Chimia 59 (2005) 887–893
© Schweizerische Chemische Gesellschaft
ISSN 0009–4293

Sustainability Aspects of Current and Future Electricity Supply Systems

Stefan Hirschberg* and Roberto Dones

Abstract: Approaches to comprehensive and consistent evaluation of sustainability of electricity supply systems including fossil, nuclear and renewable technologies are described. Sustainability can be assessed in a comparative manner using a comprehensive set of indicators derived using a variety of methods. Examples of indicators are provided for a variety of current systems. Some trends for future systems are briefly described. Finally, conclusions are drawn on performance of the various technologies with respect to economic, ecologic and social criteria.

Keywords: Electricity · Fossil · Indicators · Nuclear · Renewables · Sustainability

Introduction

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 [1]. 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.

The Brundtland definition of sustainability has been of fundamental importance as a starting point for the discussion and promotion of sustainability within the various sectors, energy in particular. However, the definition as such does not allow for the operationalisation of the sustainability concept if the objective is to differentiate between the performances of various energy technologies of interest.

Within the Project GaBE (Ganzheitliche Betrachtung von Energiesystemen; Comprehensive Assessment of Energy Systems [2]) the Paul Scherrer Institut (PSI) has developed during the last decade a systematic approach to the evaluation of energy systems with regard to sustainability. The results of such assessments provide direct decision-support to the main actors on the energy scene including regulators and utilities, and serve as a basis for discussions with stakeholders, decision- and opinion-makers. This paper shortly summarizes the approach used and provides examples of selected indicators employed in the evaluations.

Overview of Methodology

A systematic, multi-disciplinary, bottom-up methodology for the assessment of energy systems has been established and implemented. Fig. 1 illustrates the assessment methods used and the basic interactions between the various analysis modules. The overall approach is process-oriented, *i.e.* the technologies of interest and their features are explicitly represented, thus enabling a straight-forward accounting for technological features including planned or potential improvements. The following short summary of methods used is limited to approaches which enable generation of indicators associated with the various sustainability criteria. The emphasis is on methods for the assessment of ecological performance since they are in relative terms most sophisticated and require substantial resource investment.

The approach used as a basis for generating most environmental indicators is Life Cycle Assessment (LCA). LCA is a systematic method for the establishment of energy and material balances of the various energy chains. LCA utilises process chain analysis specific to the types of fuels used in each process and allows for the full accounting of burdens such as emissions, also when they take place outside national boundaries. 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 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. Detailed environmental inventories (*i.e.* burdens such as emissions or wastes) for current and future energy systems during normal operation have been established for a wide spectrum of European countries, with the highest level of detail for Switzerland [3][4]. Selected environmental inventories (burdens) may be used directly as indicators or may serve as input to health and environmental impact analysis.

**Correspondence*: Dr. S. Hirschberg
Systems/Safety Analysis
Paul Scherrer Institut
CH-5232 Villigen PSI
Tel.: +41 56 310 2956
Fax: +41 56 310 4411
E-Mail: stefan.hirschberg@psi.ch

