Risk from Nuclear Power Utilization after Fukushima Accident

Preliminary Communication

Zdenko Šimić
Faculty of Electrical Engineering and Computing
Unska 3, HR-10000 Zagreb, Croatia
zdenko.simic@fer.hr

Vladimir Mikuličić
University of Zagreb
Faculty of Electrical Engineering and Computing
Unska 3, HR-10000 Zagreb, Croatia
vladimir.mikulicic@fer.hr

Igor Vuković
University of Zagreb
Faculty of Electrical Engineering and Computing
Unska 3, HR-10000 Zagreb, Croatia
igor.vukovic@fer.hr

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Abstract *– The enormous discrepancy between risk perception and the risk associated with nuclear power utilization will further perpetuate after the recent accident in Fukushima Daiichi nuclear power plant (NPP) in Japan. Complete and transparent risk assessment is an assumption for an improvement in risk understanding. This paper contains an overview of approaches and the results of risk assessment of nuclear power in the context of energy utilization. It is possible to improve understanding of the risk based on numerous risk assessments carried out for NPPs worldwide, our own experience, and assessments based on cumulative operating experience. The paper presents an updated risk assessment from nuclear power in the light of a recent accident in Japan and it also implies possible causes that led to overlook a concrete hazard from tsunami in the original risk assessment. Assessment of relevance of the Fukushima event on reliability of risk assessment from nuclear power in the world is of huge importance for further deliberation on utilization of nuclear power. It is undisputable that these activities will demonstrate, and at some locations improve, NPP's high safety level. Still, perception in general public remains one of the most relevant challenges for optimal planning of the future of the energy sector.*

Keywords *– Fukushima, nuclear power, risk assessment, risk perception*

1. INTRODUCTION

Risk is generally defined as a potential exposure to loss created by a hazard. A hazard is a situation (physical or societal) that, if encountered, could initiate a range of undesirable consequences. Risk assessment is the process of obtaining a quantitative estimate of a risk (probability and consequences), [1].

There are several questions one might raise when considering risks. Excluding the questions related to risk assessment, it seems very important to realize that risk management is not possible without answers to some additional questions. Here we raise two especially important ones. How do we decide if a certain risk is acceptable or not? Having a risk in mind, what about the benefits of technology utilization? Without having the complete picture of the risk we are facing and answers to at least these two additional questions, it seems impossible to rationally decide on an optimal solution with the least risk. We then behave with danger that unnecessary fear is a bigger risk than what we are afraid of in the first place.

This paper presents results of risk assessment from nuclear energy in comparison with other energy sources, and regular risks we face in everyday life. This is done by the idea to point out that there is a greater need to focus our risk reduction strategies better, and perhaps to reduce our total risk from energy use with wasting fewer resources. This approach is applicable in other areas of life but this is beyond the scope of this paper.

2. RISK FROM NUCLEAR POWER

Nuclear power plants are technical facilities for electricity generation in large amounts from nuclear fuel, characterized by high capacity and availability factor. Like any advanced technology, there exists a relatively small risk related to the operation of nuclear power plants and it is realized with three major accidents.

In general, we approach risk assessment depending on the existing evidence and experience. New risks from unknown technology and small risks from very reliable technology are estimated by means of risk modeling. This is an approach where expert analysts develop a mathematical representation of a physical facility and a risk imposed to the environment and human health. With big risks, a situation is simpler because it can be assessed statistically. The risk of utilization of nuclear energy in nuclear power plants is an example of a small risk with few accidents where only limited consequences have occurred, and certain crucial characteristics are very unique.

The risk can affect people, materials and the environment. In terms of the time of realization, the risk is usually divided into two categories: short-term (immediate, acute) and delayed (subchronical and chronical). The uncertainty of assessed risks grows with time, and this presents a significant problem with certainty of particular predictions.

2.1. RISK ASSESSMENT

There are numerous methods developed and used for risk assessment, and some of the well known are e.g. What-if, HAZOP, Fault Tree, and Event Tree analysis. Most comprehensive risk assessment is usually known as probabilistic safety assessment (PSA), where usually a combination of fault and event tree methods is used with full coverage of special type of events and failures (i.e., external events, human errors, and common cause failures). Figure 1 presents a schematic of general framework used in all risk assessment methods.

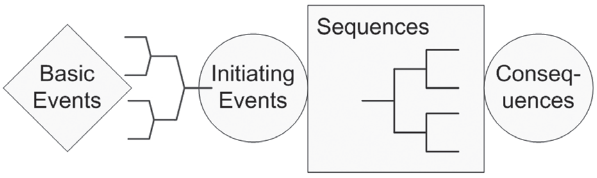


Fig. 1. General framework used in all risk assessment methods, [14]

The risk of utilization of nuclear energy in nuclear power plants is typically assessed based on a mathematical and logical model of the plant. This is often referred to as probabilistic safety analysis (PSA). PSA is the most comprehensive approach to quantification of risk and safety where risk is a combination of probability and severity of that harm, while safety is freedom from unacceptable risk.

According to Hirschberg et al. [2], the use of a plant-specific PSA is the most rationale basis for the estimate of hypothetical consequences of severe accidents and the associated monetized damages. The results obtained from such an approach are by definition representative of the case being studied. In addition, it enables treatment of uncertainties in a transparent and disciplined way. In the case where this approach is not feasible, any extrapolation of results obtained for a specific plant in a specific environment must be done with great care and the reference case should be carefully selected with a view to similarities in the design philosophy and the operating environment. Some assessments published earlier do not exhibit such necessary care.

