PAUL SCHERRER INSTITUT

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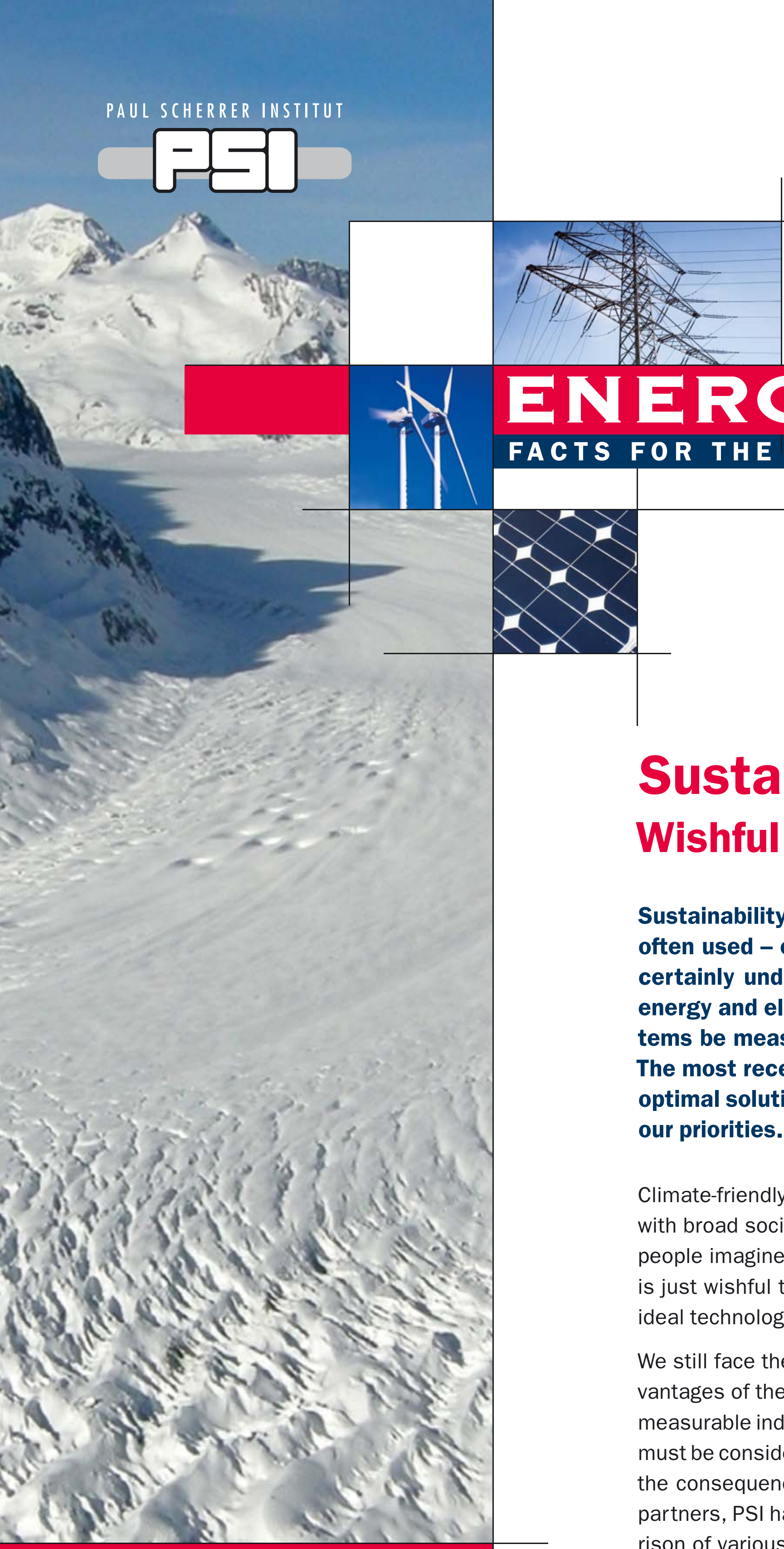
ENERGIE-SPIEGEL

FACTS FOR THE ENERGY DECISIONS OF TOMORROW



Sustainable Electricity:

Wishful thinking or near-term reality?

Sustainability is a hot topic today. Hardly any other concept is so often used – or abused. The desire for sustainable development is certainly undisputed, but what does this mean concretely in the energy and electricity sector? Can the sustainability of energy systems be measured objectively? Which technologies perform well? The most recent research at PSI shows that there are currently no optimal solutions, and that our choice will depend on where we set our priorities.

Climate-friendly, sparing of resources, free of emissions, safe and reliable, with broad social acceptance and, naturally, economical – that's how most people imagine a sustainable electricity supply. Unfortunately, for now this is just wishful thinking. We will have to get by for a long time without such ideal technologies.

We still face the necessity to weigh and balance the advantages and disadvantages of the various alternatives against each other. The best available, measurable indicators for such environmental, economic and social aspects must be considered, for example pollutant emissions, generation costs, and the consequences of possible accidents. In cooperation with its research partners, PSI has developed new methods that allow the systematic comparison of various electricity supply options. Using so-called Multi-Criteria Decision Analysis (MCDA), the measured indicators can be combined with subjective preferences. The comparative sustainability of individual technologies therefore also depends upon which indicators are given the most weight.

