Health Effects of Technologies for Power Generation: Contributions from Normal Operation, Severe Accidents and Terrorist Threat

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Abstract: As a part of comprehensive analysis of current and future energy systems we carried out numerous analyses of health effects of a wide spectrum of electricity supply technologies including advanced ones, operating in various countries under different conditions. The scope of the analysis covers full energy chains, i.e. fossil, nuclear and renewable power plants and the various stages of fuel cycles. State-of-the-art methods are used for the estimation of health effects. This paper addresses health effects in terms of reduced life expectancy in the context of normal operation as well as fatalities resulting from severe accidents and potential terrorist attacks. Based on the numerical results and identified patterns a comparative perspective on health effects associated with various electricity generation technologies and fuel cycles is provided. In particular the estimates of health risks from normal operation can be compared with those resulting from severe accidents and hypothetical terrorist attacks. A novel approach to the analysis of terrorist threat against energy infrastructure was developed, implemented and applied to selected energy facilities in various locations. Finally, major limitations of the current approach are identified and recommendations for further work are given.

Keywords: Power Generation, Health Effects, Normal Operation, Severe Accidents, Terrorist Threat, Life Cycle Assessment, Environmental Impact Assessment, Comparative Risk Assessment

1. INTRODUCTION

The goals of sustainability include minimization of negative health impacts of energy systems. Such effects may arise due to emissions of pollutants from the normal operation of power plants and the associated fuel cycles as well as from accidents, thus contributing to increased mortality and morbidity. In fact, health damages of power generation are major contributors to the corresponding external costs (e.g. [1]).

The health risks associated with energy supply are of high public interest and are frequently in the focus of attention in debates addressing the pros and cons of specific options. However, this is subject to major deficiencies and misunderstandings due to the lack of solid basis in terms of systematic comparisons of health effects caused by the normal operation on the one hand and by random or intentional accidents on the other hand. The scope of such comparisons should cover not only the power plants but also the full energy chains. Furthermore, proper attention has to be paid to the appropriate, balanced choice of reference technologies since the results are technology-specific.

In our previous work (e.g. [2]) we provided examples of comparisons of health risks associated with the portfolio of current and future electricity supply options of a major Swiss electric utility. This covered both normal operation and accidents. The present paper broadens the scope of the comparisons by including the terrorist threat, illustrates the impact of technological features and operational conditions, and reflects the new methodological developments and major extensions of the relevant databases.

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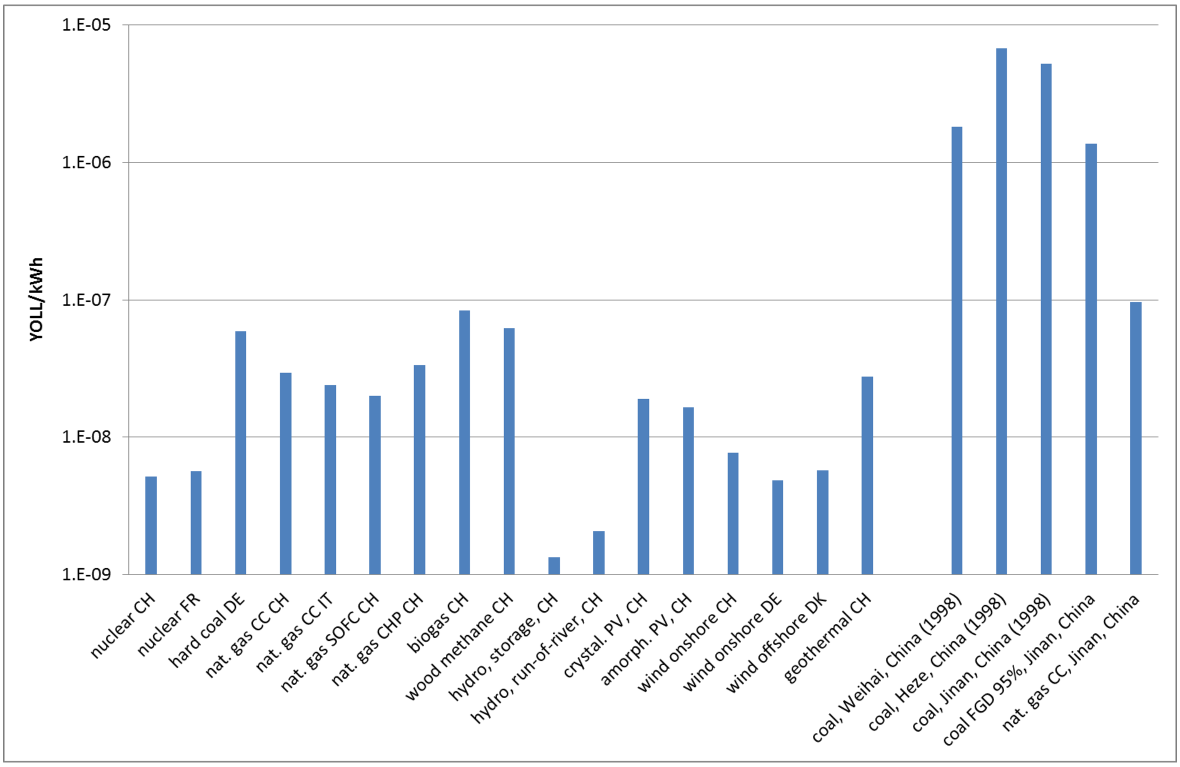
2. HEALTH IMPACTS OF NORMAL OPERATION