One of the results for NPP's PSA is an estimate of the so-called core damage frequency (CDF). The nuclear reactor core is melt to some extent (partially or completely) in case when generated heat is not sufficiently removed during operation or shutdown mode. This frequency is within the range of 10^{-6} to 10^{-3} per year for the fleet of reactors in operation. These results are proven by numerous specific PSA studies

For new reactors to come into operation the CDF is estimated to be within the range between 10^{-8} and 10^{-6} per year, and this represents a significant improvement in plant design. Such high improvement from already safe designs is realized with additional safety systems redundancy or, what is much better, with so-called passive or inherent safety where a safe state is achievable without an immediate need for power supply or human actions. A PSA must be done separately for each power plant but here are some typical results: a fuel meltdown might be expected once in 20,000 years of reactor operation. In 2 out of 3 meltdowns, there would be no deaths, in 1 out of 5 there would be over 1,000 deaths, and in 1 out of 100,000 there would be 50,000 deaths. The average for all meltdowns would be 400 deaths. Very high radiation doses can destroy body functions and lead to death within 60 days, but such "noticeable" deaths would be expected in only 2% of reactor meltdown accidents; there would be over 100 in 0.2% of meltdowns, and 3,500 in 1 out of 100,000 meltdowns, [6].

Radiation causes ionizations in the molecules of living cells. These ionizations result in the removal of electrons from atoms, forming ions or charged atoms. The ions then can go on to react with other atoms in the cell, causing damage. The principal risks associated with nuclear power arise from health effects of potential radiation. It is difficult to estimate risks from radiation, for most of the radiation exposures humans receive are very close to background levels.

The use of radiation and nuclear techniques in medicine, industry, agriculture, energy and other scientific and technological fields has brought large benefits to society. The benefits in medicine for diagnosis and treatment in terms of human lives saved are enormous.

Radiation is a key tool in the treatment of certain kinds of cancer. Three out of every four patients hospitalized in the industrial countries benefit from some form of nuclear medicine. The beneficial impacts in other fields are similar. No human activity or practice is totally devoid of associated risks. Radiation should be viewed from the perspective that the benefit from it to mankind is far less harmful than from many most common agents.

According to the Biological Effects of Ionizing Radiation Committee V (BEIR V) [3], the risk of cancer death is 0.08% per rem for doses received rapidly (acute) and might be 2-4 times (0.04% per rem) less than that for doses received over a long period of time (chronic). These risk estimates are an average for all ages, males and females, and all forms of cancer. There is a great deal of uncertainty associated with the estimate. Later report BEIR VII [4] risk estimates for fatal cancer are similar to the values from BEIR V, but they also estimated incidence rates, which were about 50% of the fatal cancer rate. Other scientific groups have estimated risk from radiation exposure. The other estimates are not the exact same as the BEIR V estimates, due to differing methods of risk and assumptions used in the calculations, but all are close.

Based on the PSA performed for NPPs, a short term radiation risk is about 10^{-6} per man-year, and smaller for delayed effects. Uncertainty about prediction for delayed risk is extremely uncertain and because of this surrounded by many controversies. The act that risk from nuclear power plant operation is one of the most explored and analyzed is not sufficient to reduce its controversy.

2.2. RISK FROM NUCLEAR POWER BASED ON OPERATING EXPERIENCE

In more than fifty years of nuclear power usage three major accidents have occurred in NPPs. This happened because of breach in so-called defense in depth safety approach for preventing and mitigating accidents. This means redundancy, diversity and independence for safety features. This approach guarantees a very high level of safety if implemented with careful investigation of all internal, and especially external threats (so-called initiating events). This technical reality means little with biased and incomplete media coverage of everything what happens regularly in some NPP, [6].

Practical experience from NPP operation is most important after safe design. Incident reporting has become an increasingly important aspect of the operation and regulation of all public health and safety-related industries. Diverse industries such as aeronautics, chemicals, pharmaceuticals and explosives all depend on operating experience feedback to provide lessons learned about safety. The structured reporting system is an essential element of the international operating experience feedback system for nuclear power plants. These reports contain information on events of safety significance with important lessons learned. These experiences assist in reducing or eliminating recurrence of events at other plants. For nuclear energy current cumulative operating experience of commercial nuclear power plants worldwide is about 15,000 reactor-years.

Three major accidents have happened during this period: Three Mile Island partial core meltdown in 1979 in Pennsylvania; Chernobyl complete core meltdown and disintegration in 1986 in Ukraine; and Fukushima Daiichi major core meltdowns in three reactors in 2011 in Japan.

It is demonstrated in different ways in all these accidents that defense in depth could be compromised if there is a neglected possibility that a particular condition (disaster) might knock out all backup systems. Even the reactor can have many layers of reserve defense, if they can all be disabled by a same cause (e.g. tsunami beyond design basis in case of Fukushima), then redundancy does not mean any additional protection as it was planned.

In the Three Mile Island accident where at least two equipment failures were severely compounded by human errors, two lines of defense were still not breached. Essentially the radioactivity remained sealed in the steel reactor vessel, and that vessel was sealed inside the heavily reinforced concrete and steel lined containment which was never even challenged. It was clearly not a close call on disaster to the surrounding population. This accident did not have any short-term, or delayed casualties.

The Soviet reactor in Chernobyl, built on a much less safe design concept did not have a protective containment structure; if it had, that disaster would have been contained without radioactive contamination. This accident has caused hundreds of short-term deaths, and thousand long-term deaths (numbers are equally controversial and impossible to check).

The earthquake that hit Japan was several times more powerful than the worst earthquake the NPP was built for. When the earthquake hit, all nuclear reactors successfully went to shutdown. At this point, the cooling system has to carry away the residual heat, about 7% of the full power heat load under normal operating conditions. The earthquake destroyed the external power supply of the nuclear reactor. This is a very challenging accident for a nuclear power plant, and is referred to as a "loss of offsite power." The reactor and its backup systems are designed to handle this type of accident by using backup power systems to keep the coolant pumps and instrumentation and control working. Furthermore, since the power plant was shut down, it could not produce any electricity by itself. For the first hour, the first set of multiple emergency diesel power generators started and provided the electricity that was needed. However, when the tsunami arrived, it flooded diesel generators, causing them to fail, and made lots of damage to the site which prevented a number of safety functions and activities for their recovery.