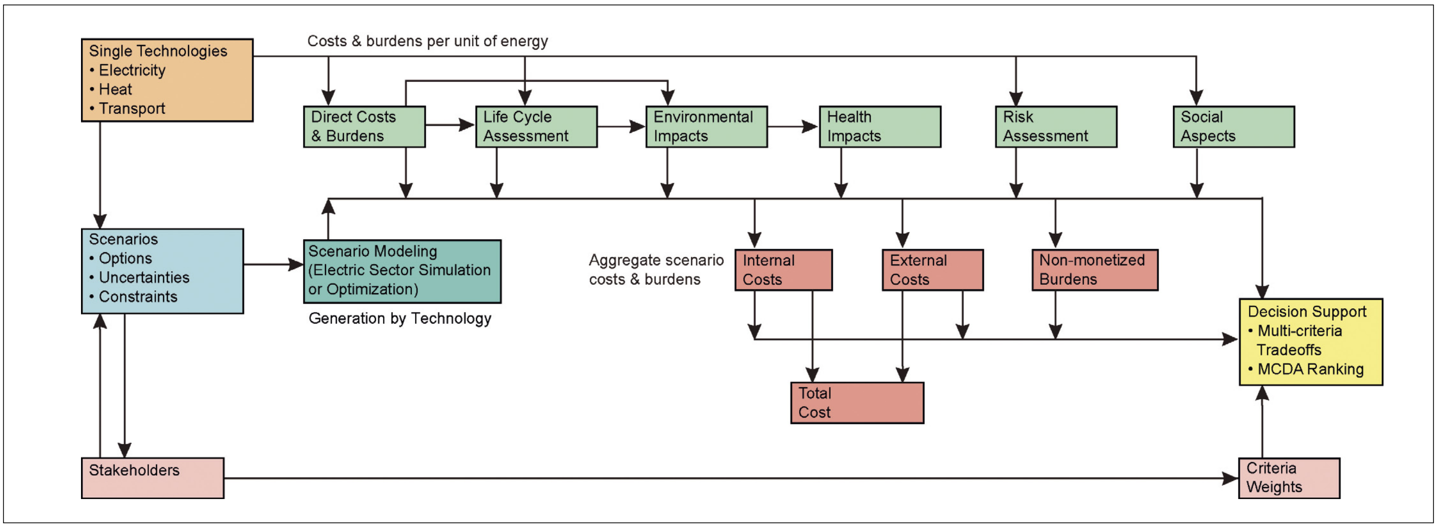

Fig. 1. PSI's integrated framework for comprehensive energy systems analysis

Life cycle impact assessment (LCIA) methods have been developed with the goal to facilitate the understanding of the results of the inventory phase and at the same time to include a number of environmental damage attributes (*e.g.* [5]). A measure of potential environmental impacts is given in some LCIA methods as one single indicator score. For its calculation, subjective factors (weighting) are applied, which are not entirely transparent to the final user of the results unless the major assumptions for the application of the methodologies are provided. Current LCIA methods exhibit a number of simplifications that are time- and resource-saving but depending on the purpose of the analysis may not allow for sufficient differentiation between the results; for example, dependence on the location of the source of pollution or influence of meteorological conditions are ignored.

The 'impact pathway' approach [6][7] to environmental impact assessment is substantially more resource-intensive than LCIA and allows appropriate representation of location-specific aspects including accounting for chemical transformations of major air pollutants, which have a decisive influence on the resulting damages. Model species include primary particles, oxidized sulphur or SO_x (SO_2, H_2SO_4, $(NH_4)_2SO_4$), oxidized nitrogen or NO (NO, NO_2, HNO_3, NH_4NO_3, non-specific nitrate aerosol) and reduced nitrogen or NH_x (NH_3, NH_4NO_3, $(NH_4)_2SO_4$); their interaction in the chemical scheme is illustrated in Fig. 2. The steps involved in the impact pathway approach are: technology and site characterization, prioritization of impacts, quantification of burdens (emissions and other), description of the receiving environment, quantification of impacts (using dispersion models for atmospheric pollutants and dose-response functions), and economic valuation. In this manner, environmental external costs, *i.e.* health and environmental damages currently not included in energy prices, can be estimated.

The methods described above address normal operation of power plants and the associated energy chains. Separate treatment is needed for severe accidents. Analysis of severe accidents for the purpose of generation of consistent relevant indicators can be based on historical evidence, on Probabilistic Safety Assessment (PSA), or on combinations of these. PSA provides a structured and logical approach to identify credible accident sequences, assess the corresponding likelihood, and delineate the associated consequences. 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 [9][10]. This applies in particular to the completeness of historical records, quality and consistency of the information, and coverage of various types of damages. For the purpose of comparative severe accident analysis the world-wide most comprehensive database ENSAD (Energy-related Severe Accident Database) has been established by PSI. Also applications of PSA are steadily growing, predominantly in the nuclear sector; in the context of consequence analysis suitable for the comparative assessment a resource-saving limited scope approach has been developed and applied [11].

Estimation of economic indicators such as production costs is rather straight-forward as it is based on available data, at least what concerns operating systems. Technology-specific social indicators are less well