2.1. Estimates Based on Impact Pathway Approach

Health effects of normal operation are estimated using methods of Environmental Impact Assessment (EIA). The Impact Pathway Approach (IPA), allowing accounting for site-specific effects, is combined with detailed Life Cycle Assessment (LCA). The Impact Pathway Approach is based on methods developed in the European ExternE project series ([1], [3] and [4]). Methods and data for China refer to ([5] and [6]). The life cycle data are derived from the ecoinvent database ([7]), the most comprehensive LCA database worldwide.

Figure 1 shows health impacts of normal operation for different electricity generation technologies, different fuels, and different locations in Europe and China. The selected current (2010) European technologies represent very good environmental standards. For the Chinese case the typical, environmentally unfriendly technologies are contrasted to those having similar standards as the European ones. The health effects in terms of mortality are expressed in Years of Life Lost (YOLL) per kWh electricity produced (kWh_e). Large and small systems are considered. The biogas and natural gas combined heat and power (CHP) plants are of the order of 200 kW_e. For CHP, the environmental burdens are allocated to the generated electricity and heat according to the exergy allocation scheme. All results include contributions from the life cycle of the systems. Health effects due to climate change effects are not included.

Figure 1 Mortality in terms of Years of Life Lost (YOLL) per kWh electricity produced for different systems and different locations. Sources: Data for China plants from China Energy Technology Program ([5] and [6]); Swiss/European plants based on system choice in the Axpo project [8], adjusted to year 2010. (CH=Switzerland, FR=France, IT=Italy, DE=Germany, DK=Denmark, CC=Combined Cycle, CHP=combined heat and power, SOFC=solid oxide fuel cell, PV=photovoltaic, FGD=flue gas desulfurization).



The health impacts due to normal operation of the selected systems vary over almost four orders of magnitude, depending on the technology but also strongly on the location of power plants. Each plant-site is characterized by specific population density, meteorological conditions and concentration of species relevant for chemical transformations leading to production of secondary particulates.