The first explosion at the reactor caused a dozen injuries, and the subsequent mass evacuation of more than 100,000 people brought with it risks and social impacts. Some sickness and injury occurred among the workers trying to stabilize the plant, although exposure was managed within accepted emergency rates. Despite this, in an earthquake catastrophe that claimed some 27,000 lives, the nuclear accident has not caused any fatalities. Radiation effects from beyond the plant and its nearby surroundings have been short-lived.

Such major underestimation of tsunami is evidently a mistake. It is easier to understand that mistake when it is known that tsunami does not happen with every (ocean) earthquake, and this one in Japan has had an amplification effect from three sources of water mass movements (see Figure 2).

gency battery power. The batteries were designed as one of the backup systems to provide power for cooling the core for 8 hours. Flooding resulted in an electrical system failure even before these 8 hours expired. The available analysis shows that the total radiological contamination in Fukushima could have been significantly reduced if only reactor relief had been initiated sooner after station blackout condition had occurred. The irony is that relief was halted for hours in order to leave time for evacuation, but that caused a too high temperature in the reactors, release of hydrogen and consequently further destruction and much higher total radiological release.

In essence, it is evident that even with the worst possible scenario in Fukushima 1 there was no short-term casualty, and the delayed casualties were so far limited to only few extra exposed workers at the site during emergency in the beginning.

These three accidents in 15,000 reactor years of experience provide the basis for the statistical risk estimate.

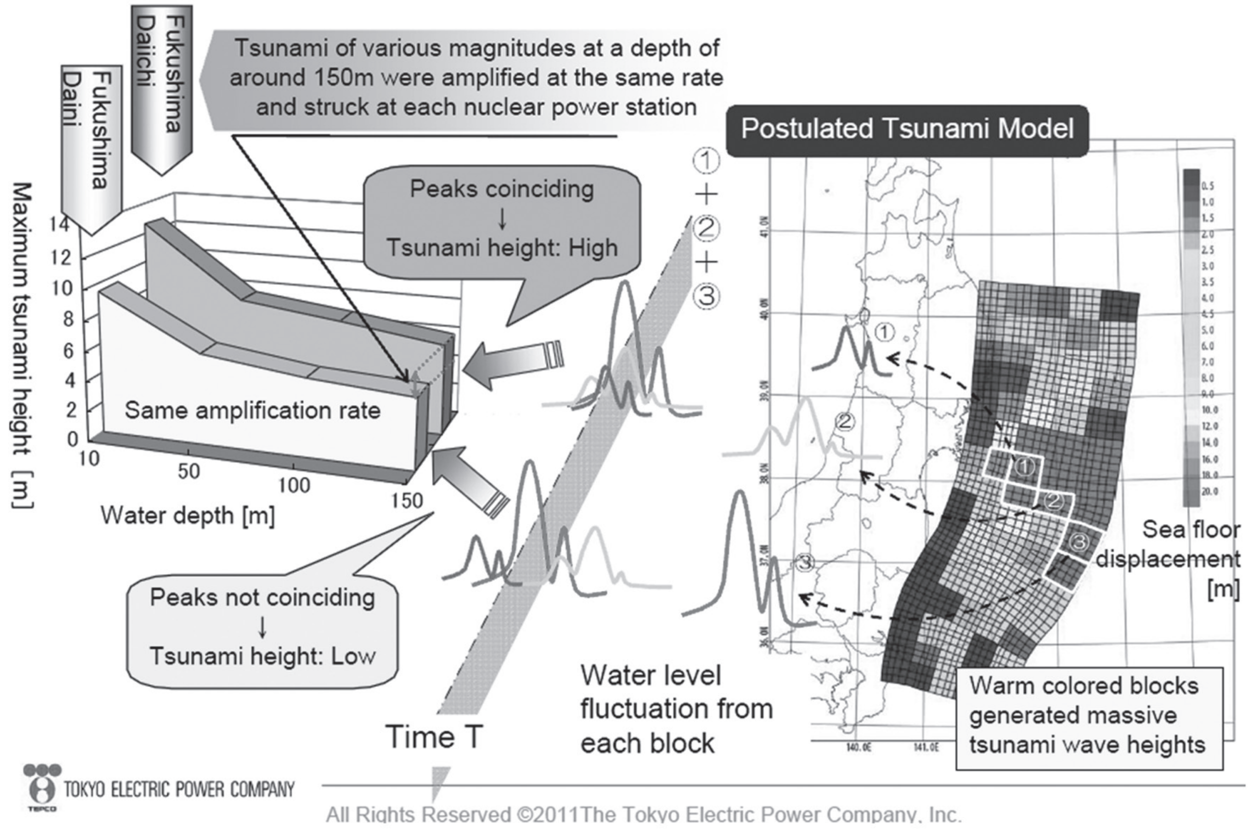


Fig. 2. Model for explanation of tsunami height in Fukushima 1 accident, [5]

The concept of defense in depth guides engineers to design a plant that can withstand severe catastrophes, even when several systems fail. In Fukushima 1, implemented protection was insufficient in a number of ways. Firstly, physical protection from tsunami was far too inadequate. Then, the redundant on-site power supply was unnecessarily placed on the lower levels, and left without waterproof protection. When the diesel generators failed after the tsunami, the reactor operators switched to emer-

Results derived from PSA models are comparable to simple calculation with cumulated nuclear energy experience. A number of realized accidents over cumulative experience provides that practically proven CDF is about 10-4 per reactor year.