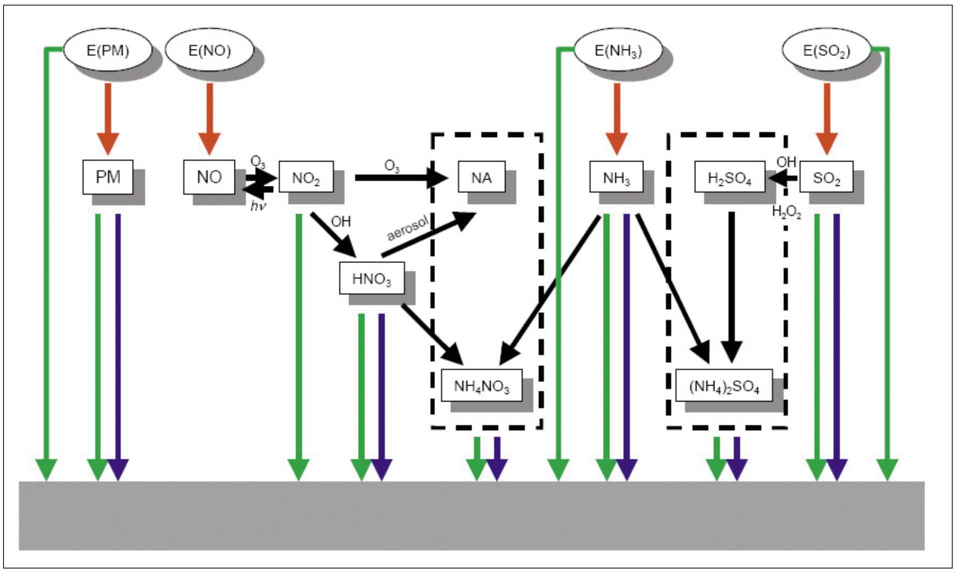

Fig. 2. Coupled life cycles of the air pollutants (presentation modified from [8]). PM is short for particulate matter, NA for non-specific nitrate aerosol. Total nitrate aerosol (left dashed box) includes NA and NH_4NO_3, sulphate aerosol (right dashed box) includes H_2SO_4 and $(NH_4)_2SO_4$. Emission is indicated by red, chemical conversion by black, dry deposition by green and wet deposition by blue arrows.

established. Some of them, such as direct employment may be based on the analysis of statistical data. Other social indicators may be closely related to risk issues such as risk aversion or necessity of assuring the confinement of critical wastes for a very long time.

External cost 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 (*e.g.* [12–15]). It has been proposed by some authors that the total system-specific cost of energy production could serve as an integrated relative indicator of sustainability since it reflects the economic and environmental efficiency of energy systems (*e.g.* [16]).

Another approach to aggregation is based on the applications of multi-criteria decision analysis (MCDA). MCDA allows the combination on an aggregated level of the central results of the analyses within the economic, environmental and social sectors with stakeholder preferences [13][15][17][18]. The technology-specific indicators constitute the analytical input to the evaluation. In comparison to the total cost assessment, MCDA brings the social dimension to the surface.

Table 1. Criteria and indicators employed in the present study [15]

Dimension	Impact Area	Indicator	Unit
Economy	Financial Requirements	Production cost	*c/kWh*
		Fuel price increase sensitivity	*Factor*[a]
	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*

[a] Increase of production costs due to doubling of fuel costs

Application Examples

Evaluation Criteria and Associated Indicators

Evaluation criteria used in the latest major study carried out by PSI [15] are summarized in Table 1. The study addressed in a comparative manner sustainability of electricity supply technologies under German conditions. The indicators were quantified based on the methods described above. In the present paper examples of indicators are provided for a different set of technologies as described in the next section.

Characteristic Features of Reference Technologies

PSI analyses both current and future technologies for electricity and heat supply. Here current (reference year 2000) electricity generation systems are addressed. As the reference, modern technologies, represented in the energy part of the ecoinvent database [3][4], are selected. Tables 2 and 3 provide the basic characteristics of these technologies.

The scope of the analysis is not limited to power plants but covers also the associated entire energy chains. Below follow comments on the reference power plant technologies shown in Tables 2 and 3, and on the basic assumptions concerning the chains, essential for the quantification of indicators provided in the next section.

Table 2. Characteristics of selected reference fossil and nuclear technologies

Technology Characteristics	Lignite (Austria)	Hard Coal (Austria)	Natural Gas Combined Cycle (Europe)	Natural Gas Cogeneration (Europe)	Diesel Cogeneration (CH)	Nuclear (CH)
Capacity	330 MW	400 MW	400 MW	1 MW	200 kW	1000 MW
Load factor	0.54	0.4	0.57	0.46	0.46	0.87
Annual electricity production [GWh]	1550	1400	2000	4.0	0.8	7600
Annual heat production [GWh th]	–	–	–	4.6	0.9	–
Net Efficiency	0.38	0.42	0.58	0.38(el); 0.44(th)	0.39(el); 0.43(th)	0.32
$DeSO_x$ efficiency	0.85	0.91	–	–	–	–
$DeNO_x$ efficiency	0.89	0.8	–	–	0.93	–

Table 3. Characteristics of selected reference renewable technologies

Technology Characteristics	**Hydro Reservoir (CH)**	**Hydro Run-of-river (CH & Austria)**	**Photovoltaic (CH)**	**Photovoltaic (Southern Europe)**	**Wind Onshore (CH)**	**Wind Offshore (Northern Europe)**
Capacity	0.5–1200 MW	23–237 MW	3 kWp	3 kWp	800 kW	2 MW
Average	120 MW	80 MW	–	–	–	–
Load factor	0.24	0.52	0.1	0.15	0.14	0.43
Annual electricity production [GWh]	252	364	0.0027	0.0039	0.98	7.5
Net Efficiency	0.84	0.88	0.12	0.12	0.25	0.25

