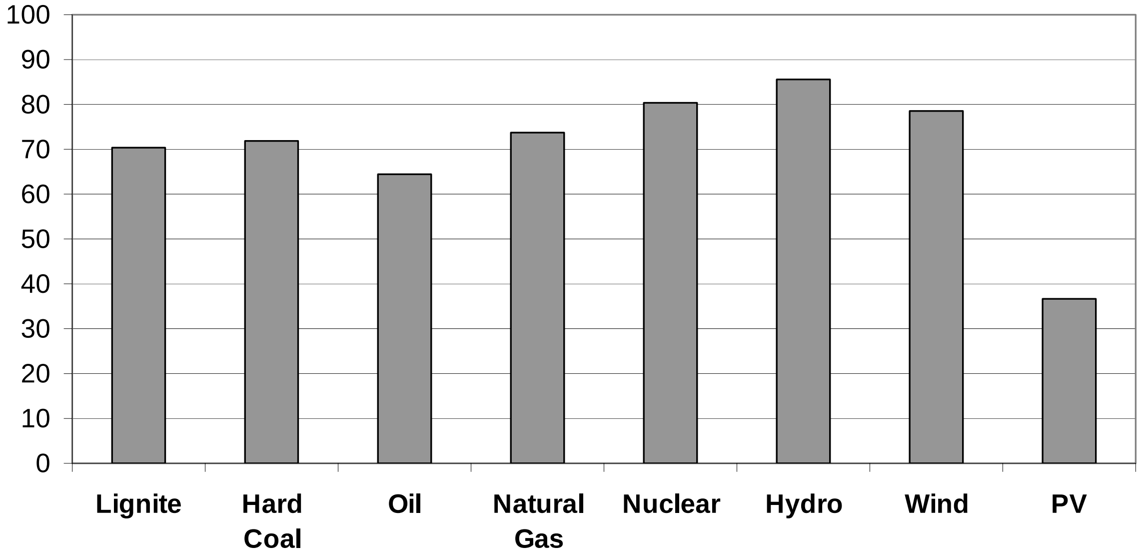

Fig. 23 Multi-criteria sensitivity mapping for Germany: Economy centred case.

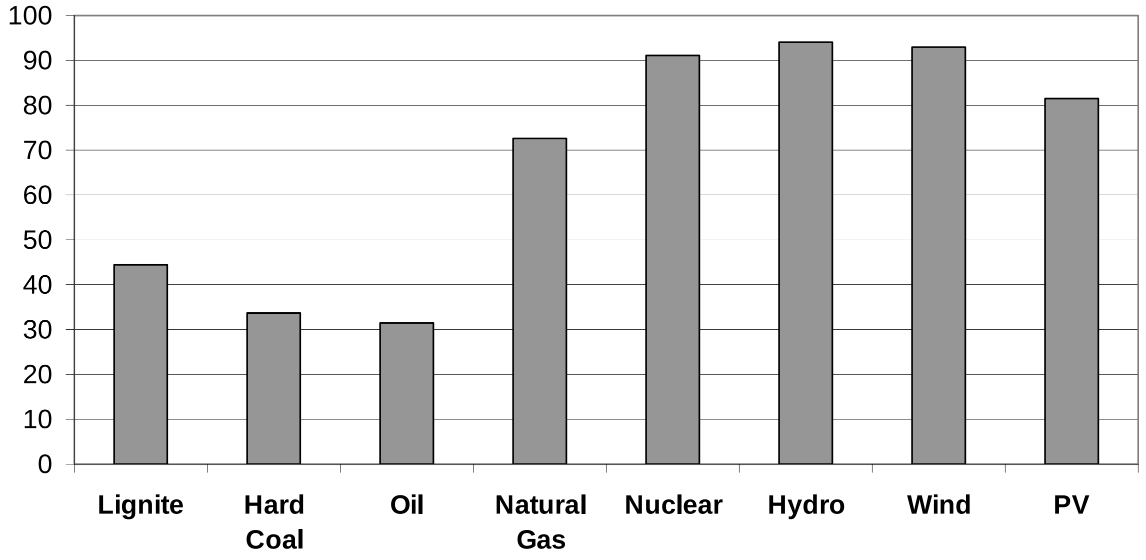

Fig. 24 Multi-criteria sensitivity mapping for Germany: Environment centred case.