From all NPP accidents, it is obvious that short-term casualties are possible only with a highly unsafe approach and lack of standard containment protection like in Chernobyl. The only risk that remains in the case of significant radiological contamination is the one related to the delayed consequences. This is the case with Chernobyl and it will be the case with Fukushima 1. It seems that the problem of estimating the number of delayed casualties is highly neglected and usual approaches are not properly suited for the problem. One context is defining the regulation limits with conservatism and technology capabilities in mind, and very different when real life consequences for certain exposure to small levels of agents occur. An inflated number of delayed casualties from Chernobyl and Fukushima accidents is based on the so-called linear no threshold hypothesis (LNT). This is based only on the extrapolating low-dose consequences from the known and demonstrated relations. The fact that LNT was never proven and that in fact numerous studies have proven quite the opposite is simply ignored because of the main purpose of LNT: a simple and conservative regulation. Effects measured for small doses prove that at the low-dose level there is not just a smaller consequence, but LNT also predicts positive effects. This is a known and researched phenomenon with other agents (i.e., chemicals) and it is called hormesis. Figure 3 illustrates the main differences between LNT and hormesis models.

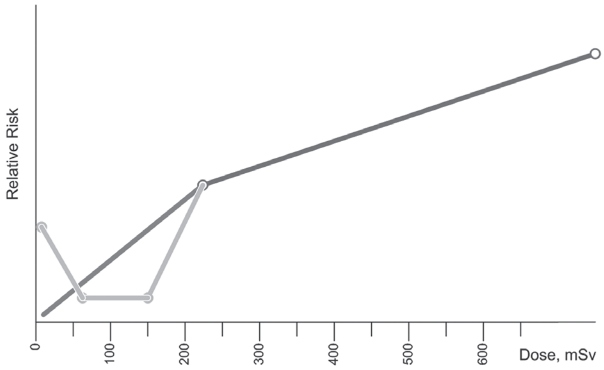


Fig. 3. Radiation dose consequence relation based on the LNT and hormesis model, based on [7]

Consequences are measurable and verifiable with doses around 200 mSv (for some, this threshold is 100 mSv); all exposures below this are possible to estimate with prediction. The LNT model simply draws the line to zero consequences when the dose is zero. Obviously, this simplification has as a result that our surrounding naturally occurring radiation has a certain risk for us. The problem is that millions of people are exposed to a variation of several times the difference of this radiation with extremes of 50 times higher doses without any noticeable effects and without any proof that LNT is correct. In fact, hormesis is proven by a number of studies made on patients and special occupation exposures to low levels of radiation doses [7]. Therefore, the hormesis model is proposed in order to estimate more accurately consequences from small doses. With this model, effects are much smaller from small doses, and they in fact have a positive influence when compared to the total elimination of radiation. This is not yet understood but it is linked to the evolution and cellular mechanisms of making cells more protected with small continued stimulus. Similar mechanisms are demonstrated with different chemicals, but they have also not been included in the regulation yet, [8].

For the Chernobyl accident, there is no evidence of radiation-induced cancer in humans at doses less than 100 mSv from acute doses or at doses less than 500 mSv for protracted doses. The rate of DNA damage caused by background and low doses of ionizing radiation is exceedingly small compared to DNA damage caused by breathing oxygen (~500 g O2 per day for standard man).

One interesting example is when about 10,000 people occupied 1,700 apartments in Taiwan for up to 20 years, receiving a cumulative average radiation dose of 400 mSv from construction steel contaminated with 60Co. A sharply reduced incidence of cancer and birth defects was seen in apartment inhabitants, [7]. It is claimed in [7] that the most effective method for reducing lung cancer risk from smoking, other than quitting, may be to have an annual full-body CT scan.

The first conclusion is that the factual and theoretical evidence points to replacing the classical causal regulatory defaults used to deal with low dose – response, the LNT, and the linear at low - dose – response models, or monotonic functions, with the J-and inverse J-shaped models or relations. These models have been demonstrated to apply to toxicological and cancer outcomes for a very wide range of substances and diseases. The classical defaults may still be applicable to a case by case basis. The reasons for changing the defaults include the fact that the J-shaped class of models quantifies a wide set of health benefits that are completely excluded from estimations that use monotonic models.

Abandoning LNT will reflect directly in a number of dimensions. Regulation would be then relaxed, and this will significantly reduce the required resources for nuclear industry and medicine. Decommissioning requirements would be more realistic and this will make all related activities less resources intensive. This will apply to regular decommissioning of facilities after operation, but, even more significantly wide areas accidentally contaminated. Finally, the estimated delayed consequences would be more realistic and will allow for better perception of the total risk.

It is because of LNT that so many people are not able to get back to their homes and that about $500 billion are spent for decommissioning wide areas. The government in the USA is scheduled to spend about $350 billion for cleaning up radioactive contamination and waste and decommissioning about 100 old nuclear power plants in 31 states in the next few decades. The same reason is that the number of predicted delayed casualties is estimated to several thousands (some extreme anti-nuclear organizations produce 100 times higher casualty estimates based on the models which are even more conservative than LNT). However, the fact is that this risk is so small that it could not be measured and it is completely covered with statistical noise and much more significant regular life risks.

The evidence of how fear from risk might cause the highest risk could be found in the fact that after the Chernobyl accident there were an estimated 1,250 suicides and thousands excess elective abortions, while 200,000 individuals experienced an unnecessary traumatic evacuation.