- *Lignite:* Austria is chosen as the reference country since Austrian lignite plants exhibit the best environmental performance in Europe [3][4]. The plant is assumed to be used for base load with about 5000 h operation at full capacity per year.
- *Hard Coal:* Also in this case Austria serves as a reference, for the same reasons as for lignite. The power plant is assumed to be used for middle load with about 3500 h operation at full capacity per year.
- *Natural Gas:* The German reference power plant, which is representative for a new combined cycle plant of the 400 MW class with best technology available on the European market has a 265 MW gas turbine and a 140 MW steam turbine. The fuel is assumed to be supplied by natural gas high pressure network for average European conditions.
- *Cogeneration:* Both cogeneration plants are assumed to operate 4000 h per year and represent average technology currently available on the European market. The gas fuel is assumed to be supplied by natural gas network for average European conditions.
- *Nuclear:* The Swiss nuclear electricity supply mix consisting of 55% Pressurised Water Reactors (PWR) and 45% Boiling Water Reactors (BWR) is represented. The average burn-ups of 48.6 MWd/kg and 53 MWd/kg heavy metal of finally discharged fuel elements have been assumed representative for the lifetime of the modelled BWR and PWR plants, respectively. Over the lifetime of the PWR plant it is assumed that 8% of the energy will be produced by mixed oxide (MOX) fuel elements made with plutonium from reprocessing and depleted uranium from enrichment. Considered radioactive waste streams from both reactor types are: spent fuel to reprocessing (approximately 40%) and direct conditioning (60%); operational low active waste for conditioning in the interim depository (Zwilag); and, contaminated waste from decommissioning of the plants.
- *Hydropower:* Average technology as employed in operational Swiss reservoir and run-of-river plants is represented. A representative sample of Swiss dams with a height of more than 30 m as well as four Swiss and one Austrian run-of-river power plants are considered for calculating averages.
- *Photovoltaic:* The modelled photovoltaic plants are monocrystalline and polycrystalline silicon 3 kWpeak slanted roof top units. The manufacturing process reflects current European technology. Operational conditions in Switzerland and in Southern Europe are considered. In the latter case the Swiss mix of the two base technologies (83% monocrystalline and 17% polycrystalline) is assumed and the performance is based on a yield of 1300 kWh/kWpeak (the Swiss average yield is 885 kWh/kWpeak).
- *Wind Power:* A typical modern onshore 800 kW wind turbine (Nordex N50/800) for Swiss onshore wind conditions at Mt. Crosin (Jura) with a capacity factor of 14% is modelled. For offshore, modern technology (Bonus 2 MW turbine) is considered. Very good offshore wind conditions are assumed, with a capacity factor of 43% based on the expected electricity production at the Danish wind park Horns Rev.

Selected Indicators

Selected indicators for the technologies characterised above are provided in Tables 4 and 5. As illustrated in Table 1 it is necessary to quantify a broader spectrum of indicators in order to carry out the full scope assessment. Depending on the technologies considered and on the goals of the assessment the set of criteria and associated indicators may change.

The non-aggregated environmental indicators are primarily based on LCA inventories [3][4]. Cumulative environmental inventories for each environmental burden calculated for each energy chain include indirect contributions. This explains for example that also non-nuclear systems exhibit radioactive wastes due to electricity inputs, which include nuclear electricity in the mix.

It should be noted that based on the impact pathway approach the emission indicators may be aggregated to obtain health effects such as mortality (reduced life expectancy) or change in unprotected ecosystem area (see Table 1). Such aggregations are based on an objective state-of-the-art approach and thus avoid subjective weighting of various emissions.

Production (internal) costs mostly illustrate a range of values for power plants available in Switzerland or the expected costs would the plants be built in Switzerland today. External costs are dominated by health effects, which in turn are driven by the emissions of major air pollutants (SO_2, NO_x, PM_{10}). The values for external costs provided in Tables 4 and 5 reflect ranges for Western Europe; these depend on specific technologies used, locations and uncertainties in the assessment. As pointed out earlier the total costs represent an aggregated measure of economic and environmental components of sustainability. The main limitation of this measure is that some elements of the social dimension of sustainability, which are shown to be essential for acceptability, are not adequately reflected in the total costs.

Trends for Advanced Systems

Few recent studies have implemented extensions to future systems. This can be done based on the literature as well as on direct information from the industry and application of expert judgment. The result-driving environmental parameters are: emissions, efficiencies, material intensities (for construction and operation), and transportation requirements. The relative importance of these parameters varies significantly between energy chains.

