Comparative health and environmental risks for various energy sources

A report of results from a key issues paper at Helsinki

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The first attempts to compare the environmental and health impacts of different electricity production systems were made in the 1970s. At that time, fundamental decisions had to be taken on the best way of satisfying the rapid growth in electricity demand. Promoters of this generation of comparative studies were basically inspired by a willingness to rank on a unidimensional scale of risk the different options available at the time with regard to their negative impacts on the public at large.

Initial studies dealt with isolated or single-installations, because the main concern of the population was anxiety about living close to power stations. The scope of comparative studies has since been enlarged with the development of related methodologies. It soon became evident that a fair comparison of different electricity generating options should consider the whole spectrum of the entire cycle of the energy systems.

The next step in the development of comparative studies was to include the construction and dismantling phases of the installations. In fact, analysis revealed that, for many installations, these were the most important parts of risk.

This shift towards including the construction phase opened the way for even broader comparisons, such as the effects associated with production of the materials used to manufacture the necessary equipment. Within such a large perspective, comparison of health and environmental impacts is rejoining macroeconomic aggregates such as investment or employment, and comes close to the idea of "technology assessment". With the second generation of comparative studies, the main change lies in the importance given to the decisional context of the comparative risk assessment process.

The objective of ranking the different electricity generation systems is generally recognized as providing an insight into the respective merits of energy systems. Interest has now turned towards integration of health and environmental effects into alternative scenarios for electricity production that comprise various energy sources, and comparison of these scenarios in relation to specific socio-economic contexts, either at the local, regional, or national level.

It should be noted that the comparative studies made to date have covered the environmental impacts of different energy sources to a much lesser extent than the health impacts.

Comparison of health risks

A critical and extensive survey of earlier comparative risk assessment studies was performed by the UK Health and Safety Executive (HSE). The HSE survey (in 1980) particularly highlights the deficiencies in aggregating the various dimensions of risk into a single indicator, and the uncertainties associated with quantifying certain risks which may not be amenable to quantification; in particular, to uncertainties in quantifying dose-effect relationships, including the delayed and long-term effects of exposure to chemicals.

The HSE report indicates that non-nuclear risks are often less well understood than the corresponding nuclear risks, and calls for greater

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understanding of a) the significance of upper and lower limits to alleged chronic sulphur effects; b) long-term effects of non-nuclear wastes; c) the potential severe accidents associated with certain non-nuclear plants; and d) the distinction between the average risk of a system and that associated with marginal change.

The study made by A.F. Fritzsche (in 1989) is one of the most recent and comprehensive reviews of comparative risk assessment for different energy sources. The risk results are broadly founded on the international risk literature, which is critically reviewed. The results based on this study carefully differentiate between the various dimensions of risk, specifically those associated with normal and accident conditions, and are believed to be representative of the large modern power stations which could be built at the present time in Europe. *(See graphs.)*

Although ranking of the various energy systems from a health risk perspective may be done, the absolute values must be viewed and interpreted with caution, and on a relative basis, because of the variations that exist in sites and technologies.

Taking into consideration the above reservations in interpreting the results, the following comparative statements, based on the findings of Fritzsche's study *(excluding severe accidents)* can be made on health risk impacts:

- ***Immediate occupational risk.*** For the coal cycle, occupational risk is distinctly higher than those for oil and gas; it is the same order of magnitude as those associated with renewable energy systems and about 8-10 times higher than the corresponding risks for light-water reactors (LWRs). Future technological advances for renewable solar and wind energy sources may result in a significant reduction in the immediate occupational risk associated with these systems (up to a factor of four). Hydraulic electricity generation remains a comparatively risky option with respect to immediate occupational risk.

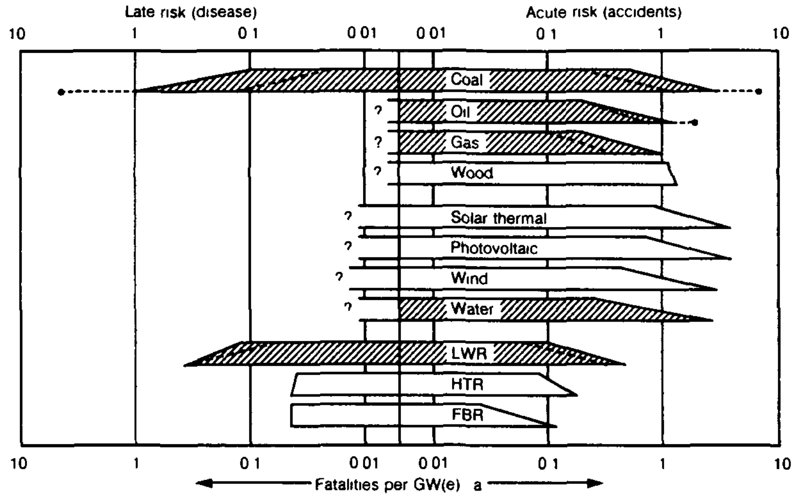
- ***Delayed occupational risk.*** Delayed fatalities arise mainly in coal and uranium mining, and are of the same order of magnitude. Underground coal mining, however, appears to be more dangerous than underground uranium mining on the basis of a normalized unit of electricity generated.