There is a perception of nuclear energy being dangerous even during normal operation regardless of numerous studies proving the opposite. The peaceful use of nuclear power technology produces materials that are radioactive. These materials can come into contact with people principally through small releases during plant operation, accidents in NPPs, accidents in transporting radioactive materials, and escape of radioactive wastes from confinement systems. All of them taken together, with accidents treated probabilistically, will eventually expose the average American to about 0.2% of his/her exposure from natural radiation. Since natural radiation is estimated to cause about 1% of all cancers, radiation due to nuclear technology should eventually increase our cancer risk by 0.002% (one part in 50,000), reducing our life expectancy by less than one hour. By comparison, our loss of life expectancy from competitive electricity generation technologies, burning coal, oil, or gas, is estimated to range from 3 to 40 days [6]. This is all even using the conservative LNT method .

In reality, consequences from the LNT model are enormously significant because they put an unnecessary burden on society resources and influence risk perception very significantly.

3. RISK ACCEPTANCE

Risk perception refers to an individual’s intuitive judgment about some choices. This is something everybody uses without an opportunity to have insights in risk assessment results. That is something where one believes that has the complete picture where not only probability of occurrence and the severity of the associated consequences are included but also benefits from a certain activity. Regardless of the base for risk perception that is crucial for certain activity risk acceptance. Risk acceptance involves subjective balancing of benefits with risks.

Good public policy involves a balanced approach to overall society risks. Public perception of the risk posed by environmental hazards also depends on person’s background, income, gender, education, etc. Perceived risks may also stem from the perception that government officials cannot be trusted to competently manage the risks of hazardous facilities, and that private interest will stand before what is in the best interest of the society as a whole.

Overall benefits might include not only direct advantages related to the development but also lots of specific advantages like employment, increased local tax revenues, and infrastructure enhancements. More generally, support is also related to the perceived need for the facility. Local residents may also be more inclined to favor a facility when employees of the facility are in their social network. Familiarity with the activities and technology related to the facility also appears to decrease risk perceptions [10].

A public perception of risk and policy preferences depends on history and it is also dynamic and may respond to events and policy developments at specific points in time. The overall support in the USA for nuclear energy declined following the Three Mile Island nuclear power plant accident in 1979, and dropped again after the Chernobyl nuclear reactor disaster in 1986. However, it did not happen in Great Britain, and some other countries have much stronger reactions (i.e., a recent example is a decision about a quick nuclear energy phase out in Germany after the Fukushima accident).

In general, risk acceptance is very different and important. Risk assessment is a much easier problem than to estimate risk acceptability. This might be in part because there are no transparent and universally accepted safety goals so for every activity new rules and new approaches are applied. This necessarily results in increased inefficiencies of risk reduction and suboptimal resources use. The best approach would be to set up safety goals that are neutral in respect of the choice of technology or activity. Practically, the lack of safety goals or their differences, costs society enormously, and actually increases the risk.

3. 1. SAFETY GOALS

Basically, any facility/activity should be built/operated in such a way as to satisfy a given set of safety goals. This is a goal-oriented approach where goals are first specified, and then the facility, activity or item is designed, created, operated and maintained accordingly. However, two problems must be answered for the goal-oriented approach:

1. How safe is safe enough? This requires a set of safety goals to be satisfied.
2. How to deal with uncertainties? The current risk quantification involves significant uncertainties.

Some countries apply numerical safety goals regarding NPP operation and modifications. According to Berg [11], this approach is well illustrated in the nuclear industry uses of PSA for compliance with formal criteria but without similar success related to the public risk perception. However, the role and interpretation of such quantitative guidelines vary from country to country. A dominant opinion is that safety goals should not be used within a regulatory framework of strict acceptance or non-acceptance criteria but should be considered as one factor in arriving at regulatory judgment.

In July 2011, the Western European Nuclear Regulators Association (WENRA) proposed safety goals for new NPPs built in Europe. Safety goals for a new reactor factor were learned from lessons referring to the Three Mile Island and Chernobyl accidents in 1979 and 1986. Compared with reactors currently in operation, the goal concerns in particular are as follows:

- Reduction of the risk of an accident with core meltdown,
- Reduction of radioactive releases to the environment in the event of a core meltdown, and
- Resistance to airplane crashes.

In addition, the reinforcement of the defense in depth concept for new reactors is proposed:

- The practicability of safety improvements at design stage is greater than that for an operating plant, more stringent application of the reference levels is expected for new reactors.
- There is room for safety improvements that go beyond the intent of the reference levels for existing reactors and which reflect the use of state-of-the art methodologies and techniques and the results of safety research.

There is no practical definition of safety goals. Perception and attitudes towards the safety goals vary significantly among different industry sectors and countries. The risk acceptance is very specific for every hazard. Even the state agencies/regulatory bodies are not consistent on the subject of risk acceptance. So in this way the comparison of risks from different technologies is a very complex task accompanied by many controversies. The safety goal is sufficiently defined by the level of acceptable risk.

Perhaps the most widely sought quantity in the management of hazardous technologies is the acceptable level of risk. Technologies whose risks fall below that level could go about their business, without worrying further about the risks they impose on others. Riskier technologies would face closure if they could not be brought into compliance.

For designers and operators, having a well-defined acceptable level of risk would provide a clear target for managing their technology. For regulators, identifying an acceptable level of risk would mean resolving value issues at the time standards are set, allowing an agency's technical staff to monitor compliance mechanically, without having to make case-specific political and ethical decisions. For the public, a clearly enunciated acceptable level of risk would provide a concise focus for evaluating how well its welfare is protected, saving it from having to understand the details of the technical processes creating those risks, [12].

The acceptability of risk could be an absolute or a relative concept and it involves different factors. Considerations in these judgments may include the certainty and severity of the risk, the reversibility of the health effect, the knowledge or familiarity of the risk, whether the risk is voluntarily accepted or involuntarily imposed, whether individuals are compensated for their exposure to the risk, the advantages of the activity, and the risks and advantages for any alternatives.