The most important expected changes towards improvements of ecological performance of evolutionary future electricity generating technologies are (see *e.g.* [19]):

Table 4. Selected indicators for fossil and nuclear energy chains

Indicators	**Units**	**Lignite (Austria)**	**Hard Coal (Austria)**	**Natural Gas Combined Cycle (Europe)**	**Natural Gas Cogeneration (Europe)[a]**	**Diesel Cogeneration (CH)[a]**	**Nuclear (CH)**
Greenhouse Gases	kg (CO$_2$-equiv.) kWh$_e$	1.06E+00	9.70E-01	4.23E-01	5.87E-01	7.31E-01	7.86E-03
SO$_2$	kg/kWh$_e$	7.60E-04	5.67E-04	1.47E-0	1.90E-04	1.04E-03	2.34E-04
NO$_X$	kg/kWh$_e$	7.16E-04	8.15E-04	3.29E-04	1.04E-03	1.06E-03	3.92E-05
PM$_{10}$	kg/kWh$_e$	1.74E-04	1.70E-04	1.82E-05	1.94E-05	8.96E-05	1.27E-05
Fossil energy input	MJ-equiv./kWh$_e$	8.55E+00	1.13E+01	7.71E+00	9.79E+00	1.05E+01	1.13E-01
Iron ore	kg/kWh$_e$	6.26E-04	1.88E-03	1.08E-03	1.44E-03	2.29E-03	2.97E-04
Total non-radioactive waste	kg/kWh$_e$	1.57E-01	1.24E-01	1.79E-03	3.22E-03	1.38E-02	4.66E-03
Total radioactive waste	kg/kWh$_e$	8.28E-05	2.25E-04	1.48E-05	2.39E-05	2.33E-04	1.16E-02[b]
Internal cost[c]	Rp/kWh$_e$[d]	n.a.	5.7–7.4	4.7–5.8	~9	~9 – ~13	4.1-5.3
External costs[c]	Rp/kWh$_e$[d]	n.a.	3.1–15.8	0.8–5.5	n.a.	n.a.	0.2-1.3
Total costs[c]	Rp/kWh$_e$ [d]	n.a.	8.8–23.2	5.5–11.3	n.a.	n.a.	4.3-6.5

[a] All LCA indicators for cogeneration systems are based on allocation by exergy.
[b] Thereof 99% low level wastes from uranium milling that will not be stored in the geological final repository.
[c] The ranges used refer to various technologies as applied in Switzerland and/or in Western Europe. These technologies may exhibit worse performance than the ones used as reference here but their locations may also be more or less favourable.
[d] One Swiss centime (Rappen = Rp) corresponds approximately to 0.8 US cents.
n.a. = not available

Table 5. Selected indicators for renewable energy chains

Indicators	**Units**	**Hydro Reservoir (CH)**	**Hydro Run-of-river (CH)**	**Photovoltaic (CH)**	**Photovoltaic (Southern Europe)**	**Wind Onshore (CH)**	**Wind Offshore, (Northern Europe)**
Greenhouse Gases	kg (CO$_2$-equiv.)/kWh$_e$	4.24E-03	3.05E-03	7.9 IE-02	5.38E-02	1.50E-02	9.34E-03
SO$_2$	kg/kWh$_e$	4.29E-06	3.97E-06	2.08E-04	1.42E-04	5.44E-05	3.10E-05
NO$_X$	kg/kWh$_e$	2.62E-05	3.15E-05	2.94E-04	2.00E-04	5. 5 IE-05	3.92E-05
PM$_{10}$	kg/kWh$_e$	1.08E-05	1.75E-05	9.77E-05	6.65E-05	4.66E-05	3.79E-05
Fossil energy input	MJ-equiv./kWh$_e$	3.10E-02	2.87E-02	1.14E+00	7.76E-01	1.97E-01	1.13E-01
Iron ore	kg/kWh$_e$	2.18E-04	3.1 IE-04	1.38E-03	9.38E-04	2.80E-03	1.63E-03
Total non-radioactive waste	kg/kWh$_e$	2.98E-02	2.33E-02	5.97E-02	4.07E-02	9.28E-02	1.56E-02
Total radioactive waste	kg/kWh$_e$	1.04E-05	6.51E-06	2.39E-04	1.62E-04	4.37E-05	2.3 IE-05
Internal costs[a]	Rp/kWh$_e$[b]	4.0–10.0	2.9–7.4	70–100	n.a.	12–24	9.5–18.6
External costs[a]	Rp/kWh$_e$[b]	0–1.2	small	0.1–1.5	small	0.1–0.6	small
Total costs[a]	Rp/kWh$_e$[b]	4.0–11.2	2.9–~8.0	70.1–101.5	n.a.	12.1–24.6	n.a.