If economical electricity is most important, then renewable energy cannot currently prevail. If one wants a supply of electricity with the least possible climate, environmental and health damages, then one must avoid natural gas and, above all, coal plants. If one wants the broadest possible social acceptance, nuclear energy and other large thermal power plants will receive few positive points. If we want to design a sustainable energy supply for the future, then we must weigh the long-term development possibilities of these technologies, and their relationships to our economy and society.

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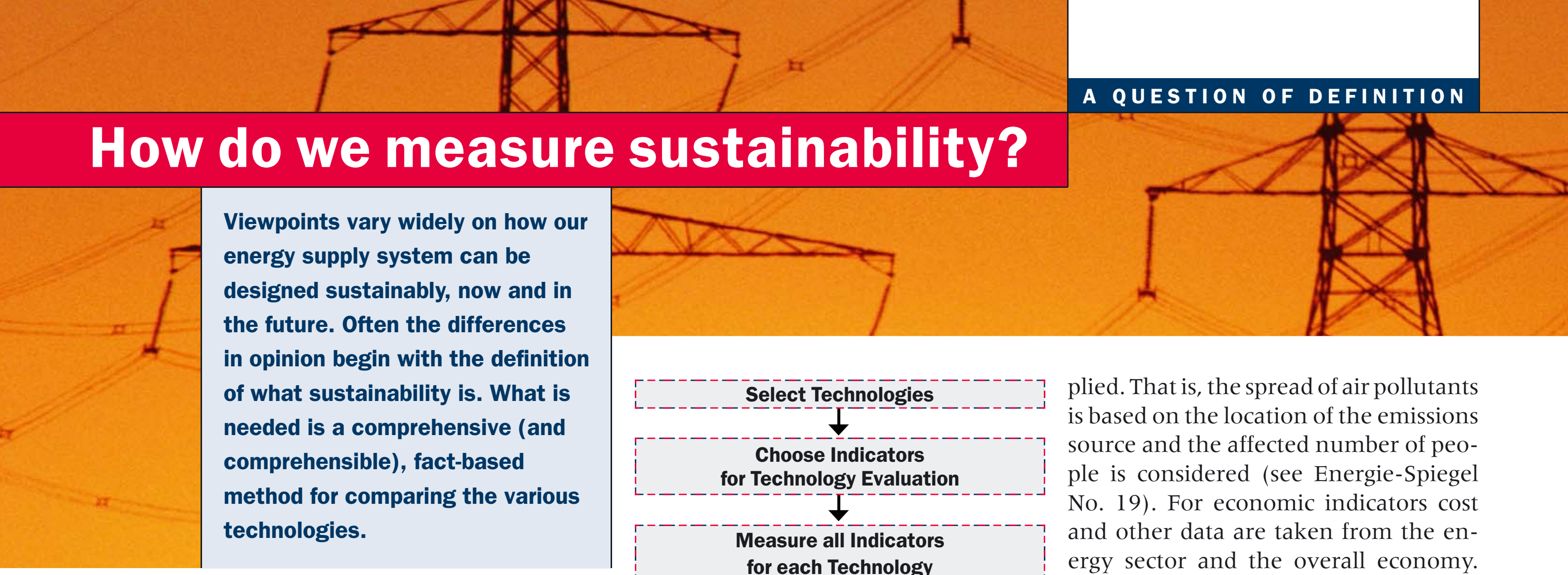

How do we measure sustainability?

Viewpoints vary widely on how our energy supply system can be designed sustainably, now and in the future. Often the differences in opinion begin with the definition of what sustainability is. What is needed is a comprehensive (and comprehensible), fact-based method for comparing the various technologies.

Barely 700,000 hits: That's how many results google.ch finds when the German search terms for "sustainability and "electricity" are entered. They include such various items as Energie-Spiegel No. 3, life cycle assessment of photovoltaic plants, a file on the environment and sustainability of the Leibstadt nuclear plant, the energy and CO_2 vision of the Coop supermarket chain, as well as tips for sustainable investments by the Zurich cantonal bank. From this wide range it is clear – the concept of sustainability is in every mouth. But it is also clear that not all have the same underlying understanding, and that some use the concept for image and public relations campaigns.

Origin and Concept

The "3 pillar model" of sustainability is broadly recognized today, based on fair and just development and environment policies that go back to the so-called "Brundtland Report" of the UN in 1987. In this model, sustainability is based on three equally important areas – environment, the economy and society (see box). At the same time it is recognized that we must strive for global equity, and that the current generation should not live at the expense of the future.

The 3 Pillar Model: Sustainability in Brief

Environment: Nature and the environment must be left intact for future generations.

Economy: Our economy must offer a lasting basis for prosperity.

Society: All members of society must have equal rights to participate in social processes.

Concrete Implementation

In order to be able to judge within these guide rails how sustainable the electricity from a single power plant is, we must be able to measure sustainability concretely. Only so can different systems be compared quantitatively. For this purpose, the tool of multi-criteria analysis was introduced and has since been optimized at PSI (see insert sheet).