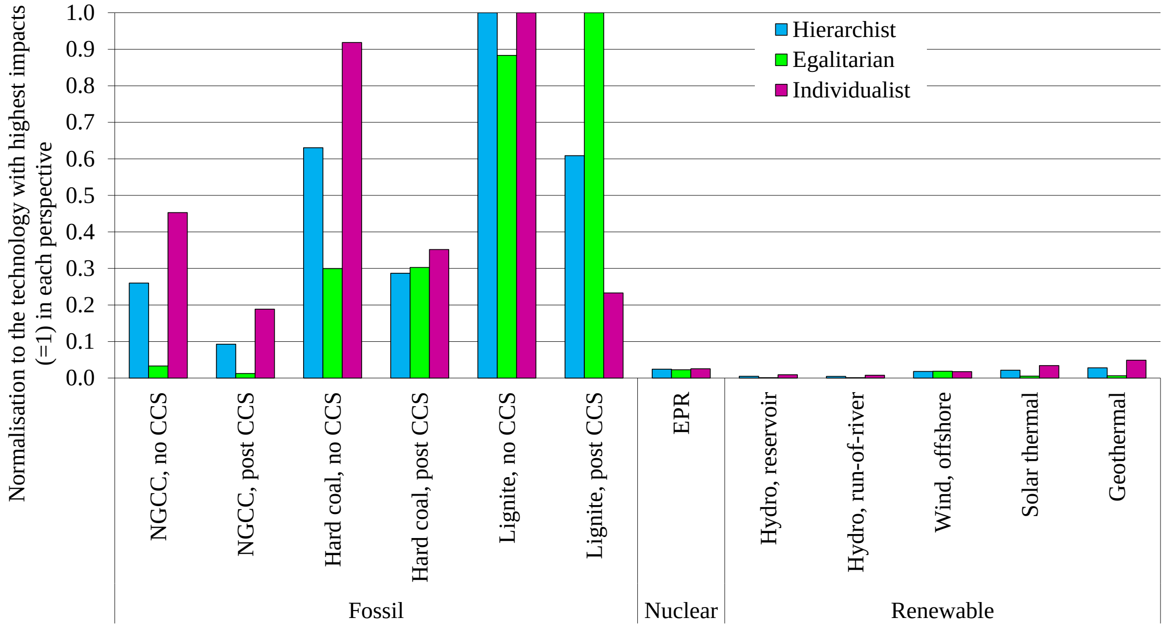
Hydro power plants show the lowest health damages per kWh electricity. Most other renewables and nuclear are in the middle range. Coal power plants without emission reduction measures, located in high population areas in China, yield the highest health damages per unit of electricity produced among the selected systems; use of clean coal technologies and modern combined cycle gas plants leads to large reduction of health effects.

2.2. Estimates Based on Life Cycle Assessment

The impacts of electricity production during normal operation can alternatively be assessed by means of Life Cycle Assessment. Human Health Damage is an endpoint in different Life Cycle Impact Assessment (LCIA) methods, expressed in Disability Adjusted Life Years (DALYs; DALY = Years of Life Lost + Years Lived with Disability). Depending on the LCIA method chosen and the social perspective taken, the influence of impact categories on the total human health impacts (HHI) varies significantly. The technologies chosen are based on ([7]- [11]). As opposed to the IPA the LCIA approach does not allow for representation of site-specific dependencies.

Figure 2 shows the total HHI of a number of European electricity producing technologies and the associated energy chains under three social perspectives used in the LCIA context, i.e. Hierarchist (H), Egalitarian (E) and Individualist (I). By normalizing to the technology with the highest impact within each of the three perspectives, the influence of the value choice on the ranking is reflected in the results. All three perspectives result in a clear difference in HHI of nuclear and renewables (N&R) on the one side and hard coal and lignite on the other side. In the Egalitarian perspective, impacts from natural gas are in the same range as those from N&R. With this perspective, the effect of the implementation of carbon capture and storage (CCS) is not as clearly advantageous as with the (H) and (I) perspectives.

Figure 2 Total HHI of future electricity production in Europe, normalized to the technology with highest impacts in each of the three perspectives [9]. NGCC: Natural Gas Combined Cycle; CCS: Carbon Capture and Storage, EPR: European Pressurized Reactor.



Whereas the (H) and (I) perspectives are mostly dominated by impacts due to climate change and, to a lower extent, by particulate matter formation, most of the impacts according to the (E) perspective originate from long-term effects of (ground)water pollution.

Figure 3 shows the comparison of DALYs for the same technologies and the associated energy chains as those covered in Figure 1 where IPA was used as the basis for the estimation. The most commonly used (H) perspective was employed. Table 1 summarizes the results for all three perspectives.

Figure 3 Impacts on human health from normal operation for electricity production, calculated with ReCiPe Endpoints (Hierarchist, Europe H/A) in DALY/kWh. “Other categories” include Human toxicity, ionizing radiation, photochemical oxidant formation, and particulate matter formation. All inventory data are for current European technologies and are based on [8].