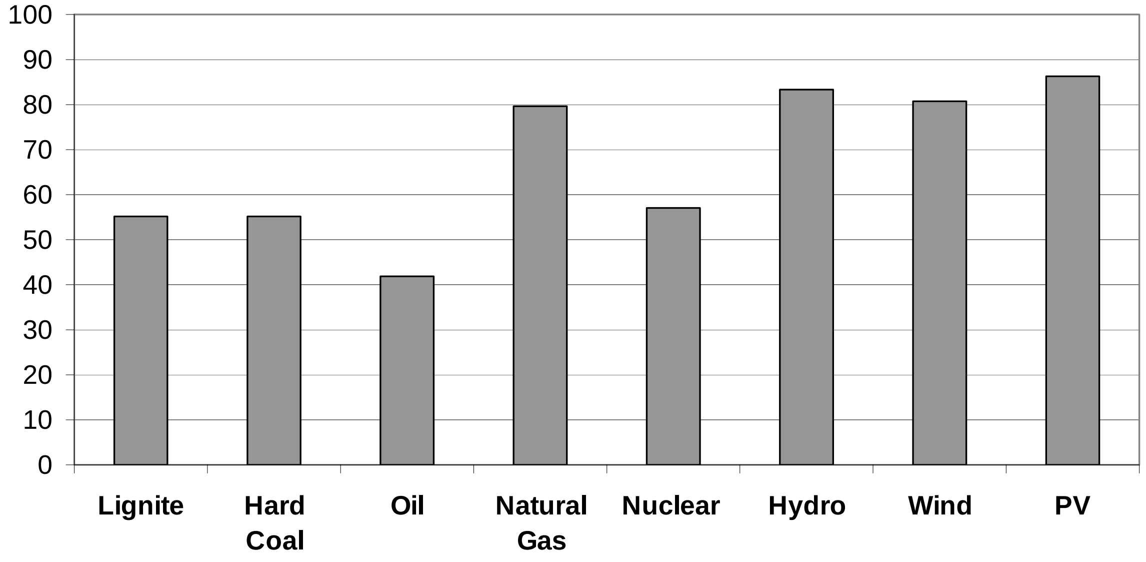

Fig. 25 Multi-criteria sensitivity mapping for Germany: Socially centred case.

The results are thus highly sensitive to the variation of weights at the highest level. While the weights given to lower levels of criteria may in most cases be regarded as arbitrary, the ranking of systems remains, however, quite stable given a moderate variation of these weights.

Also, the impact of possible future nuclear-specific technological improvements was examined. This includes strong design-based limitation of the consequences of hypothetical nuclear accidents along with radical reduction of necessary waste confinement times to a historical time scale (Fig. 26). 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 currently pursued major developments in nuclear safety and waste research. It needs to be said that advancements are also feasible and likely for other technologies though at this stage no specific developments of comparably decisive character as for nuclear, have been identified. We refer to (Dones et al., 1996) for the systematic investigation of the impacts of evolutionary improvements of electricity generation technologies and associated energy chains on environmental burdens.