[a] The ranges used refer to various technologies as applied in Switzerland and/or in Western Europe. These technologies may exhibit worse performance than the ones used as reference here but their locations may also be more or less favourable.
[b] One Swiss centime (Rappen = Rp) corresponds approximately to 0.8 US cents.
n.a. = not available

- *Gas Systems:* reduction of gas leakage from pipelines, improvements of power plant burner performance characteristics and of overall power plant efficiency;
- *Hard Coal Systems:* increased methane recovery in underground mining of the coal; gasification and fluidised bed technologies developed in addition to advanced pulverized coal combustion, leading to overall power plant efficiency and drastic reduction of airborne emissions; possible implementation of CO_2 capture and storage technologies (this can apply to all fossil fuels);
- *Nuclear Systems:* 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). These improvements primarily reduce the burdens from normal operation. Most important prospective advancements of nuclear systems focus on the issue of hypothetical severe accidents. The reactors belonging to Generation III/III+, for example the European Pressurised Reactor (EPR), show further reductions of severe accident risks due to passive safety elements. For Generation IV reactors new concepts are being developed aiming at strong limitation of maximum credible consequences of accidents along with radical reduction of the necessary waste confinement time. Such advancements would have a highly favourable impact on the overall sustainability of the nuclear energy chain.
- *Hydro Systems:* overall power plant efficiency improvements (turbine);
- *Solar Photovoltaic Systems:* improvements in the manufacturing of monocrystalline-silicon (m-Si) and amorphous-silicon (a-Si) solar cells (yield, electricity consumption) and in cell efficiencies.

Some of the above improvements have already been implemented in currently available best technologies that are not yet widely disseminated.

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. For detailed analysis of expected cost developments of new renewables and new nuclear technologies with the time horizon until 2035 and beyond we refer to [20].

The aggregated results in terms of total (internal and external) costs obtained for future systems operating under Swiss conditions are shown in Fig. 3 [13]. In the case of fossil systems, the Combined Cycle (CC) technology has been considered for natural gas and oil, the Pressurized Fluidized Bed Combustion (PFBC) technology for hard coal power plants. The estimated external costs are relatively low since the analyzed systems have in most cases a superior environmental performance in comparison with technologies typical for the current situation. They remain, however, significant in the case of fossil systems, which implies that consideration of avoided pollution damages when switching to CO_2-free systems is important also for advanced technologies.

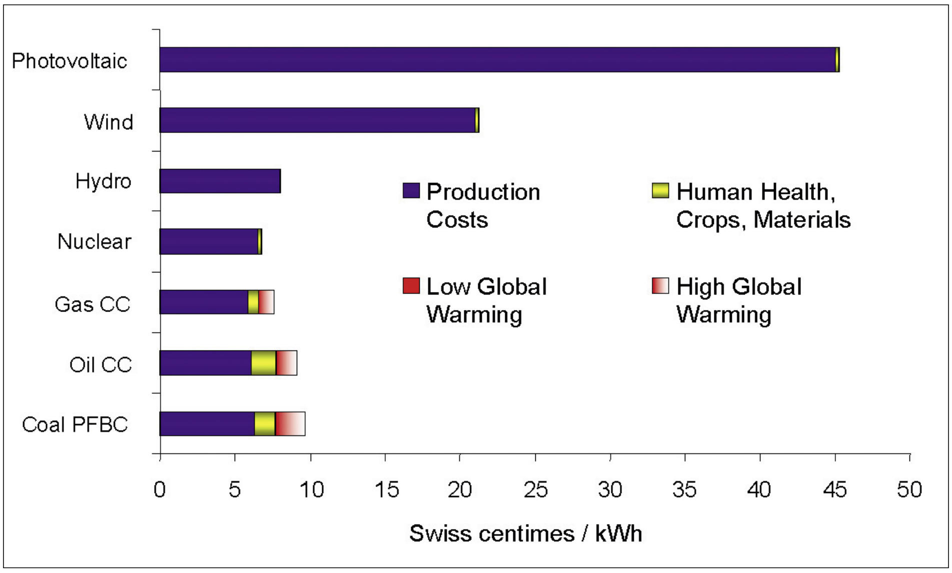

Fig. 3. Total costs for advanced systems under Swiss conditions [13]. Same location has been chosen for fossil systems and nuclear while for wind and solar photovoltaic average Swiss conditions have been assumed. Based on the latest study [20], future internal costs of wind energy at good locations in Switzerland as well as of nuclear are expected to be lower but this will not affect the technology ranking based on total costs as shown in the figure. (CC = Combined Cycle; PFBC = Pressurized Fluidized Bed Combustion; One Swiss centime corresponds approximately to 0.8 US cents.)