Specific approaches to setting risk acceptance criteria are based on a combination of fundamental principles and deductive methods. Most cultivated is the ALARP approach (As Low As Reasonable Practicable), capitalizing the advantages of formal analysis and all principal criteria. Requiring risk to be as low as reasonably practicable, ALARP provides conditional rather than absolute criteria; uniquely capturing that risk acceptance is a trade-off problem. Problems are yet addressed, notably in resource intensiveness and the imprecise notion of gross disproportionality. Conceptually close, but practically far from ALARP, is ALARA (Achievable instead Practicable). Whereas the upper criteria represent the start of ALARP discussions, they serve as the endpoint in ALARA. Arguments of reasonableness considered are already built into the strict upper limits of ALARA, [13]. The ALARP approach resolves how to deal with risks between acceptable and unacceptable levels, and in that way cover uncertain estimates.

Strict criteria are also provided by the GAMAB approach requiring new systems to be globally as good as any existing system already in use. GAMAB (globalement au moins équivalent) can be seen as learning-oriented bootstrapping, but may reject developments on an erroneous standard of reference [13].

The third example of a specific approach with risk objectives is MEM (Minimum Endogenous Mortality). With this approach any acceptable risk has to have only strictly defined relative contribution to the overall life risk (defined based on the least threatened part of population aged between 5 and 20). Figure 4 shows one example where it is visible that acceptable risk is reduced for dangers which could result in an increased number of fatalities per accident. This is related to the worse perception of such type of accidents regardless of a risk-neutral view that only values cumulative risk. Safety goals for short-term fatalities for NPP are e.g. at the 10-6 level (in Japan and the USA), all industry average risk is at about half of the MEM reference 10-4, [9]. How conservative this is might be more clear if one has in mind that the average home accidents fatality rate is at the MEM level, and that all causes are at the level of one order of magnitude higher for 40 year-old persons, and two orders of magnitude for 60 year-old persons, with most dominant contribution from cancer (data for England and Wales from [9]).

It is clear that the problem is not a lack of available methods for risk goal determination or acceptable levels of risk but the whole environment in which decisions about risk are made by different stakeholders in any question. Perhaps this environment includes perception of risk, history, culture, and the current state of the decision making process and risk management. However, by accepting the risk goal method all stake holders involved could improve communication and set the crucial central point around which an optimal solution for society might emerge.

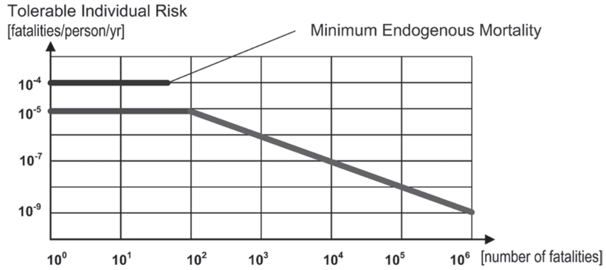


Fig. 4. Tolerable individual risk and relationship with a high number of fatalities - MEM approach, [14]

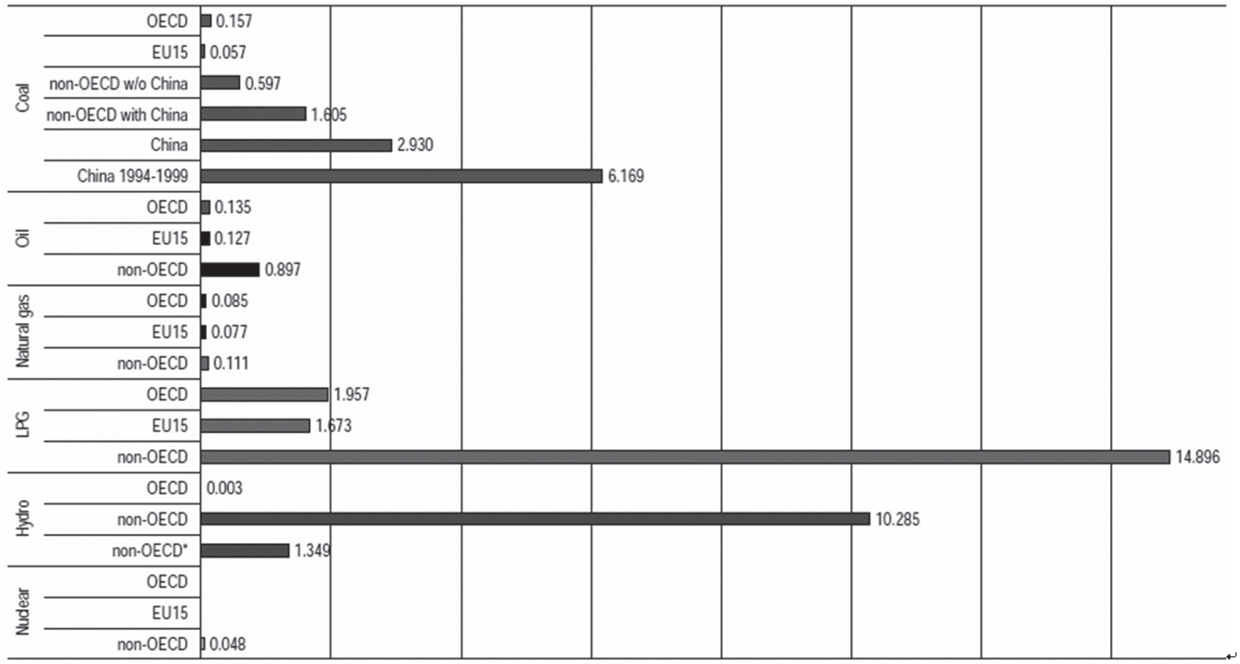
3.2. RISK OF ENERGY PRODUCTION COMPARISON

An alternative approach to risk management from having risk goals might be to compare risk in a certain domain and always choose the best available option. This is in general an interesting idea, but it is a burden in reality with almost all issues mentioned before. There are so many different prospectives and uncertainties that summing them with agreement of all stakeholders seems too hard to reach the objective. Here we would like to make certain facts which might help to compare risks and benefits from different available energy sources.