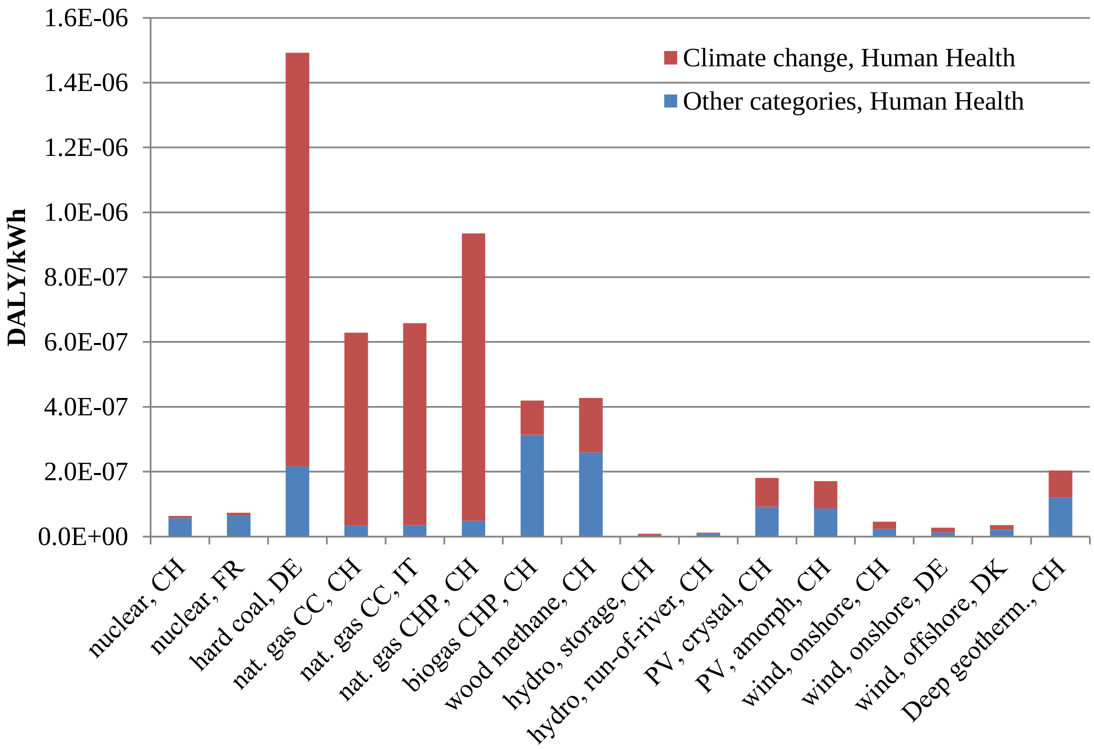


Table 1 Total human health impacts of different electricity producing technologies in nano-DALY/kWh for results calculated with ReCiPe and in nano-YOLL/kWh for results calculated with IPA. Abbreviations: ReCiPe, R (H) = Hierarchist, R (E) = Egalitarian, R (I) = Individualist; CC = Climate Change; IPA = Impact Pathway Approach; CCS = Carbon Capture and Storage; EPR = European Pressurized Reactor.

		Fossil						Nuclear	Renewables				
		Hard coal, no CCS	Hard coal, post CCS	Lig-nite, no CCS	Lig-nite, post CCS	NGCC, no CCS	NGCC, post CCS	Nuc-lear, EPR	Hydro, reser-voir	Hydro, run-of-river	Wind, off-shore	Solar thermal	Geo-thermal
Total human health, with CC	R(H)	1449	660	2300	1399	598	213	56	11	10	42	49	64
	R(E)	13819	13956	40738	46122	1527	570	1039	38	35	851	245	288
	R(I)	1121	429	1220	284	553	230	31	11	9	21	42	60
Total human health, w/o CC	R(H)	319	390	1000	1192	30	32	49	5	6	30	18	30
	R(E)	11117	13434	37497	45636	146	177	1024	23	24	824	179	208
	R(I)	60	77	99	91	27	28	25	4	5	10	14	27
IPA		59	-	-	-	27	-	5	1	2	6	-	28

It should be noted that the results of IPA and LCIA are not directly comparable. The estimation methods are much different with LCIA involving subjective elements related to the various social perspectives while IPA is based on natural sciences and allows simulation of site-specific effects. The health impact estimators have different scopes, i.e. YOLLs derived using IPA are a subset of DALYs generated using LCIA. The estimates based on LCIA cover not only health impacts of major pollutants but also the highly uncertain ones caused by the climate change; the latter are not included in IPA-estimates.