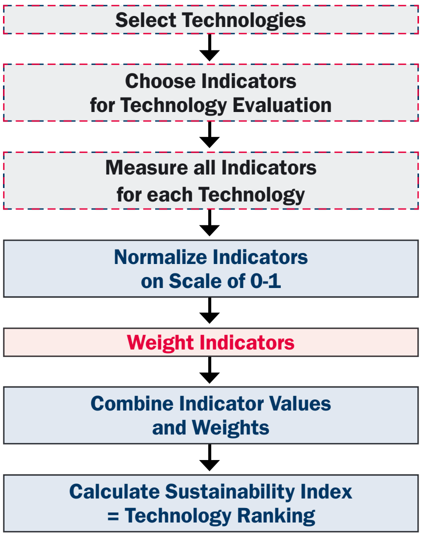

Figure 1: Chart of the multi-criteria analysis process (subjective elements in red, objective steps in blue).

In a multi-criteria analysis the technologies that are to be compared must first be defined (see Figure 1). Next, indicators are established that cover all three areas of the 3 pillar model, and can be measured for each individual technology (see Table 1). These single indicators can already be used for a technology comparison. And from them a single, comprehensive index value can be calculated. This index (or rank) reflects how sustainable the individual technologies are compared to each other. When the overall index is calculated the indicators are each weighted, based on the individual user preferences. The results for the sustainability index differ, depending on the weighting of the indicators, and there is therefore no "right" or "wrong" outcome.

Various methods are used to measure or determine the different indicators. The environmental indicators are mostly based on environmental inventories (see Energie-Spiegel No. 11). Likewise for the objective social indicators, e.g. health damages due to air pollution, where in addition the so-called "impact pathway approach" is also applied. That is, the spread of air pollutants is based on the location of the emissions source and the affected number of people is considered (see Energie-Spiegel No. 19). For economic indicators cost and other data are taken from the energy sector and the overall economy. For measuring subjective social indicators, as for example the perceived risk, experts are often requested to estimate the positions of the populace. This produces an important difference: while the environmental indicators are based on facts from the natural sciences, many social indicators are based on subjectively estimated factors, or in other words, a "gut reaction."

> Sustainability must be concretely measured

Environment	RESOURCES	– Energy Resources – Mineral Resources
	CLIMATE CHANGE	
	ECOSYSTEM DAMAGE	– Impacts from Normal Operation – Impacts from Severe Accidents
	WASTE	– Chemical Waste in Underground Depositories – Radioactive Waste in Geological Repositories
Economy	IMPACTS ON CUSTOMERS	– Price of Electricity
	IMPACTS ON OVERALL ECONOMY	– Employment – Autonomy of Electricity Generation
	IMPACTS ON UTILITY	– Financial Risks – Plant Operation Characteristics
Society	SECURITY & DEPENDABILITY OF ELECTRICITY SUPPLY	– Political Threats to Continuity of Energy Service – Flexibility and Adaptability
	POLITICAL STABILITY	– Potential of Conflict induced by Energy Systems – Necessity of Participative – Decisionmaking Processes
	SOCIAL AND INDIVIDUAL RISKS	– Expert-based Risk Estimates for Normal Operation – Expert-based Risk Estimates for Accidents – Perceived Risks – Terrorist Threat
	QUALITY OF LIVING CONDITIONS	– Landscape Quality – Noise Exposure

Table 1: Sustainability criteria and indicators (PSI/NEEDS: Hirschberg, et al. 2008). A range of European stakeholders were engaged in establishing the set shown, which found broad support.

And what are the results?

The optimum electricity supply for everyone – cheap, environmentally friendly and always available – does not exist. Neither today nor tomorrow. Depending upon personal preferences, different technologies can come out on top in a sustainability comparison.

The cheapest electricity or low CO_2 emissions? Or rather a low risk electricity supply – what is more important? How can such factors be weighed against one another, and what compromises must be made? Such questions present themselves in implementing a sustainable electricity supply. The answers will be different, according to whether the stakeholder is a producer, consumer, politician or environmentalist. And on these answers depends which technologies will be chosen for the electricity supply. How this weighing of values has been solved in two projects, the resulting picture of sustainability assessment and how it compares to the total cost of electricity generation is illustrated below and in the insert sheet.

