W. Kröger*

Measuring the sustainability of energy systems

Today's energy policies are characterised by a contradictory position. In theory, there is a clear will to respond to emerging threats, e.g. evidence of man-made climate change, irresponsible use of limited resources, geopolitical discrepancies with unbalanced satisfaction of vital needs. In practice, decision making is dominated by economic competitiveness and maximisation of short-term profit. The use of fossil fuels is unbroken and still increasing. A recent Green Paper concluded that the EU countries have to reduce growing structural weaknesses by limiting dependence on fuel imports and to give priority to energy systems that do not emit global warming gases.[1]

As a matter of principle, our energy supply must reach a higher degree of sustainability. The major goal must be to stop carbonising and finally decarbonise the current worldwide energy systems as much as possible. This huge task can only be achieved in a stepwise approach. For the transition phase, the "most sustainable" options among the fossil energy systems must be identified and used. Non-fossil options need to be further developed and implemented. But the use of carbon-free energy systems (hydro, nuclear, new renewables) also has to be balanced in a way that optimally and equally fulfils economic, ecological and social criteria as elements of sustainability. For this purpose, appropriate tools and suitable attributes are needed to assess technological options, both to strategically choose the most adequate energy mixes and to foster, guide and control necessary technological developments.

Assessment matrix

To make the concept of sustainability operational and to provide technical input for decision-making processes we need to transfer the somewhat abstract idea into principles. This can only be done for a defined field of application or sector. The Swiss *Paul Scherrer Institut* has developed a set of sector-specific indicators with which different options for electricity supply can be evaluated. They are applicable both to different technologies and to different levels of development (current – advanced – potential) within a single technology. These indicators must be determined comprehensively on the basis of whole energy chains. Besides life cycle analyses (LCA), environmental impact assessment (EIA) and risk assessment (RA) provide the methodological framework. The proposed indicators (see Table 1) correspond to a restricted number of criteria derived from sustainability principles. They are mostly independent and unaggregated to ensure sufficient transparency. In addition, they aim to be quantifiable, although a few will probably remain at least semi-qualitative. At the same time they are representative of the much larger number of attributes used in current sustainability assessments.

The first principle "no exhaustion of resources" includes natural resources like fuels but also other materials. Following a broad interpretation, it covers not only the environment, but also human resources like public health as well as social peace and economic welfare. In detail, safety aspects

** Prof. Wolfgang Kröger is Director of the Nuclear Energy and Safety Department at the Paul Scherrer Institute (e-mail: wolfgang.kroeger@psi.ch).*

Table 1: Assessment matrix for different energy systems, each considering the same level of development

Principles	Criteria	Indicators	Units of measure
"no" exhaustion of resources	use of fuel /	availability of reserves [1]	years
	other materials (example: Cu ore)	consumption	tons *
	extent of land losses	plant operation	km^2 *
	effects on water (example: pollution by Zn)	pollution or consumption	tons *
	environmental impact through emissions	climate relevant gases	kilotons CO_2 equiv. *
		gases damaging the ozone layer	tons FCKW equ. *
	impact on human health	normal operation	years of life lost *
		accidents / collective risk	fatalities *
	impact on societal aspects	risk aversion	land losses (km^2)/ fatalities per accident [2]
		work opportunities	Δ persons/year *
		proliferation threat	qualitative
	economic efficiency	internal and external costs	currency unit/kWh
"no" production of non-degradable waste	produced amount of hazardous substances		m^3 *
	necessary confinement times [3]		years
"no" high sensitiveness to social and environmental factors	supply and disposal security	foreign dependency	qualitative
		technology availability [4]	currency unit *
	robustness, i.e. no necessity for...	...rapid external interventions [5]	hours
		...socio-political / financial stability	qualitative

* per GWa_e or GWh_e.
1) Under the assumption of a stabilisation at today's production level.
2) Maximum value identified through risk analyses for a 1 GW(e)-plant.
3) Necessary to achieve "natural levels".
4) Expected costs for R&D up to commercialisation.
5) Time period following an abnormal event, before human corrective actions become necessary.

are accounted for in "collective risk" (as expected value for fatalities caused by undesired events and corresponding frequencies), and in maximum losses due to the worst conceivable accident. Economic competitiveness is considered through both internal (production) and external (environmental damage) costs.

The second principle of "no production of non-degradable waste" is specified by the amount and the necessary confinement times (based on the evolution of waste toxicity or radiotoxicity over time). The degree of public acceptance is not treated as a specific criterion; instead, other aspects that may influence the social perception of technology (risk aversion, jobs, threats, etc.) are explicitly considered.

The principle of "no high sensitiveness to social and environmental factors" is hard to specify; security of supply and robustness of technical systems have been selected as criteria.

Cross comparison of indicators

Comprehensive analyses made to date show that most of the proposed indicators can already be quantified. Corresponding results reveal the strong and weak points of the different energy chains (see Table 2 for a subset of quantified indicators).

The fossil-fuel systems are subject to limited energy resources. They show the well-known problematic ecological characteristics and also relatively unfavourable risk features; natural gas is the best performer among them. Hydropower shows an excellent performance but the cost range is broad, as new hydro plants are expensive. The "new" renewables (solar and wind) are environmentally superior to fossil sources. They also have the highest potential for technical improvements. However, they need large amounts of non-energetic (material) resources and, in the short to medium term, they only have a strongly constrained potential to become major suppliers of electricity at competitive prices.

Challenges for nuclear energy

Nuclear energy is not only characterised by low levels of emissions, but within the Western world, also by an excellent safety record. This is reflected in comparatively low estimated collective risks for both normal operation and severe accidents.