Conclusions

Sustainability of energy can be comprehended and judged in a balanced manner only in a comparative perspective that addresses nuclear energy along with other major technological options for generating electricity. Detailed, systematic, and structured approaches to such comparisons have been developed and implemented in the last decade.

The overall assessment of energy technologies can be based on: (a) Total (internal + external) costs or on (b) Multi-criteria Decision Analysis (MCDA). Cost-benefit analysis based on (total) costs has great attractions for guiding public policy but monetisation is not accepted by all stakeholders and social factors may be monetised only to a limited extent. Multi-criteria analysis allows 'mapping' of a controversy (such as choice of energy technologies) and improves the quality and transparency of the debate. It is recommended to use both approaches in view of their complementary character.

The following technology-specific conclusions build on a broader range of criteria and indicators than those presented in Tables 4 and 5, utilising experience from a number of PSI references cited in the present paper.

- The fossil systems are subject to limited energetic resources and show in relative terms, at least with respect to coal and oil, unfavourable ecological and accident risk features. Natural gas is by far the best performer among fossil energy carriers but is burdened by substantial greenhouse gas emissions.
- Nuclear energy in industrialised countries such as Germany or Switzerland exhibits very good economic as well as environmental performance. Within OECD-countries it also has an excellent safety record, reflected in very low estimates of technical risks. The sensitive issues for nuclear energy include risk aversion towards hypothetical accidents with very severe consequences 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.
- Hydro power in the OECD-countries under consideration shows a highly favourable picture, in spite of case-by-case issues related to local environmental effects. The 'new' renewables (solar and wind) are environmentally mostly superior to fossil sources but still use rather large amounts of energetic and non-energetic resources. The overall

performance of wind energy is quite favourable, particularly in emerging offshore applications, while economic competitiveness of solar photovoltaic systems is still extremely low primarily due to high solar cell production costs.

- Coal and oil chains exhibit the highest environmental external costs. The external costs associated with natural gas (Combined Cycle) are the lowest among the fossil chains. Renewables and nuclear are characterised by low quantifiable external costs. In terms of total costs nuclear and hydro (particularly run-of-river) show again top performance, superior to other currently implemented technologies. Thus, internalisation of external costs would favour these technologies.
- Since no single system exhibits a superior performance on all criteria trade-offs between environmental, economic and social sustainability components are necessary. Comprehensive assessments of futures system, based on an extended set of criteria and indicators, are presently pursued by PSI and partners on a national level as well as for the European Union. The presented analytical framework is also being applied to heating systems, to energy supply scenarios, and to transportation technologies.

Received: July 5, 2005

---

[1] G. Brundtland (Ed.), 'Our common future: The World Commission on Environment and Development', Oxford University Press, Oxford, **1987**.

[2] S. Hirschberg, R. Dones, 'Analytical Decision Support for Sustainable Electricity Supply', in Proc. VDI Conference on Energy and Sustainable Development: Contributions to Future Energy Supply, VDI, Düsseldorf, **2000**, p. 168–187.

[3] R. Dones, C. Bauer, R. Bolliger, B. Burger, M. Faist Emmenegger, R. Frischknecht, T. Heck, N. Jungblut, A. Röder, 'Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries – Final report ecoinvent 2000 No. 5', Paul Scherrer Institut, Villigen, Swiss Centre for Life Cycle Inventories, Duebendorf, Switzerland. Online version under: *www.ecoinvent.ch*, **2004**.

[4] R. Dones, C. Bauer, R. Bolliger, B. Burger, M. Faist Emmenegger, R. Frischknecht, T. Heck, N. Jungblut, A. Röder, 'Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz – Final report ecoinvent 2000 No. 6', Paul Scherrer Institut, Villigen, Swiss Centre for Life Cycle Inventories, Duebendorf, Switzerland. Online version under: *www.ecoinvent.ch*, **2004**.

[5] M. Goedkoop, R. Spriensma, 'The Eco-indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment', PRé Consultants, Amersfoort, The Netherlands. Available from: *www.pre.nl/eco-indicator99/,* **2000**.

[6] European Commission, DG XII, Science, Research and Development, JOULE, 'Externalities of Fuel Cycles', in 'ExternE – Externalities of Energy – Volume 7: Methodology 1998 update', EUR 19083, European Commission, **1998**.

[7] W. Krewitt, A. Trukenmüller, T.M. Bachmann, T. Heck, 'Country-Specific Damage Factors for Air Pollutants. A Step Towards Site Dependent Life Cycle Impact Assessment', *Int. J. LCA* **2001**, *6*, 199–210.