- ***Immediate public risk.*** These risks are mostly due to transportation accidents and are highly dependent on the distances travelled and the mode of transport. The risk of the nuclear option is 10-100 times lower than all the other options, mainly because of the relatively low quantity of materials that have to be transported per unit of electricity produced. By the same token, the coal cycle has the highest immediate public risk because of the large material transport requirements.

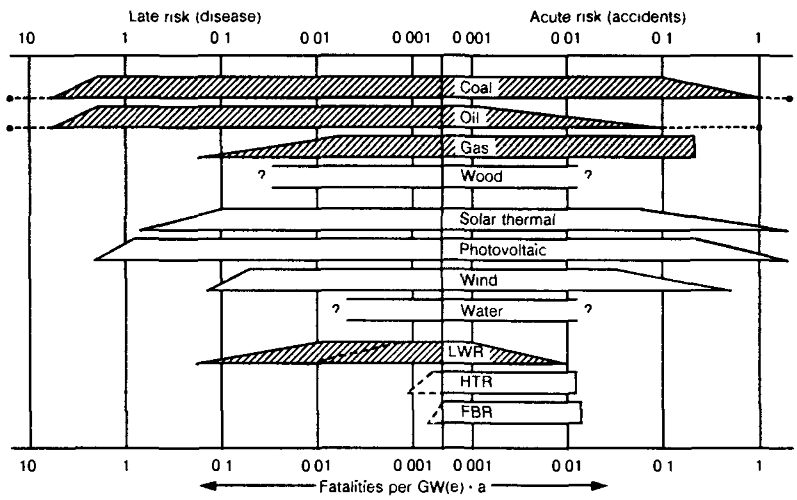
- ***Delayed public risk.*** There are great uncertainties associated with the estimations of delayed public risks from all the energy sources. The results should, therefore, be interpreted with great care. Such results indicate that delayed public risks for nuclear and natural gas are of the same order of magnitude, at least 10 times lower than those for coal and oil. It should also be noted that delayed public risks for certain types of renewables are also relatively high, although future developments are expected to result in significant decreases in such risks.

