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External Costs of Electric Power Generation

Are Accidents Adequately Treated?

The growing environmental awareness of the public and concerns about social compatibility of large-scale technology stimulate, along with such phenomena as acid rain and chernobyl, the debate on «external costs». In the past such costs have not been explicitly taken into account in the decision-making process, although they do present a burden for the society. Current external cost studies often show large differences in terms of approaches and numerical results. Consequently, an appropriate basis for far-reaching decisions is not evident. This applies particularly to the treatment of rare accidents with severe consequences. The present article describes the state-of-the-art, presents results of own work in the context of other contributions and underlines the most important knowledge gaps.

External Costs in the Electricity Sector

By externalities we understand economic consequences of an activity (such as energy production and use) that accrue to society, but are not explicitly accounted for in the decision making of activity participants. In economic terms detrimental consequences are called external costs; positive consequences are called external benefits.

It is a simple truth that neither electric power generation nor any other large-scale industrial activity is free from external effects such as health and environmental impacts. These impacts are traditionally not accounted for in the price of energy. It is only recently that the issue started to receive the attention it deserves. In fact, since the late eighties the energy sector in particular has been subject to a debate (and in some cases to specific steps) concerning internalisation of external impacts, i.e. creating conditions where the damages from production and consumption are taken into account by those who cause these effects. The current trend is clear - externalities play an increasingly important role in decision-making and planning of utilities and other actors in the energy market. Proper consideration of externalities can help to optimise allocation of limited resources and to avoid undesirable developments - an optimal policy for addressing externalities is one that balances the costs of reducing damages with the benefits and is generally not one that would lead to zero pollution impacts.

Two fundamental types of externalities can be distinguished: environmental and non-environmental. Non-environmental externalities include for example public infrastructure, energy security and government actions (such as R&D expenditures). Some of these externalities, particularly those related to the imperfections of the market, are difficult to assess. Others may be rather straight-forward to identify but there may be differences of opinion whether some of them should be subject to internalisation or not. The focus of current evaluations (and of this article) is on environmental externalities like public and occupational health (mortality, morbidity), impacts on agriculture and forests, biodiversity effects, aquatic impacts (ground water, surface water), impacts on materials (such as buildings, cultural objects) and global impacts (greenhouse effect).

It is worth noting that a substantial number of potential external impacts has been effectively internalised through regulation and standards to which the power industry must comply. Thus, the damages associated with power generation are implicitly minimised. However, it needs to be acknowledged that the standards applicable to the different energy sources and to the various steps of fuel cycles (such as extraction, processing, transportation, power generation, waste management), are not homogenous and not everywhere implemented to the same extent. Notably, when considering a specific fuel cycle, these activities may be taking place in different countries.

Further consideration of external costs is beneficial not only to the society but also to electric utilities, particularly when considering the alternatives for the future. Accounting for environmental externalities may help to avoid costs of future environmental controls and substantially reduce uncertainties in utility resource planning. Despite some initial reluctance, there are now internationally many examples of utilities systematically using adders for environmental impacts in their planning. In Switzerland the debate on external costs has been intensified following a recent publication of the study by Infras and Prognos [1], concerning this topic. The study advances the state-of-the-art in some respects but also uses, when addressing certain specific areas, approaches that are at least questionable. Treatment of severe accidents is one such issue.

Current State of Knowledge

A number of attempts have been made to assess the costs of environmental impacts associated with energy production. In order to estimate such costs three steps are necessary:

- Identification of externalities specific to each activity.
- Evaluation of resulting physical impacts. For effects that originate from rare events rather than from continuous releases of pollutants this step necessarily involves the assessment of frequencies associated with consequences of different magnitudes.
- Monetisation of damages. Explicit monetisation allows to express the cost of a specific damage per unit of energy produced. Advantages of such representation are clear - the detrimental effects are expressed in a manner which allows direct and consistent comparisons between internal and external costs, between different contributors to external costs and between various fuel cycles.

At the same time many difficulties and limitations are associated with the whole process which finally leads to monetisation of damages.