There's no optimum electricity supply for everyone

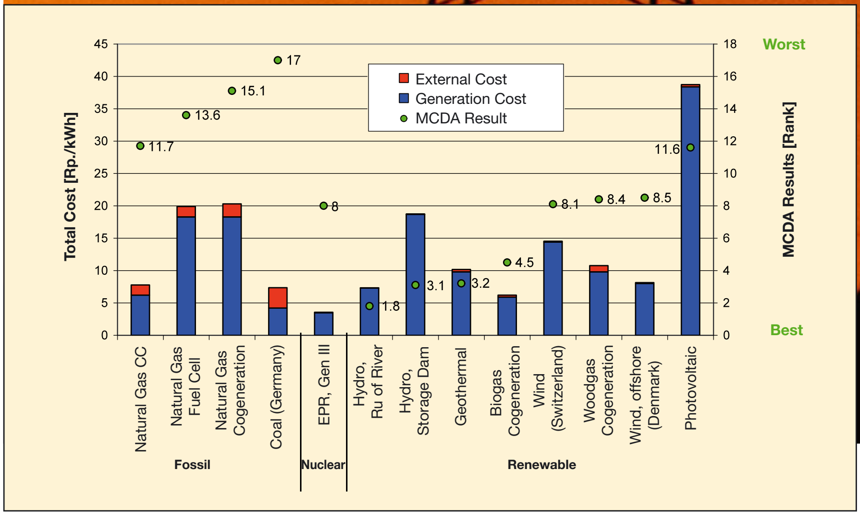

Figure 3: Results of the sustainability evaluation project for Axpo Holding AG: Total costs of electricity production (columns) vs. MCDA results (points) for electricity in Switzerland in 2030 (Roth, et al., 2009). The figure shows a selection of the 18 generation technologies evaluated. CC: Combined Cycle, Cogen: cogeneration, EPR: European Pressurized Reactor.

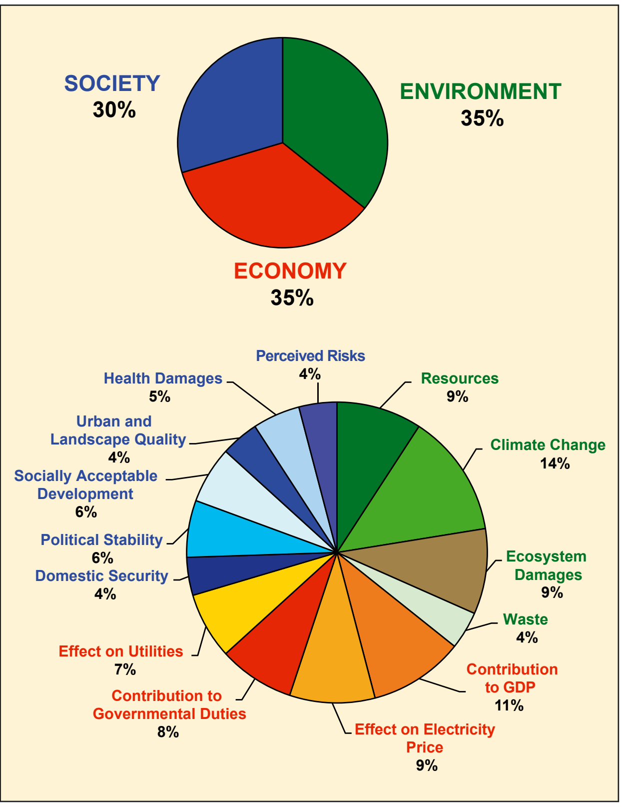

Figure 2: Indicator weights for technology evaluation (Roth, et al., 2009), based on a survey average of 85 employees of Axpo Holding AG (not representative of the general population).

A view of Switzerland…

Figure 2 shows the weight distribution for an applied example in Switzerland, and Figure 3 shows the resulting differences between the individual technologies for both the sustainability comparison and the total costs for the year 2030. The spectrum of technologies includes renewable and fossil energy carriers as well as nuclear energy. Electricity from foreign power plants is also imported.

The sustainability assessment results for the fossil systems (MCDA results) appear bad, even when the total costs are low. This is based on the relatively poor results for the environmental indicators, the dependence on foreign energy resources, and above all the health damages caused by burning coal. The renewable energies lie in the top and middle of the MCDA ranking, due to their good environmental and social indicator performance. The high generation costs of photovoltiacs however also affect the MCDA evaluation. Nuclear energy shows the lowest total cost, but is in the middle of the sustainability ranking. The reason is that some factors, whose monetization is controversial, e.g. the consequences of possible accidents or the waste disposal question (see box) – were perceived as negative and relatively highly weighted.

Total costs and external costs of electricity generation

Costs are called "external" if they are not born by the party that causes them, but rather by society as a whole. They include the costs of health damages that result from air pollution. Such damages are monetized, i.e. are measured in or converted to monetary units, including those resulting from future climate change. These are very uncertain today, and can vary over a large range. Further aspects are reduced harvests and damages to buildings caused by air pollution.

Not all factors that play a role in judging a technology are measured in Francs and Rappen: This is controversial, above all the significance of subjective aspects like perceived risks or visual disturbances to the landscape.

In spite of these limitations, external costs are very valuable for cost-benefit analysis.

The total cost is obtained by adding the production (or internal) and external costs of electricity together, and is sometimes also used as a measure of sustainability, although this is controversial. Non-monetized factors are then naturally not considered.

“Provide knowledge and assist decisionmakers”

Dr. Stefan Hirschberg has been leader of the Laboratory for Energy Systems Analysis, which is affiliated with both of PSI’s energy research departments, since its creation in 2006. He has been at PSI since 1992, and was previously responsible for the systems and safety analysis section. The theme of sustainability within our energy supply has been part of his work for almost 20 years.

Why is Multi-criteria Decision Analysis (MCDA) so suitable for evaluating sustainability?