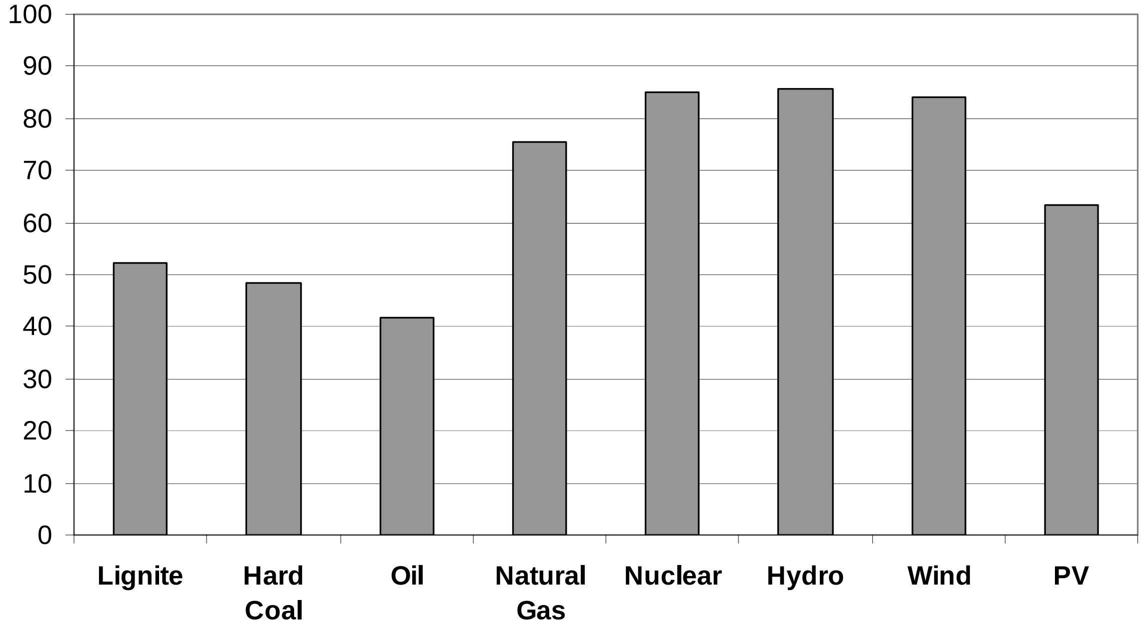

Fig. 26 Multi-criteria sensitivity mapping for Germany: Full set of criteria, equal first-level weights, scoring credit for potential nuclear advancements.

7. CONCLUSIONS

7.1 Role of Sustainability and Assessment Approach

- It is suggested that sustainability considerations should guide political decisions concerning energy supply options and associated technological developments.
- The evaluation process needs to be transparent and non-discriminative. Use of consistent and to the extent possible objective quantitative, technology-specific indicators is highly promising.
- This study provides a proposal on a suitable evaluation approach that has been implemented and applied to the current major energy chains for electricity generation, representative for Germany. This proposal could be helpful in the context of energy policy discussion conducted in Germany.

7.2 Option-specific Features

- The fossil systems are subject to limited energetic resources and show relatively unfavourable ecological and accident risk features. Natural gas is by far the best performer among fossil energy carriers.
- Nuclear energy exhibits under the German conditions excellent economic as well as environmental and health performance. Within the western world it also has an excellent safety record, reflected in 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 wastes over extremely long period of time.
- The “new” renewables (solar and wind) are environmentally mostly superior to fossil sources, but use relatively large amounts of non-energetic material resources. The overall performance of wind energy is favourable while economic competitiveness of solar photovoltaic systems is under the German climatic conditions still extremely low.

7.3 Overall Sustainability Evaluation

- Evaluations employing a variety of sustainability criteria result in a differentiated picture of the merits and drawbacks of the currently available electricity supply options. No single system exhibits a superior performance on all criteria. Most indicators characterising nuclear energy show to be favourable.
- Primarily relative statements on sustainability of the various electricity supply options are meaningful. The comparative sustainability evaluation can be based on the aggregation of indicators employing either the full cost approach or Multi-criteria Decision Analysis (MCDA).

- Coal and oil chains exhibit the highest environmental external costs. The external costs associated with natural gas are the lowest among the fossil chains, i.e. of the same order as for solar photovoltaic. The nuclear chain exhibits the lowest quantifiable external costs, followed by wind and hydropower. In terms of total costs nuclear power shows again top performance, under German conditions, superior to other currently implemented technologies. In particular, solar photovoltaic is presently burdened by high solar cell production costs.
- Some reservations have been put forward about the proposition of total costs being used as the only measure of sustainability since the societal dimension, which plays a central role in the decision process, does not come to the surface when systems ranking is purely based on costs. Taking nuclear power as an example, issues like high-level long-lived radioactive wastes, hypothetical severe accidents or proliferation, contribute marginally or not at all to the external costs. At the same time such 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. They are sensitive to value judgments. The results of MCDA based on criteria limited to the corresponding scope as the total cost assessment, i.e. equally weighted health and environmental impacts and production costs, lead to technology rankings with a number of similarities. Ranking based on all three pillars of sustainability is 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 on societal aspects nuclear.
- Developments towards strong limitation of consequences of hypothetical accidents along with radical reduction of waste confinement time 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. Sustainability perspective implies a balanced (equal) importance assignment to economic, ecological and social aspects. Unbalanced emphasis on anyone of these three dimensions is not in the spirit of sustainable development.

7.4 Possible Future Applications

- Given interest, direct interactions with stakeholders could follow upon the present study given interest.
- Study of future systems is recommended since sustainability in longer-term will be determined by technological advancements and willingness to implement them within the energy sector.
- Along with analyses of future technologies scenario analyses are recommended. They tend to be more realistic as they have a built-in representation of realistic technology-specific potentials and explicit accounting for back-ups associated with technologies exhibiting relatively low load factors as a result of strong dependence on climatic conditions.

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