- Estimation of physical impacts is a complicated and resource-demanding task which includes assessment of emissions into various media (air, water, soil), simulation of transport of pollutants through these media, assessment of exposure of receptors and use of dose-response relationships (relating the exposure to the effect). Among many other factors affecting these estimations we may mention physical characteristics of the emissions (e.g. rate, duration, location), meteorological and topographical conditions, pollutant interactions and transformations. Dose-response functions for estimation of health and environmental effects are «known» for only few major pollutants and are frequently subject to large uncertainties.
- Transferability of results obtained for a specific environment may be questionable or

not valid for the environment being examined. It would not be feasible to simulate from scratch all environmental damages for all fuel cycles on a location-specific basis. Consequently, it is attractive to use data from different studies and attempt to correct for the differences between the source and application environments by introduction of systematic factors (scaling). Bearing in mind the complexity of the estimation (see above), this process is frequently associated with large uncertainties.

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The effects of incremental loads may be non-linear, i.e. depending on the baseline level of environmental quality a small increment could lead to substantial damage.

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Establishment of boundary conditions, particularly time and space limits, for environmental damage estimation is not straightforward. Thus, the time scales for manifestation of environmental damage can vary, transboundary effects and contributions of parts of fuel cycles in foreign countries may be very important and it is an open question how deep in the structure of fuel cycles one should go in order to account for all significant contributions (e.g. material manufacturing). The focus of the estimation is normally on the production facilities, while such parts of specific fuel cycles as transportation or storage may constitute potentially important, but unaccounted-for, contributors. The effects can be local, regional or global. Usually, local and regional impacts can be assessed with more confidence than the global ones.

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Monetisation is carried out using different approaches, particularly since some of the commodities are marketable and others are not. The use of discounting, i.e. placing a lower value on damages that occur in the future as compared to the present ones, is a debatable issue with large potential impact on the numerical results.

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Scope and depth of the present analyses addressing the real or potential contribution of severe accidents to external costs is inadequate. This is partially due to the inhomogeneous state of knowledge concerning the risks associated with different fuel cycles and partially due to the use of flawed approaches.

Estimation of external costs is clearly subject to large uncertainties; some of them are inherent and will stay with us, other are matters of practice and are bound to be reduced with the increased state of knowledge and prospective agreements on procedures for carrying out balanced evaluations. Incidentally, treatment and representation of uncertainties, which appears to be central in the support of decision-making, is another weak point of current studies.

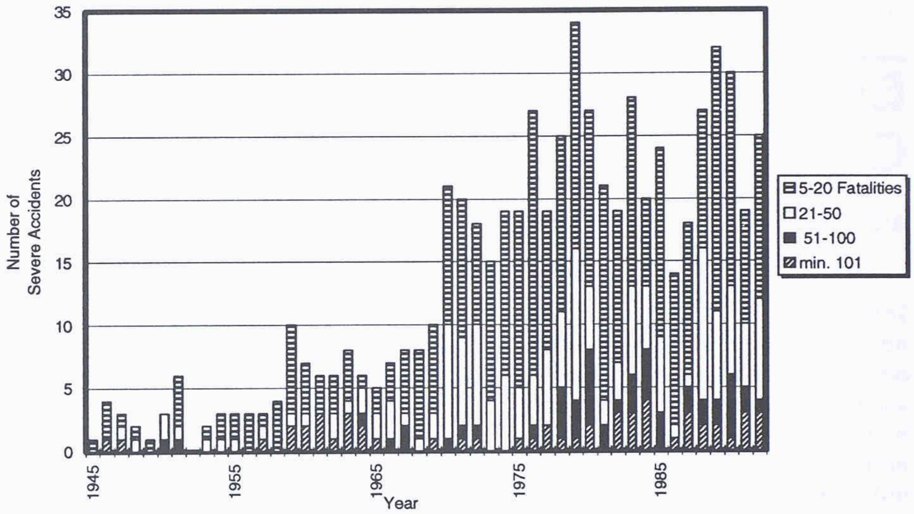

Fig. 1.
Energy-related accidents leading to different number of acute fatalities, in the period 1945–1992, according to the database recently established by the Paul Scherrer Institute [6]

In no way the deficiencies and difficulties currently being experienced should be viewed as disqualifying the efforts to estimate the costs of environmental damage. Firstly, the discipline is extremely young, and tries to penetrate partially unexplored terrain. Secondly, we know for certain that environmental damages occur, although we may have difficulties in estimating them with the desired precision. Assigning to them a value of zero, as was practised in the past, appears to be the worst possible solution.