Table 2: Selected (example) indicators for current energy systems

Applies for every option: the upper row shows a range of values for current systems; the lower row gives the corresponding values for the best future systems under Swiss conditions (time horizon approximately 20 years). All data are based on life cycle analyses.[1]

	Fuel reserves	Material consumption (copper ore)	Greenhouse gases	Sulphur dioxide	Inorganic waste in repository	High- and intermediate-level rad. waste	Production costs	External (environmental) costs
	Years	kg/GWh_e	$t(CO_{2\text{-eq}})/GWh_e$	$kg(SO_x)/GWh_e$	kg/GWh_e	m^3/GWh_e	Rp^*/kWh_e	Rp^*/kWh_e
Hard coal	160-2 300	14-19 59	950-1 200 770	920-25 000 520	5 800-54 000 4 000	0.13-0.20 0.04	5.7-7.4 6.3	3.1-15.8 5.1-8.6
Natural gas	70-170	16 8	530 390	260 150	1 500 1 100	0.04 0.004	4.7-5.8 4.7-8.2	0.8-5.5 2.5-4.2
Nuclear	120-400	7-9 4	8-29 6	56-150 33	650-1 200 600	9.0-11.0 2.4	5.1-7.5 5.7-7.2	0.2-1.3 0.3-0.4
Hydro storage	∞	< 1 < 1	4 4	8-10 7	30 30	0.006 0.002	4-21 12-16	0-1.2 0.1
Photovoltaic	∞	270-1 600 350	110-260 44	700-3 600 160	4 900-10 000 1 600	0.6-1.2 0.06	70-140 45	0.1-1.5 0.5-0.7

* Rp: Swiss cents.
1. PSI/ETH Zurich: Energie-Spiegel Nr.3, Sept. 2000.

Catastrophic events with releases of radioactive substances have not happened in power plants of Western design; studies show a potential for high-consequence events at extremely low frequency levels.

For fossil and hydro plants statistics show numerous serious accidents, a few with even more than 1000 immediate fatalities (the latter due to oil fires and dam failure in non-OECD countries). The evaluation of statistical data for OECD countries leads to average risk figures in the range of $7x10^{-2}$ (gas) to $4x10^{-1}$ (oil) fatalities per GW(e)•a. For nuclear power the accidental risk is dominated by latent effects following large releases of radioactive substances in the course of core-melt accidents combined with early containment failure. Based on probabilistic analyses (PSA level 3), up to several tens of thousands of late fatalities must be accounted for, although the frequency of such catastrophic events is extremely small ($<<10^{-7}$ per reactor year). The multiplication of these two parameters leads to calculated risk figures in the range of 10^{-1} down to 10^{-3} late fatalities per GW(e)•a for Western plants of differing designs and site conditions. If nuclear power has to play a major role in a future and more sustainable energy mix, these figures should (and can) be further reduced by technical means.

The potential for high-consequence events is perceived as a Damoclean type of risk: although their frequency is almost negligible, a large part of the public reacts adversely and refuses acceptance.[2] Therefore, improved protection against severe accidents is one of the biggest hurdles nuclear power plants have to surmount without falling into the "economy trap". Built-in design measures should allow the possibility of excluding catastrophic events and eliminating the need for off-site emergency planning. Besides strengthening the containment (e.g. for the European pressurised water reactor – EPR), other ways should be explored to enhance the use of inherent safety features and/or passive systems, both for reactivity control and after-heat removal (e.g. small, modular, high-temperature, gas-cooled reactors or passive, advanced light water reactors). Apart from their considerable innovation potential, they could offer possibilities for plant simplification and further increased availability, and therefore play an important role within a cost-reduction strategy.

Moreover, a sustainable use of nuclear energy should include the closure of the fuel cycles and strategies for waste volume reduction. Innovative technologies need to be pursued to reduce secured confinement times to historical scale, as well as the potential danger of man-made intrusion. Promising solutions are the partitioning and transmutation of minor actinides and long-lived fission products partly in novel dedicated systems. For this purpose, the option of reprocessing must remain open. The plants involved should ideally be part of an integrated system, mainly to avoid or control undue transport and proliferation risks; their safety standards must be equivalent to those outlined before.

Partitioning and transmutation (P&T) aims at reducing the potential long-term impact of high-level nuclear waste in geological disposal sites by eliminating many of the actinides (long-lived radioactive isotopes) it contains. In order to eliminate these actinides, the spent nuclear fuel needs to be reprocessed – separating the elements that can be used again from those that will need to be disposed of directly – and then "recycled" by making new nuclear fuel and burning it in a nuclear reactor (preferably a fast neutron reactor). Multiple recycling can lead to a reduction in the mass of actinides going to final geological disposal by a factor of 100. The drawback, however, is that the fuel to be handled in such a recycling scheme becomes more highly radioactive, possibly demanding new reprocessing and fabrication techniques.

New debate

To introduce sustainable development as a guiding principle into decision-making processes, consensus needs to be reached among all participating groups about which criteria and indicators are to be applied, and, in addition, on how they can be aggregated and weighted.

Nuclear energy can only play a major role if one succeeds in increasing societal acceptance. This can be achieved only partly with technical solutions and innovative developments; it is just as important to convince society of the benefits of nuclear energy and to regain trust.[2] This also means that new forms of debate need to be found with stakeholder participation and reliable technical information as transparent input.

References

1. CEC Green Paper "Towards a European strategy for the security of nuclear energy supply", COM (2000) 769.
2. The TRUSTNET Framework, EUR 19139, 2000.
3. PSI/ETH Zurich: Energie-Spiegel Nr.3, Sept. 2000.