Mortality risks due to electricity production

Occupational mortality risk



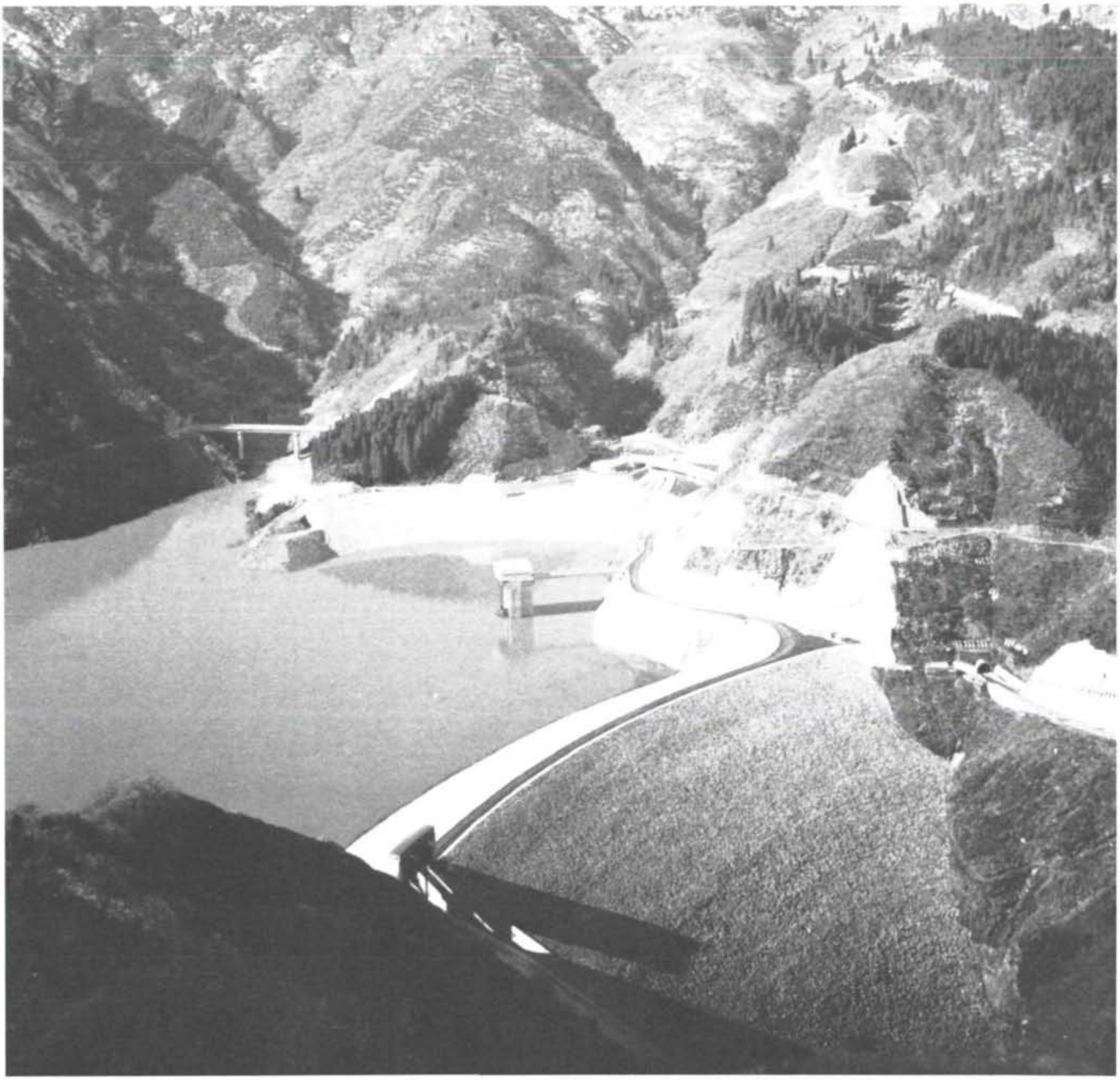
Public mortality risk



Notes: The estimates consider all steps of the fuel cycle, but do not consider severe accidents. LWR = light-water reactor; HTR = high-temperature reactor; FBR = fast-breeder reactor

Source. Adapted from A F Fritzsche, "The Health Risks of Energy Production", Risk Analysis 9, No 4 (1989)

These graphs reflect differences stemming from varying sources of data and various installations, processes, and accident frequencies: bars with shadings are well-founded risk data; those without shadings are questionable data. The sloping ends of the bars indicate the range of the risk data.



In Japan, nuclear energy and hydropower are major producers of electricity. Shown is the Tedorigawa Daiichi hydropower station. (Credit: JAERI)

Comparison of environmental risks

Environmental effects are not susceptible to the same comparative treatment, from fuel cycle to fuel cycle, as health effects. The large number of target organisms, the fact that particular ecosystems rather than individual organisms, populations, or species are the relevant units, and the need to distinguish between the effects of different substances on the functions and structure of ecosystems, mean that direct numerical comparisons may be virtually impossible. So far, there is no agreed functional characteristic or structural characteristic which, if changed, could be used as a numerical measure to make effective comparisons. It is for this reason that suggestions for other means of comparison are made.

● ***Assessment by ranking.*** This method allows general comparisons to be displayed. No attempt is made to give an overall measure of effect; rather, environmental impacts due to different perturbations from the various steps of the different fuel cycles are qualitatively presented in a matrix form. To some extent, this is a valuable feature of such representations because the differences in a single number are exposed rather than concealed.

● ***Emission values and ambient quality indices.*** Emission and effluent values may be used to assess the potential impacts of various fuels and technologies. *(See graphs.)* This aggregation of emissions highlights some interesting observations, including the fact that the total airborne emissions in terms of mass per unit of energy are almost identical for any of the fossil fuel energy groups (coal, oil, and gas), and that the SO_2 emissions are relatively high from the natural gas fuel cycle (mostly from the extraction stage) compared with other energy sources, with the exception of coal (mostly from the conversion stage). The total CO_2 emission per one gigawatt-electric per year (GWe/y) for the entire fuel cycle of the fossil fuel group used for electricity generation is about two orders of magnitude higher than the total CO_2 emitted from any other energy source fuel cycle. Within the fossil fuel group, total CO_2 emissions per 1 GWe/y (for the entire fuel cycle) for coal burning electricity generation cycles are approximately twice those emitted for oil or gas.