Because it makes it possible to combine fact-based knowledge with the subjective valuations of quite different stakeholders. And it does this in a transparent process. The strengths and weaknesses of individual technologies are clearly shown. It is also demonstrated which technologies are robust, that is, which perform consistently well with different criteria weights. Such analyses can communicate knowledge, and assist decisionmaking.

Are the results robust enough to support decisionmaking?

Yes, even when there are uncertainties. And the longer the time horizon, the larger these are. That affects the expected technology development, costs, etc. The uncertainties of indicators like health risks are fundamentally measurable. However many social indicators contain subjective elements, and so from a natural science viewpoint are “less exact,” and this inexactness is also difficult to estimate. But uncertainties in indicator values have less impact on the results of MCDA than changes in individual criteria weights. Making this clear is an important part of MCDA.

Where are the boundaries of sustainability analysis today?

At the moment, every kilowatt-hour of electricity is regarded by MCDA as equally valuable. This is independent of whether it is reliably provided or not, or how large the resource potential is. In reality however, the interplay of various systems is required. For example, when evaluating the various options for the electricity supply by means of MCDA, different overall system electricity mixes must also be considered within the range of boundary conditions. Such a future mix must also include expected energy efficiency measures. So there is still enough to do in the coming years.

How important is technology characterization for the results of MCDA?

Very important. From the beginning of an MCDA exercise it should be clear whether the analysis addresses current or future technologies, and where they are located. It is often controversial how positive the future development possibilities are judged to be for technologies that are still not on the market today.

You began your work in sustainability analysis more than 10 years ago: What have been the most important advances?

Since the beginning, we have been able incorporate more indicators that by now cover all relevant areas, and thanks to cooperation with social scientists, handle the social aspects in a significantly better way. The technology spectrum has been expanded – with a time horizon extending to 2050 – and new MCDA methods and associated user tools have been developed. And last but not least, we have been able to directly involve various stakeholders.

Which stakeholders? Could any agreement be reached regarding the significance of the individual criteria?

That depends on the project. When the interests of the various actors are similar, it is possible to reach consensus through a moderated discussion process. But when, as in the EU research project NEEDS, the stakeholder groups are very diverse – including industry, politics, science and NGO’s – then a detailed consensus is almost impossible. At least there is partial agreement that overall the environment, economy and society should be treated on an equal basis.

Is Multi-Criteria Analysis a replacement for total costs?

No. Both methods complement one another and have different purposes. MCDA does not give unique answers, since the results depend on the weights given to the indicators. In contrast, the total cost approach gives a single result that is relevant for cost-benefit analysis. The concept of external cost, most of the results and, above all, the necessity of internalizing the external costs, are all broadly accepted. But the treatment of nuclear energy is controversial. This is also shown in the comparison of results between the total cost and MCDA methods.

What’s next for sustainability analysis?

We are working to extend sustainability analysis to the transportation sector. In the next years many innovative vehicles will come on the market, for example electric and hydrogen cars, along with the necessary infrastructure. We will integrate these new concepts into the analysis, together with central and decentralized electricity sources for EV’s and the demands on the electricity grid.

Impressum

Energie-Spiegel, or Mirror On Energy, is the newsletter of PSI for the comprehensive analysis of energy systems (Projekt GaBE). Contributions to this issue come from S. Hirschberg, C. Bauer, W. Schenler and P. Burgherr.

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Energy Systems Analysis at PSI: The goal of energy systems analysis at the Paul Scherrer Institute in Villigen is to analyze present and future energy systems in a comprehensive and detailed way, considering in particular health, environmental and economic criteria. On the basis of Life Cycle Assessment (LCA), energy-economic models, risk analysis, pollution transport models and finally multi-criteria decision analysis, it is possible to compare different energy scenarios to create a basis for political decision making.

GaBE works together with:
ETH Zürich, EPF Lausanne; EMPA; Massachusetts Institute of Technology (MIT); University of Tokyo; European Union (EU); International Energy Agency (IEA); Organisation for Economic Cooperation and Development (OECD); and United Nations Organization (UNO).

Different Emphases

It all depends where the emphases are set. Different technologies score quite differently, depending on whether ecological, economic or social indicators are given preference.

A View of Europe

The analysis for Europe in the year 2050 was focused on future technologies, where significant technological advances may be expected in comparison to today. The expected advances were in some cases quite optimistic, particularly for photovoltaics and Generation IV nuclear reactors.

What is particularly noticeable is that based on the weighting shown (Figure 4, left), there is again a significant discrepancy between the lowest total cost and the moderate MCDA assessment of nuclear energy (Figure 5). It is also significant that the use of fossil energy carriers is associated with comparatively high external costs, while at the same time the MCDA assessment of them turns out to be almost consistently bad. In contrast the renewable energies perform well in the MCDA assessment: they profit from the lowest environmental and health damages, from social acceptance, and last but not least, from the assumption that their costs in the coming 40 years will decline drastically.