How do the current studies perform in terms of consistency of results? A review of some studies carried out during the last six years in Germany [2, 3, 4], Switzerland [1], USA [5] and within the EC/US study (preliminary, not yet published results), leads to the conclusion that the discrepancies between external costs estimated by different authors and associated with electricity generation based on different energy sources, are very large, sometimes corresponding to a difference of several orders of magnitude. Based on their results, some authors claim that full account of external costs of fossil and nuclear power would make solar and wind energy economically fully competitive today. Results of others contradict this claim. It appears that the latest more detailed and comprehensive studies, produce in most cases more moderate estimates, although it remains to be seen whether this is a clear trend. The dominant contributor according to the most recent studies is global warming associated with fossil sources, albeit subject to very large and understandable uncertainties.

The main reasons for the discrepancies between the studies are the different scopes and assumptions in the calculations. Factors which differ significantly are for example: credit given to renewables for avoided external costs of present (fossil, nuclear) electricity generation, resource depletion surcharge for fossil and nuclear, diverging estimates of environmental damages due to use of fossil fuels, discrepancies in the estimated public R&D transfers, and most drastically - treatment of severe nuclear accidents. There is no disagreement that the external costs associated with normal operation of nuclear power plants are small, i.e. typically below 0.1 cents(US)/kWh. Notably, accidents in fuel cycles other than nuclear have been frequently ignored or treated in a very simplistic manner. This is a serious deficiency since accidents do occur in various steps of the different fuel cycles, as illustrated by Figure 1. The Chernobyl accident (1986) is one of the accidents included in this figure; due to a very high number of estimated delayed fatalities (some of which have already occurred, particularly among the «liquidators»), and other serious health and environmental impacts, it has clearly a special «prominence» in this context, not explicitly evident from the figure.

The remaining part of this paper focuses on the estimation of external costs associated with severe nuclear accidents, an area where the discrepancies are most significant and where Paul Scherrer Institute (PSI) in co-operation with Energy Research, Inc. (ERI) has carried out research work [7].

Contribution of Severe Accidents to External Costs of Nuclear Power

Table 1 contains estimates of contributions of severe accidents to external costs of

Hohmeyer [2, 3], Germany (1988; 1990):	0.71-7.08 cents/kWh; 2.05-12.4 cents/kWh
Friedrich & Voss [4], Germany (1993):	0.006-0.041 cents/kWh
Ottinger et al. [5], USA (1990):	2.3 cents/kWh
Ferguson, [8], UK (1991):	7.4 cents/kWh (risk aversion included)
Masuhr and *Oczipka* [9], Switzerland (1994):	0.0007-0.12 cents/kWh (under «risk neutrality»)
	0.7-22.3 cents/kWh (under «risk awareness»)
CEPN [10], France (1994, preliminary):	0.00018-0.013 cents/kWh
Hirschberg and *Cazzoli* [7] (1994):	
Mühleberg (CH):	0.0001-0. 0038 cents/kWh (mean value: 0.0012)
Peach Bottom (USA):	0.0014 cents/kWh (mean value)
Zion (USA):	0.0069 cents/kWh (mean value)

Table 1.
Some results from recent studies on contribution of severe accidents to external costs of nuclear power

nuclear power, obtained in different studies in recent years. All costs are expressed in cents(US)/kWh, based on exchange rates in March 1994. The end price of electricity in Switzerland is about 10.2 cents/kWh (production mix 1990-92), which provides a perspective on the relative significance of the different estimates.

The values in Table 1 cover a range of some five orders of magnitude. No attempt to express the prices in terms of present values was made here; this would actually, in most cases, further increase the differences. It is worthwhile to consider which factors may have the primary influence on the numerical discrepancies between the different studies. The main ones are:

Accident frequency

The frequencies used in the different studies were either plant-specific, adopted from other plants or considered as generic. There are cases where relatively high frequencies were allocated to specific very severe consequences (corresponding to Chernobyl), apparently due to lack of understanding of the reference set of data used. Only this can explain differences of at least three orders of magnitude.

Magnitude of consequences

The amount of radioactivity released was either assumed, estimated on plant-specific basis or simply adopted from the Chernobyl accident. The extent of the consequences was then either calculated for the specific plant location or extrapolated using results obtained for other plants. Alternatively, Chernobyl-specific consequences were used with very limited adjustments for site-specific characteristics. In some cases the implementation of extrapolations and adjustments is subject to flagrant errors.