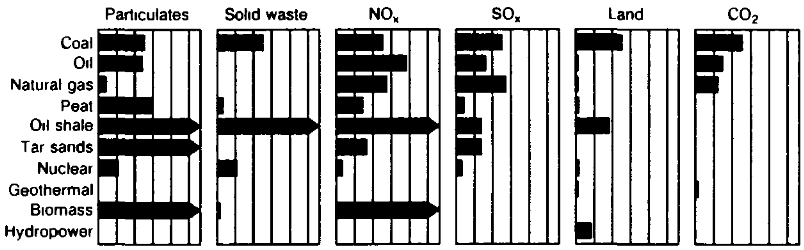
● ***The critical and target load approach.*** This approach uses critical or target load (or level) values, assigned to areas in a region and then compared with the actual deposition (or concentrations) of a pollutant. Excedence of the critical (or target) load by deposition, for example, can be taken as a quantitative measure of the impact or effect. This approach may be developed further. The outcome of various abatement strategies (for example, application of all feasible technologies to a power station) can be compared in terms of excedence (and overall abatement and cost indicated). This could then be compared with excedence maps where other strategies (or none) have been simulated. *(See table.)*

● ***Integrated comparisons of environmental impacts.*** The lack of a well developed methodology for environmental comparisons of the impacts of various fuel cycles within the electricity generation energy system does not mean that no useful comparisons can be made. Furthermore, as data are collected a reliable methodology will emerge. Development of critical load excedence assessments, and the gradual recognition of dose-response relationships for these excedences, will enable progress towards quantitative comparisons to be made.

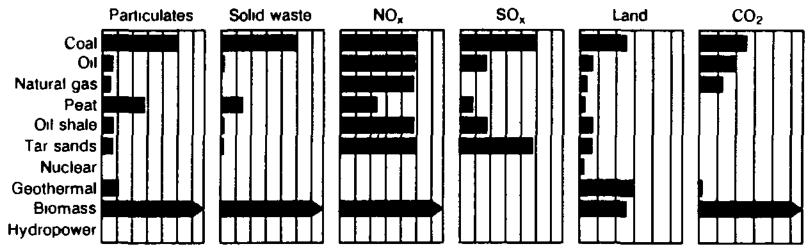
At present, emission values, or a combined index of these, allow qualitative comparisons. The scale of difference between emissions to the atmosphere ranging from fossil fuel use to solar technologies, and nuclear, is evident. Similarly, within a fuel category the scale of difference between fuels is quite evident. In the same manner, the excedence values allow ranking of impacts, and where a comprehensive attempt at this is made, the main thrust of impacts for various technologies is evident. For example, the potential global effects of fossil fuel use, through CO_2 emissions, are evident compared with other technologies, as are the potential regional impacts to the atmosphere. Such representation allows planners to focus on the main areas of concern.

Comparison of emission and effluent values

Emissions and residuals from different fuel sources



Emissions based on the conversion stage



Notes: Graphs are not drawn to absolute scale. Carbon dioxide emissions for peat, oil shale, and tar sands have not been evaluated. In terms of mass, solid wastes from nuclear conversion cycle are three to four orders of magnitude less than those for coal.

Source *After "The Environmental Impacts of Production and Use of Energy", Part IV, United Nations Environment Programme, Rep ERS-14-85, Nairobi (1985)*

These graphs compare the values for a range of fuels used in electricity generation. Data on emissions are based on results of a comprehensive comparative environmental study undertaken by the United Nations Environment Programme.

Risk of severe accidents

The potential for severe accidents (usually defined as accidents with significant off-site risk to people, property, and the environment) exists for all energy systems and at all stages of their fuel cycles. Accidents can be caused by structural or mechanical failures, process malfunctions, human error, or external events such as natural phenomena (earthquakes and hurricanes).

On the basis of a normalized per unit of electricity produced, it appears that the hydroelectric option has caused more immediate fatalities from severe accidents than any other energy source. Specific issues have to be considered when attempts are made to compare severe accidents for different energy systems:

Sulphur emissions with implementation of maximum achievable abatement by the electricity sector in Europe in the year 2000