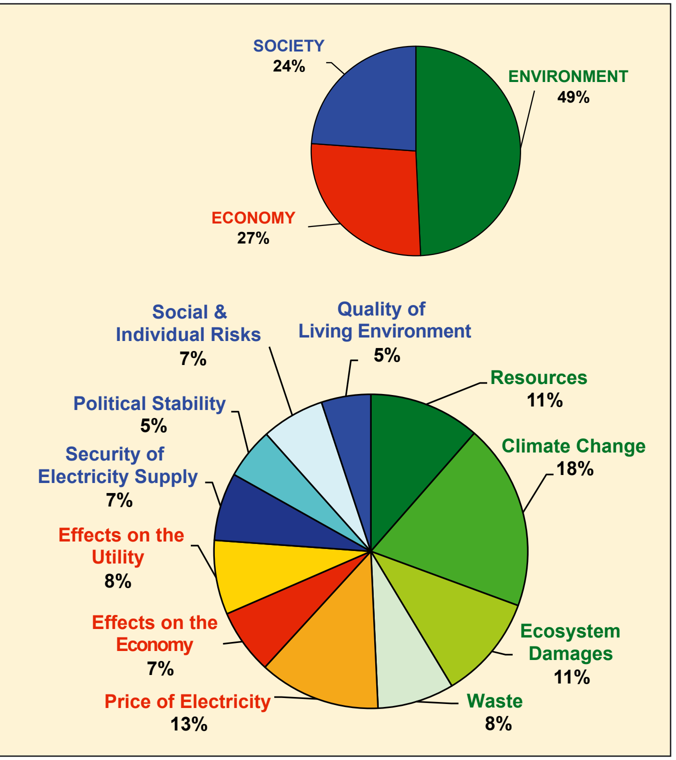


Figure 4: Average indicator weights for technology assessment (PSI/NEEDS; Schenler, et al., 2009), obtained via online survey from stakeholders engaged in the European energy sector (not representative of the overall population).

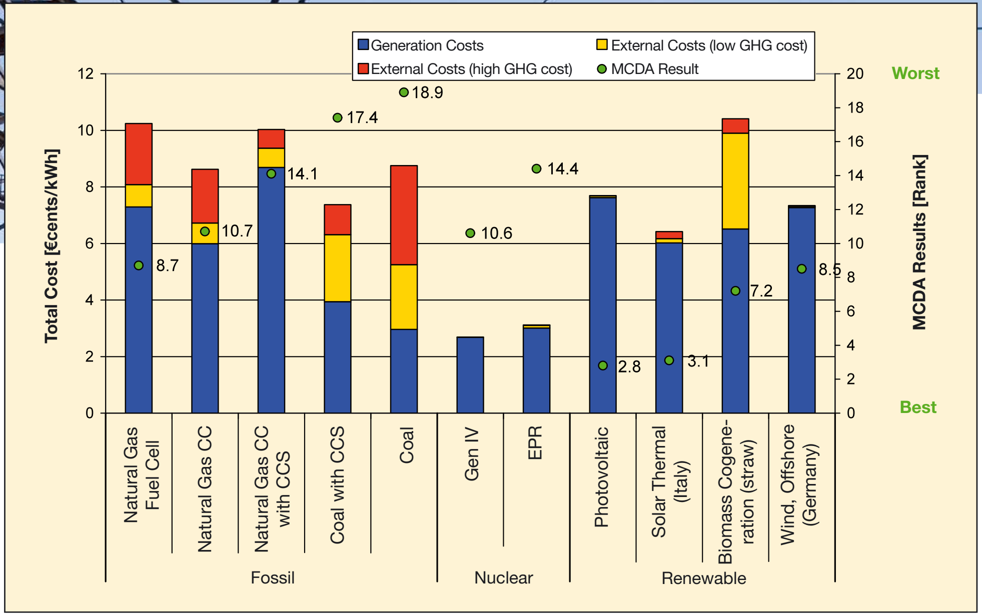


Figure 5: Results from the NEEDS project: Total costs of electricity generation (columns) vs. MCDA results (points) for supplying Switzerland in the year 2050 (PSI/NEEDS; Schenler, et al., 2009). The figure shows a selection of the 26 systems evaluated. GHG low/high values represent low and high estimates of damage costs due to climate change. For abbreviations, see Figure 3 and Table 2.

Figure 6 shows the sustainability rankings for three very one-sided weighting profiles (see Figure 7) with emphases on ecological, economic or social indicators. If the price of electricity is foremost, nuclear energy and coal are the systems selected. Renewable and natural gas technologies are then comparatively worse. If only the social indicators count, then the exact reverse is true: most renewables are at the top, while coal and nuclear energy are worst. Results for an environmental emphasis are similar: renewables are best, followed by nuclear and natural gas systems, and the worst results are again for coal.