Scope

The scope of the different studies ranges from consideration of one specific accident (typically Chernobyl) to systematic modelling of the full spectrum of hypothetical accidents; the latter approach, when properly implemented, provides a set of consequences with specific magnitudes and the associated frequencies. Some studies are limited to coverage of only one type of consequence, i. e. radiation-induced health effects, other also provide estimates of emergency measures and losses of land and property.

Risk integration

Risks are integrated by combining the consequences with specific magnitude and the associated frequencies. In most cases the so called «product formula» was used where frequency of an accident is simply multiplied by the magnitude of its consequences. Some studies consider risk aversion by explicit or implicit allocation of extra weights to events with very large consequences. As an example, the results of Prognos [9] show an increase by two orders of magnitude when such an approach is adopted.

Economic parameters

Depending on the scope of economic analysis the results are particularly sensitive to the monetary values assigned to loss of life, land and property. The degree of sensitivity may in turn be highly dependent on the plant-specific spectrum of accidents and local conditions.

Although in most cases the results have been claimed to be representative for specific plants in specific countries, they are at the same time frequently presented in a way that suggests a much more generic validity. All studies that lead to relatively high values use the total population dose estimated for the Chernobyl accident as the reference for calculations concerning plants operating in the western world. Such an approach is associated with some fundamental problems:

- One extreme accident which occurred at a plant with specific (flawed) design, operating in a specific environment (low safety culture) and located at a specific site, is chosen to represent the whole spectrum of hypothetical accidents with varying consequences, or to provide the only reference for some highly questionable extrapolations.

- The path leading to the estimation of consequences conditional on specific releases is purely deterministic (Chernobyl case); different weather conditions, accident management strategies, sheltering conditions and evacuation practices are not considered.

The above applies also to the Prognos study [9], which however, as an example of an improvement providing more realism in comparison with some of the earlier studies, for its lower range consequence estimate uses release frequencies based on the Swiss regulatory review of the Probabilistic Safety Assessment (PSA) for the Mühleberg plant [11]. The same frequencies were then applied to the other four Swiss plants which have very different designs. An arbitrary set of much higher frequencies was postulated by Prognos in order to estimate the upper range of consequences. These frequencies are unrealistic, apart from not having any basis. Furthermore, the associated highest release category is in the case of the Mühleberg plant, not relevant within the range of frequencies considered, due to the retention of radionuclides within the reactor building.

The estimate by Friedrich and Voss [4] is based on a relatively old US PSA study whose results were modified to partially reflect the German conditions (e.g. population density); the authors regard this approach as rather rough and are clearly aware of its limitations. The French study performed by CEPN [10] uses four different assumed releases for which detailed consequence calculations were carried out for a hypothetical site in Germany, using release frequencies that are partially based on US studies.

In two cases (Ferguson [8] and the second set of results obtained by Prognos [9]) subjective risks (risk perception) have been considered. Since superimposing subjective aspects on expert-based estimates may have a decisive impact on the numerical results, this matter will be further considered in the last part of the present article.

PSI/ERI Case Study for Mühleberg

The study performed by PSI in co-operation with ERI estimated external costs associated with hypothetical severe accidents at Mühleberg. The results obtained appear to be the first published attempt to assess external costs for a specific plant, based on a state-of-the-art full scope PSA that covers the full spectrum of initiating events (including the frequently dominant external ones such as fires, earthquakes, floods, aircraft crashes, etc.). Results obtained for two typical US plants (Peach Bottom and Zion) through elaboration of information from recent studies by USNRC [12], are also provided; these analyses do not cover external events.

The Mühleberg PSA was extended by calculations of economic consequences of hypothetical severe accidents, using the economic effect models in the computer code MACCS developed by Sandia National Laboratories (USA). Two types of costs were modelled - costs resulting from early protective (emergency response) actions and costs resulting from long-term protective actions. Specifically, the following costs are covered:

- food and lodging costs for short-term relocation of people;
- decontamination costs for property that can be returned to use if decontaminated;
- economic losses incurred while property (farm and nonfarm) is temporarily interdicted to allow for radioactive decay to reduce ground concentrations to acceptable levels;
- economic losses resulting from disposal of contaminated milk and crops;
- economic losses due to permanent interdiction of property.