The historical operating record of different energy options, technologies for electricity generation, and the models to anticipate risks for their utilization, enable analysts to compare these technologies. It is possible to compare different risks, e.g. immediate risks, delayed risks, environmental risks, economic risks etc. Though the experience and the analyses provide a very clear picture, their use in decision making is practically small. Thus, it is evident that risk assessment even from the significant experience is not used in the risk decision making process.

From numerous indicators here we have selected three to present how clearly the choice could be made based on the experience and hard data. Firstly, comparison of energy sources is presented based on the number of fatalities from accidents. Then comparison is made based on the delayed negative effects, and finally comparison is made based on the emissions of greenhouse gases per energy produced.

From the experience it is possible to compare different energy sources on the basis of how many people have died or how much people's life has shortened for the certain amount of energy produced. Short-term effects data are much more clear because delayed effects are not easy to measure or estimate. Figure 5 presents the number of fatalities per GWeyr for conventional energy sources (renewable are believed to be on the lower side). This advantage is even more visible when risk is presented as a distribution over a certain number of fatalities per accident by the so-called F-N curve. This is easy to understand because all major accidents with



*Different values for non-OECD are related to the most significant contribution from the Banqiao and Shimantan dam failures

Figure 5: Number of fatalities per generated GWeyr from accidents for different conventional energy sources, [15]

a big number of fatalities are connected with hydro, oil, and coal (see Table 1 for the list of major accidents).

Disproportion between data and perception is even bigger when comparison is made for the effects of normal operation of facilities for energy production. Here we present the situation for Germany where a rush decision was made to phase out nuclear power plants quickly and compensate that for conventional (natural gas and coal) and renewable energy sources (wind and photovoltaic). In Figure 6, it is visible that this decision will not only cost much more but it will in fact have exactly the opposite significant negative effect on people's life. It is clear that nuclear actually stands best, even better than all renewables (especially photovoltaic).

The evaluation of historical experience demonstrates numerical differences between the aggregated risk indicators obtained for the various energy chains, as well as between the corresponding frequency-consequence curves. Regional differences have been shown to be of utmost importance for the nuclear and hydro chains. The expectation values for fatality rates due to severe accidents are lowest for hydro and nuclear power in OECD countries. This is also reflected in low external costs associated with severe accidents estimated using state-of-the-art methods. At the same time, the extent of consequences of hypothetical extreme accidents is largest in the case of hydro and nuclear.

Source: based on Hirschberg *et al.* (2004).

Fig. 6. Years of life lost per generated GWh for different energy sources in Germany during normal operation in 2000, [16]

Global warming and human contribution to the problem is in the center of all energy planning activities. Therefore, it is very important how much greenhouse gases (GHG) certain energy source emits. Figure 7 shows CO2 equivalent GHG emissions per energy unit produced. It is again clear that nuclear is and should be part of the climate change related measures. Nuclear energy is as good as or better than renewable only on the emissions base. For example, almost 70% of electricity generated without emitting greenhouse gases in the USA during 2009 was from nuclear power plants. Thanks to nuclear power, 650 million of metric tons of CO2 were not emitted during 2009 in the USA. This is almost equivalent to CO_2 emissions from all cars in the USA (137 million cars emit 710 million Mt of CO_2).

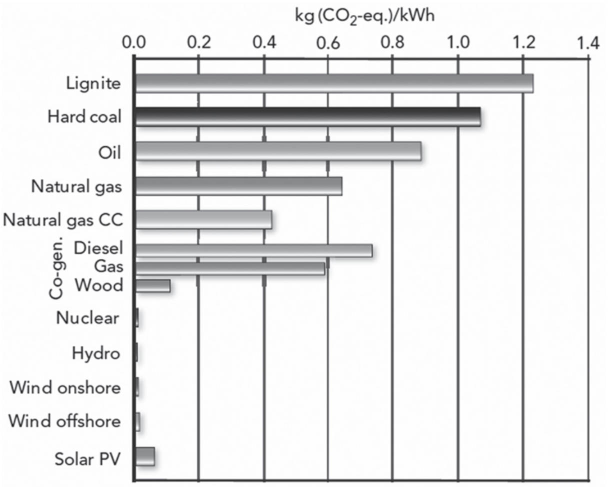
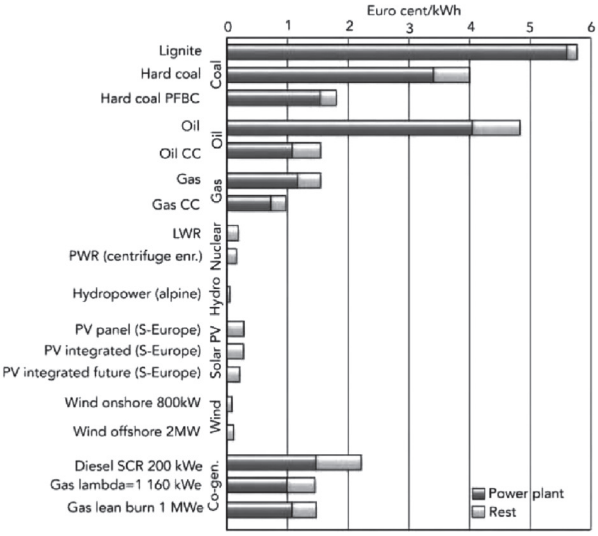


Fig. 7. Greenhouse gas emissions per kWh of electricity generated for different energy technologies, [16, based on Dones et al., 2004]

Finally, this all could be presented in some way as the cost of electricity produced. It is clear that the current production cost of electricity is significantly in favor of the conventional energy sources including nuclear, and that renewable are much more expensive even without including the cost of higher penetration (due to the power, their intermittence and additional power system costs). For a balanced decision about optimal energy sources use, it is important to try to express all cost they put to the society. This is done in lots of different ways and it is usually treated as external cost. Figure 8 presents one such comparison of different energy sources cost based on all influences on people and environment not included in the market cost (including the whole life cycle). This additional cost is only insignificant for nuclear and renewable energy sources. Other sources have external cost which is at the level of their regular cost of production which makes a practical solution for internalizing them very hard to solve. Deregulation of the energy sector makes the position of a nuclear option less competitive. The subsidies for renewable energy sources insubstantially alleviate their position, although the price is hardly predictable with stronger penetration of renewables.