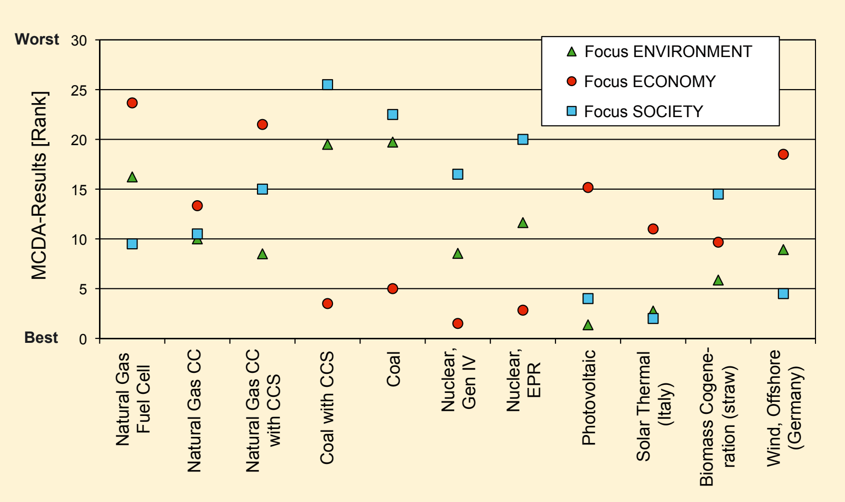
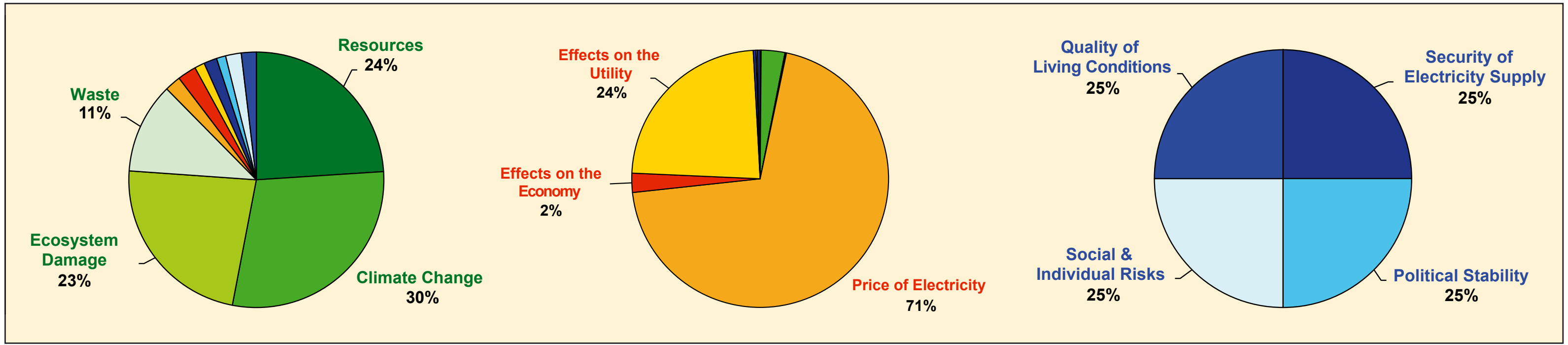


Figure 6: Results from the NEEDS project: MCDA assessment for the Swiss electricity supply for the year 2050 with three different indicator weighting profiles, see Figure 7 (PSI/NEEDS; Schenler et al. 2009). For abbreviations see Figure 3 and Table 2.

Figure 7: Indicator weights for technology assessment for very one-sided weighting profiles (a small fraction of survey respondents). Left: environmental emphasis, Middle: economic emphasis, Right: societal emphasis (PSI/NEEDS; Schenler et al. 2009).



Development of sustainability assessment at PSI

1999–2000: First Multi-Criteria Analysis for the Swiss electricity supply (ref. Energie-Spiegel No. 3).

1999–2003: China Energy Technology Program – MCDA application for China, including an interactive tool (ref. Energie-Spiegel No. 17).

2002–2004: MCDA application for the case of Germany (ILK).

2004–2006: Sustainability assessment model for the Swiss electricity supply in collaboration with the utility company Axpo and other partners (for today and 2030).

2005–2009: EU Project NEEDS – Sustainability assessment of innovative electricity supply technologies to 2050 under the leadership of PSI, and with cooperation of industry and NGO's.

2010–2014: THELMA project – Sustainability assessment of personal vehicles.