A similar economic model was used in the study carried out by CEPN [10]. Many of the contributing factors above have been either neglected or superficially treated in most other past studies, since their estimation was not possible in view of scope limitations of the economic models used. The Mühleberg analysis includes also a systematic propagation of uncertainties and an integration of the full spectrum of contributing release scenarios.

Figure 2 shows the frequency of exceedance of external costs for Mühleberg, based on the total core damage frequency (including external events); this covers the economic losses specified above.

The estimated, integrated external costs reflecting the economic consequences covered in Figure 2 (i. e. costs resulting from early and long-term protective actions) amount to 0.0002 cents/kWh (mean value). The costs of radiation-induced health effects (totally dominated by latent cancers), were quantified separately and added to those implicitly accounted for in Figure 2. This leads to an estimate of the total external costs of severe accidents at Mühleberg (mean: 0.0012 cents/kWh; 5-th percentile: 0.0001 cents/kWh; 95-th percentile: 0.0038 cents/kWh). Thus, the final results are dominated by costs associated with health effects and are moderately sensitive to the difficult to assess and possibly underestimated costs of land and property. No discounting of the value of life was used when evaluating the costs of delayed fatal and non-fatal cancers.

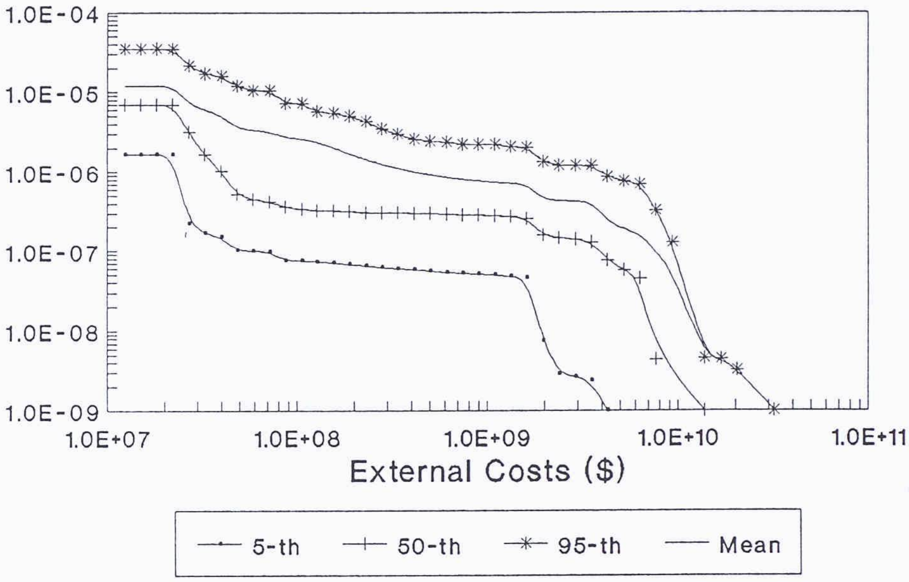

Fig. 2.
Mühleberg-specific frequency of exceedance of external costs of severe accidents with radiation-induced health effects excluded [7]. The mean can be regarded as the main reference, while the 95-th percentile can be interpreted as providing a bounding value

Conclusions

The following points summarise the essence of this article and provide some additional views based on insights gained in the course of related work carried out at PSI.

- Estimation of external costs associated with power generation is a complex and resource demanding task. Adequate analysis approaches for some of the central topics have been developed only recently and there is no general consensus on procedures that should be employed. It is an open question whether such a consensus can be reached in the near future, although an open discussion and further serious research will certainly help to resolve some of the issues today regarded as controversial. This appears to be one necessary prerequisite for serious internalisation.

- Severe accidents are not treated in a satisfactory way in the existing studies. While it is understandable that severe nuclear accidents attract most attention in this context, for a balanced and consistent assessment accidents in the different steps of other fuel cycles need to be considered as well. This statement is supported by the statistical records of energy-related accidents, as reflected in Figure 1. One problem when concerning accidents in different fuel cycles is that the state of knowledge concerning analysis of such accidents is, in several cases, very limited and inhomogeneous. It is worth noting that among the major fuel cycles the origin of dominant contributors to external costs associated with potential accidents is different. Thus, in the Swiss case, only in the case of nuclear and hydro are the domestic power production facilities expected to be dominant. For other fuel cycles the risk potential stems predominantly from up- and down-stream processes, which frequently are external to Switzerland. There is no reason for ignoring these contributions when estimating external costs.