[8] K. Barrett, Ø. Seland, A. Foss, S. Mylona, H. Sandnes, H. Styve, L. Tarrasón, 'European Transboundary Acidifying Air Pollution. Ten Years Calculated Fields and Budges to the End of the First Sulphur Protocol', EMEP/MSC-W Report 1/95, Meteorological Synthesizing Centre - West, Oslo, **1995**.

[9] S. Hirschberg, G. Spiekerman, R. Dones, 'Severe Accidents in the Energy Sector', PSI Report No. 98-16, Paul Scherrer Institut, Villigen PSI, Switzerland, **1998**.

[10] P. Burgherr, S. Hirschberg, A. Hunt, R.A. Ortiz, 'Accidents in the Energy Sector: Damage Indicators and External Costs', PSI Report, Paul Scherrer Institut, Villigen PSI, Switzerland, to be published **2005**.

[11] S. Hirschberg, P. Burgherr, G. Spiekerman, E. Cazzoli, J. Vitazek, L. Cheng, 'Assessment of Severe Accident Risks', in 'Integrated Assessment of Sustainable Energy Systems in China – The China Energy Technology Program' Eds. B. Eliasson, Y.Y. Lee, Kluwer Academic Publishers, Dordrecht/Boston/London, **2003**, p. 587–660.

[12] S. Hirschberg, M. Jakob, 'Cost Structure of the Swiss Electricity Generation under Consideration of External Costs', in 'Tagungsband SAEE Seminar: Strompreise zwischen Markt und Kosten: Führt der freie Strommarkt zur Kostenwahrheit?', Berne, Switzerland, 11 June **1999**.

[13] S. Hirschberg, R. Dones, U. Gantner, 'Use of External Cost Assessment and Multi-Criteria Decision Analysis for Comparative Evaluation of Options for Electricity Supply' in Proc. 5th International Conference on Probabilistic Safety Assessment and Management PSAM 5, 27 Nov.-1 Dec. Osaka, Japan, Eds. S. Kondo, K. Furuta, Universal Academy Press, Inc., Tokyo, **2000**, p. 289–296. (The results cited here are based on the updated version of this paper, employing the most recent damage functions. It was published in 'PSI Annual Report **2000** – Annex IV'.)

[14] S. Hirschberg, T. Heck, U. Gantner, Y. Lu, J.V. Spadaro, W. Krewitt, A. Trukenmüller, Y. Zhao, 'Environmental Impact and External Cost Assessment', in 'Integrated Assessment of Sustainable Energy Systems in China – The China Energy Technology Program', Eds. B. Eliasson, Y.Y. Lee, Kluwer Academic Publishers, Dordrecht/Boston/London, **2003**, p. 445–586.

[15] S. Hirschberg, R. Dones, T. Heck, P. Burgherr, W. Schenler, C. Bauer, 'Sustainability of Electricity Supply Technologies under German Conditions: A Comparative Evaluation', PSI report Nr. 04-15, Paul Scherrer Institut, Villigen PSI, Switzerland, **2004**.

[16] A. Voss, 'Sustainable Energy Supply – Specification of Guiding Principles' (in German), Proc. VDI Conference on Energy and Sustainable Development: Contributions to Future Energy Supply, VDI, Düsseldorf, **2000**, p. 122–140.

[17] A. Sterling, 'Multi-criteria Mapping: Mitigating the Problems of Environmental Valuation?', in 'Valuing Nature? Ethics, Economics and the Environment', Ed. J. Foster, Routledge, London and New York, **1997**, p. 186–210.

[18] P.A. Haldi, J. Pictet, 'Multi-criteria Output Integration Analysis', in 'Integrated Assessment of Sustainable Energy Systems in China – The China Energy Technology Program', Eds. B. Eliasson, Y.Y. Lee, Kluwer Academic Publishers, Dordrecht/Boston/London, **2003**, p. 661–701.

[19] R. Dones, U. Gantner, S. Hirschberg, 'Environmental Inventories for Future Electricity Supply Systems for Switzerland', in 'Knowledge Infrastructures and Decision Support Systems for Integrated Modelling in Energy Management and Policies', Ed. A.V. Gheorghe, *Special Issue of Int. J. of Global Energy Issues* **1999**, *12(1-6)*, 271–282.

[20] S. Hirschberg, C. Bauer, S. Biollaz, P. Burgherr, W. Durisch, K. Foskolos, P. Hardegger, A. Meier, W. Schenler, T. Schulz, S. Stucki, F. Vogel, 'Erneuerbare Energien und neue Nuklearanlagen', Swiss Office of Energy, Berne, PSI Report No. 05-04, Paul Scherrer Institut, Villigen PSI, Switzerland, **2005**.