		Nuclear [1]			Fossil										Renewable											
		Gen II	Gen III	Gen IV	Natural gas CC [2]			Nat. gas CC [2], CCS [3]		Coal (DE)			Coal, CCS [4] (DE)		Hydro, Storage [5]		Photovoltaic, Rooftop [6]			Wind, onshore [5]		Wind, offshore (Northsea)			Biogas cogen [5]	
		today	2030	2050	today	2030	2050	2030	2050	today	2030 [a]	2050	2030	2050	today	2030	today	2030	2050	today	2030	today	2030	2050	today	2030
Greenhouse Gas Emissions	kg(CO$_2$-Äq.)/kWh	0.008	0.004	0.001	0.426	0.388	0.385	0.120	0.119	0.912	0.753	0.685	0.205	0.084	0.004	0.004	0.062	0.030	0.003	0.017	0.016	0.010	0.010	0.003	0.077	0.037
Ecosystem Damages	PDF*m2*a/kWh [7]	1.2E-03	8.3E-04	3.6E-04	3.6E-03	3.3E-03	3.3E-03	4.5E-03	4.5E-03	1.4E-02	1.3E-02	1.3E-02	2.0E-02	4.5E-03	3.1E-04	3.1E-04	6.9E-03	5.4E-03	1.2E-03	6.1E-03	3.4E-03	3.2E-03	3.4E-03	1.1E-03	4.9E-02	3.7E-02
External Costs	Rp./kWh	0.08	0.07	0.07-0.11	1.6	1.6	0.6-3.3	n/a	0.5-1.3	3.5	3.1	2.2-7.5	n/a	1.4-2.6	2.6	2.7	0.5	0.3	0.06-0.09	0.2	0.1	0.1	0.1	0.04-0.06	1.6	0.3
Generation Cost [8]	Rp./kWh	4-5	5.8-7.2	3.9-8.4	10.8-11.4	11.8-12.5	13.8-14.4	15.5-16.2	14.7-15.4	6.0-6.7	6.0-6.7	6.0-6.7	7.8-8.8	7.5-8.3	10.5	11.9-28.0	42-66	15-34	8-25	21.4-26.5	16.2-19.8	11-13	9-11	8-11	10.4	6.3
Capital Cost	1'000 CHF/kW$_{el}$	[b]	3.5-5.0	2.5-7.0	0.9-1.4	0.8-1.3	0.8-1.3	1.400-2.0	1.2-1.8	2.0-2.7	1.8-2.5	1.7-2.4	2.7-3.7	2.5-3.3	[b]	4.0-10	5.0-8.0	1.7-4.0	0.9-3.0	1.8-2.5	1.5-2.0	2.7-4.0	1.7-3.0	1.5-2.7	6	4.2
Fuel Price Sensitivity [9]	%	5-6	4-5	0	63-67	67-71	72-75	54-56	53-56	47-52	50-56	51-57	44-50	45-50	0	0	0	0	0	0	0	0	0	0	15	22
Health Damages	YOLL/kWh [10]	5.2E-09	4.7E-09	2.7E-09	2.8E-08	3.3E-08	7.4E-08	n/a	8.7E-08	6.5E-08	7.3E-08	2.7E-07	n/a	2.3E-07	1.2E-09	1.4E-09	1.8E-08	1.2E-08	8.4E-09	7.0E-09	6.6E-09	4.6E-09	5.9E-09	6.3E-09	1.2E-07	1.5E-08
Severe Accidents [11]	deaths/GWa	7.3E-03	1.1E-05	1.6E-04	4.5E-02	3.1E-02	6.9E-02	7.5E-02	7.4E-02	1.8E-01	1.0E-01	1.2E-01	1.9E-01	1.4E-01	3.7E-03	3.7E-03	1.0E-02	1.0E-02	1.0E-04	1.5E-02	4.3E-03	6.8E-03	1.0E-03	2.7E-03	1.5E-02	2.1E-03
Max. Accidental Consequences [12]	deaths	10'000 [c]	50'000	3'000	109	109	109	109	109	434	434	272	434	272	276 [d]	285 [d]	10	10	5	5	5	10	10	10	5	5
Waste, Radioactive	m^3/kWh	5.6E-08	2.3E-08	1.7E-08	6.2E-11	3.5E-11	1.1E-10	8.6E-10	3.5E-10	6.1E-10	3.4E-10	2.0E-10	1.40E-09	4.4E-10	5.3E-11	4.0E-11	8.3E-10	2.7E-10	4.3E-11	1.6E-10	8.4E-11	1.3E-10	6.3E-11	2.2E-11	9.3E-10	6.2E-10
Waste, in underground depository [13]	m^3/kWh	9.6E-10	6.3E-10	2.2E-10	4.9E-09	4.5E-09	4.4E-09	1.7E-08	5.2E-09	1.7E-08	1.1E-09	1.4E-08	3.8E-08	7.3E-09	6.6E-11	6.4E-11	4.4E-08	2.9E-08	1.8E-09	7.2E-09	5.7E-09	5.6E-09	7.5E-09	1.9E-09	1.1E-09	9.7E-10

1) 2030: EPR – European Pressurized Reactor; 2050: EFR - European Fast Reactor
2) CC: Combined Cycle power plant
3) CCS: Carbon Capture and Sequestration; 2030 & 2050: post-combustion process
4) Carbon Capture processes: 2030 post-combustion; 2050 oxyfuel combustion
5) No significant changes expected for 2050 v. 2030
6) 2010 & 2030: crystalline silicon; 2050: thin film cells
7) PDF: stands for loss of species diversity
8) Interest rate 6%; Nuclear & Hydro from plants operating today, capital costs partially depreciated; Biogas: heat credit included
9) Increase in generation cost due to doubling of fuel price
10) YOLL: Years of Life Lost by premature death (due to normal operation)
11) Maximum consequences from theoretically possible accident; values rounded for nuclear
12) Special waste, not radioactive
a) Cost data for customary power plant; other indicators: Integrated coal gasification
b) No new construction realistic
c) ca. 400 MW power plant
d) Valid for a real 50 MW power plant; max. accidental consequence for large storage hydro, Swiss: 11,000 without forewarning

Table 2: Indicators for technology characterization: partially different data sources for 2030/2050.