- Estimates of external costs of severe nuclear accidents show the largest discrepancies in the past studies and are considered controversial. Independently of the numerical results, use of the Chernobyl accident as the only reference for the assessment of environmental consequences is more than questionable. Generally, state-of-the-art, rational and defensible methodological approaches, based on full scope plant-specific PSAs, have not been used before in this context.

- The results obtained for the Mühleberg plant by use of a full scope PSA show a low (quantifiable) contribution of severe accidents to the external costs of nuclear power. This insight appears to be consistent with the results obtained for two US plants and for a French plant, using analysis approaches which have more limited scope but some basic methodological similarities with the one employed for Mühleberg. Generalisations should be avoided - the indication is applicable to plants with high safety standards and only within the limited boundaries of the analyses performed (see below). Risks are strongly plant- and site-specific; the results obtained for Mühleberg are expected to represent the lower range of risks and consequently of external costs attributable to nuclear accidents. Reasons for this expectation are: relatively low radionuclide inventory (low power), low population density in the immediate proximity of the plant and the extensive backfitting that has been implemented (resulting in low accident frequencies).

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Within the limited scope of the economic consequence models that have been applied, the most important cost-driving parameters in the case of accidents with very extensive external consequences are: the value of life and the price of interdicted/condemned land. Both these parameters may be assigned according to different principles and the absolute levels are disputable. Most of the studies (including the one carried out by PSI/ERI) use about 4 million US$ for each cancer fatality and no discounting; this value is usually considered as high. There is much more variability with respect to the assigned prices of rural and urban land. Although there is reason to believe that these values have been underestimated in the PSI/ERI study, in which common with most other studies cited here the cost of health effects dominate, the final results are moderately sensitive to prices of land. This means that although the total external cost assessed for the Mühleberg plant could increase substantially in relative terms given a very large increase of the value of land, it would still remain low in comparison with the internal costs.

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While the physical impact models employed in the state-of-the-art PSA analyses are subject to a number of intrinsic limitations, they are by and large adequate as a basis for estimation of external costs. On the other hand, while the current economic models connected to the consequence codes and employed in the CEPN and PSI/ERI studies are more advanced than those used in the other studies, they are still relatively primitive. Generally, the analyses are limited to the land areas that are directly affected by the accident. For accidents which lead to long disruption periods there will be impacts on other areas and many sectors of the economy are likely to be affected. To simulate such effects, both at regional and national level, the input-output methodology that accounts for the interactions between the economic sectors, could be employed. Furthermore, recreational value of land or impacts on tourism have not been explicitly considered. Consideration of ecological damages has been limited to agriculture. The question of reasonable boundaries for the analysis of external costs applies naturally not only to nuclear accidents but to external cost analyses in general.

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Few of the past studies try to account for subjective aspects of risks (risk perception). The available attempts to express risk aversion in terms of external costs do not inspire much confidence and lack scientific basis. This means that in principle any result can be obtained and that once the subjective risks are superimposed on the objective ones (not perfect but obtained as a result of a systematic and transparent process), they tend to overshadow them. The aversion towards specific risks is not homogenous within any society. The issue is, however, important and deserves attention. Extreme nuclear accidents which potentially could lead to severe land contamination of long duration, would also result in social detriment much beyond the quantifiable components of health and economic detriments. In spite of reassuring expert assessments some people will remain worried about cancers, genetic damage and safety systems that may fail to perform as planned. Perceptions of risk may lead to behaviour that in turn leads to actual costs. It is clear that the public perception of risks must be taken into account in the decision-making process (acceptability of technology) but it is a different issue as to whether this aspect has anything to do with external costs. If yes, methods for treatment of this topic that are better suited than the primitive ones employed in few of the past studies, are now emerging.

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External costs associated with rare severe accidents are of interest primarily for comparison, which in turn may support the decision-making process. There appears to be a disputable rationale behind internalisation of costs of events which with a very high probability will not occur during the life-time of the plants being examined. A question arises how would the funds being accumulated be used after decommissioning of plants with successful operational records (no accidents). Practical implementation issues are also partially open in the case of effects of normal operation of energy sources. However, detrimental impacts associated with normal operation and with operational incidents, are not hypothetical but deterministic.

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