Country	Unabated	Sulphur removed	%	Cost
Albania	200	64	32	23
Austria	186	68	37	90
Belgium	282	90	32	137
Bulgaria	1 151	630	55	256
Czechoslovakia	1 303	723	55	301
Denmark	193	121	63	192
Finland	203	36	18	119
France	697	130	19	354
German, Dem. Rep.*	3 224	2 166	67	668
Germany, Fed. Rep.*	1 499	799	53	1 214
Greece	523	396	76	255
Hungary	805	479	60	189
Ireland	100	55	55	74
Italy	1 311	612	47	939
Luxembourg	18	0	0	0
Netherlands	210	65	31	117
Norway	71	1	1	3
Poland	2 182	1 006	46	618
Portugal	205	66	32	84
Romania	1 322	725	55	325
Spain	2 126	1 556	73	600
Sweden	219	29	13	111
Switzerland	54	7	13	16
Turkey	1 755	700	40	301
USSR	10 890	6 241	57	2 075
UK	1 765	974	55	1 474
Yugoslavia	1 891	1 209	64	536
Total	34 385	18 948	55	11 068

Notes: Emissions are in thousands of tonnes. Costs are in millions of US dollars (1985).
Source M J Chadwick, Stockholm Environment Institute (1990)
* These data were estimated before the unification of Germany in October 1990.

● Two main methodological considerations should be noted: first, such risks should be presented and compared separately from the risk resulting from routine operations; second, data based on historical (actual) occurrences should not be compared directly with data based on probabilistic predictions of likely future events.

● The comparison cannot be made only on the basis of consequences of such accidents. The likelihood (or probability) of occurrence should also be taken into account. Hence, estimation of the frequency of such accidents is relevant. Such estimation necessitates reliable information on the past records of such accidents and their effects and/or the application of probabilistic methods that predict the likelihood of their future occurrence.

● It is difficult to assess and compare the frequency and the health and environmental damages caused by severe accidents because such data are not systematically collected by a single national or international agency. This applies particularly for the non-nuclear energy systems. Data on incidents and accidents for the nuclear fuel cycle are more readily and systematically available, relative to the other energy systems.

● There are virtually neither data nor estimations on the delayed effects on health from severe accidents for non-nuclear energy systems in particular. All health effects in such cases are reported in terms of immediate fatalities, with immediate injuries reported in a few cases. This makes complete comparison difficult, since the total impact may be underestimated for the non-nuclear energy systems.

- The ultimate long-term environmental effects, from severe accidents in particular, are difficult to establish. Because of the one-time or infrequent exposure of ecosystems to accidental emissions, it may be difficult to establish whether the effect is irreversible or whether a recoverable effect is possible.

General conclusions

The results of comparative risk assessments of the different energy systems for electricity generation indicate that, under routine operating conditions, nuclear power and renewable energy systems tend to be in the lower spectrum of health risk, and that energy systems based on coal and oil are in the higher spectrum of health risk. Variations in the magnitude of risk could be near a factor of ten. However, all the fuel cycles, when fitted to state-of-the-art technology, are able to deliver electricity at relatively low risks to health and the environment. An exception is CO_2 emissions from fossil fuels. As such, the control of CO_2 emissions is at the top of the current environmental impacts agenda.

Comparative risk assessment will play an increasingly important role in energy planning by providing decision makers with critical input into the formulation of appropriate modes and mixes of electricity generation. Future decisions in the field should include, as a priority issue, the establishment of a comprehensive, internationally co-ordinated database on the health and environmental impacts of different energy sources.

Normalized fatality rates for severe accidents (1969–1986)

Energy option	No. of events	Immediate fatalities/ event	Total immediate fatalities	Energy produced (GWa)	Immediate fatalities/energy (fat./GWa)
Coal					
Mine disaster	62	10–434	3 600	10 000	0.34
Oil					
Capsizing	6	6–123	NA	21 000	—
Refinery fire	15	5–145	450		0.02
During transportation	42	5–500	1 620		0.08
Natural gas					
Fire/explosion	24	6–452	1 440	8 600	0.17
Hydropower	8	11–2 500	3 839	2 700	1.41
Nuclear	1	31	31	1 100	0.03

NA = not available.

Notes: The estimated total energy produced from fossil fuels has been multiplied by a factor of 0.35 to convert it into equivalent output of electrical energy and hence enable the comparison with hydropower and nuclear.

Reported fatalities are in terms of immediate fatalities; delayed fatalities, particularly relevant for the nuclear accident at Chernobyl, are not included.

Source: After A.F Fritzsche, "The Health Risks of Energy Production", Risk Analysis 9, No. 4 (1989)

Rough estimates suggest that the risk to human health from severe accidents from nuclear, oil, and natural gas are of the same order of magnitude, and two orders of magnitude smaller than that from the hydroelectric option. There are, however, important factors that must be taken into account to reach such conclusions: under-reporting of accidents in the fossil fuel cycle and the smaller number of nuclear power plant accidents make the results of little statistical significance. The late cancer fatalities for Chernobyl, as well as the late effects for non-nuclear accidents, are not included.