It is evident that a sufficient base exists not only with models but also with hard date and experience to make a comparison between different energy sources. However, in reality, this is often neglected, and there seems to be a long way before judgment and decisions about energy sources selection will be based on the rationale grounds when that is possible and beneficial for the society as a whole. Some old and recent experience illustrates how strong perception is regardless of evidence and experience. This year, during the Fukushima accident progression, 51 miners died in coal mines in Pakistan and that was barely covered by news. In 1975, the Banqiao dam in China, which was designed for 1 in 1,000 year flood, failed because of Typhoon Nina collision with the cold front-line causing thereby flood of order 1 in 2,000 years. Consequently, the total of 62 dams failed. According to the Hydrology Department of Henan Province, in the province, approximately 26,000 people died from flooding and another 145,000 died during subsequent isolation and epidemics. In addition, about 5,960,000 buildings collapsed, and 11 million residents were affected. This disaster was declassified in 2005.



PFBC: pressurised fluidised bed combustion.
CC: combined cycle.
Note: These external costs are associated with emissions from the operation of power plants and with the rest of the energy chain.
Source: Dones *et al.* (2005).

Fig. 8. Electricity costs for different energy technologies, [16]

Table 1. Major accidents in energy related facilities with a large number of immediate deaths

Location	Year	No. of immed. deaths	Cause
Benxihu Colliery, China	1942	1,549	Coal dust explosion
Banqiao Dam, China	1975	26,000	Typhoon Nina
Machhu II, India	1979	2,500	Dam failure
Hirakud, India	1980	1,000	Dam failure
Cubatao, Brazil	1984	508	Oil fire
Mexico	1984	498	Liquefied petroleum gas
Chernobyl, Ukraine	1986	56	Nuclear power plant
Asha-ufa, Siberia	1989	600	Liquefied petroleum gas
Dobrinja, Yugoslavia	1990	178	Coal mine
Durunkha, Egypt	1994	580	Fire in oil tank
Warri, Nigeria	1998	>500	Fire in oil pipeline

4. CONCLUSION

The conclusion can be drawn that electricity generation is one of the activities in our society whose health and environmental risks are relatively well known, even with respect to the probability of unlikely but possibly serious events.

Small risks of utilization of nuclear power can only be assessed with significant uncertainties both for scenarios and for impact of doses on consequences. Enhanced protection from small doses costs enormously and increases risk (not only for nuclear power utilization). Education, communication and the total risk approach can serve as a basis for risk management in the way to maximize the benefits for the society, without conniving to the prejudices and without generating increased costs and real risk. There is no life without risk and the most important is how big the relative risk is, and how much it would cost to decrease it. This is a real situation where the risk itself has become and was demonstrated as the biggest risk of all.

One way of determining a quantitative risk level is to consider PSA. PSA perspective on severe accident risks is particularly important for energy chains whose risks are dominated by power plants since the historical experience of accidents is scarce or/and its applicability is highly restricted to a particular type of plant. Thus, PSA studies are expected to provide most representative results for hydro and nuclear power plants.

Based on the results of risk analysis, risk management supports the process of decision making both for the industries and the respective regulatory bodies. Whenever decision alternatives have been identified and ranked by comparing the expected value of benefits or losses on the basis of risk assessments, the risks must be considered in regard to their acceptability. It is suggested to differentiate between tangible and intangible risk, i.e. risks which may be easily expressed in monetary risks and others. Which intangible values should be considered in a given case has to be checked by risk identification.

But without having safety goals this is not good enough. Ideally, such quantitative safety goals are not limited to one type of plants but to any large industrial plant or any industrial activity that requires safety-related systems to ensure safety (e.g., petrochemical facilities, aviation, railway, etc.). Therefore, the need for the development of risk criteria, which would support risk informed decision-making, is expressed worldwide. However, risk acceptance is also correlated to non- technical factors (i.e., cultural context, etc.).

Compared with other sources of energy, nuclear power is one of the safest. Millions of people in the developing world still live in poverty, and it can alleviate their access to energy. Global energy demand will continue to rise, so energy will continue to get more expensive as fossil fuels become more and more difficult to extract. The use of renewables is increasing and will play an important part in the future energy mix, but it is questionable whether renewables alone will be able to satisfy rising energy demands, and what is going to be the final economical benefit.

The impacts of the Fukushima accident itself have not been justified as significant enough to exclude continued use of nuclear energy. It is evident that the ultimate solution for nuclear safety is further improvement of design. Dependence on the external power supply is an intolerable risk. Generation III+ of reactors already in use incorporate isolated and protected power supply, as well as passive cooling systems. Open containment of spent fuel rod ponds is also an unnecessary risk.

Nevertheless, the case of nuclear power remains strongly based on all evidence considering social, economical and environmental factors. All forms of energy generation carry risks. However, a lack of safety goals, differences in risk perception, methods, values, and distrust threaten to prevent the society from achieving optimal solutions regarding risks and benefits.

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