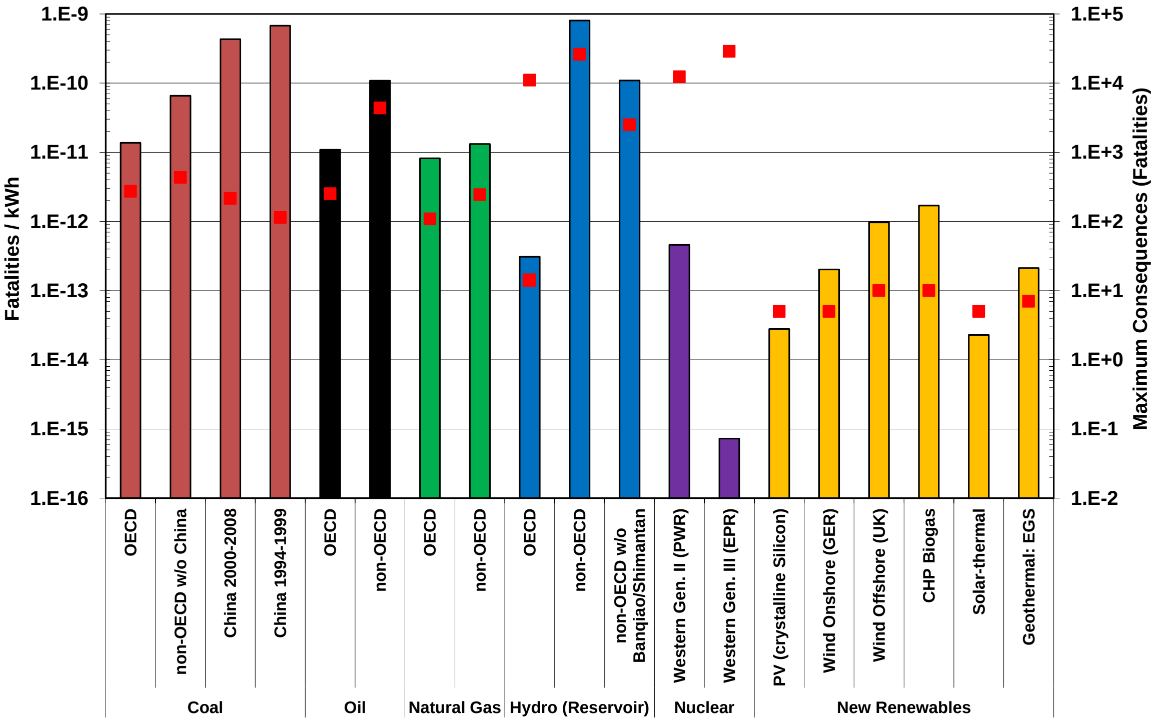
Overall, the IPA-estimates are more robust than those generated using LCIA. In spite of the differences in approaches a closer examination of the numerical results shows some consistency between the relative results for the estimates of health effects caused by pollution as obtained using the two methods. For the European technologies analyzed in this work these impacts are lowest for hydro and highest for coal, biogas and synthetic natural gas from wood, with nuclear, natural gas and other renewables in the middle range.

3. HEALTH IMPACTS OF SEVERE ACCIDENTS

The results presented here build on evaluations based on our database ENSAD (ENergy-related Severe Accident Database) and applications of simplified Level III Probabilistic Safety Assessment (PSA) for nuclear power plants. ENSAD and the framework for the comparative assessment of severe accidents was originally established in 1998 [12] and then further developed and refined ([13]-[17]).

Figure 4 shows the expected severe accident fatality rates and maximum consequences (square points) assessed for selected electricity supply technologies with the associated energy chains ([18]-[21].

Figure 4 Severe accident fatality rates and maximum consequences (red points) assessed for selected electricity supply technologies with the associated energy chains (after [18]-[21]).



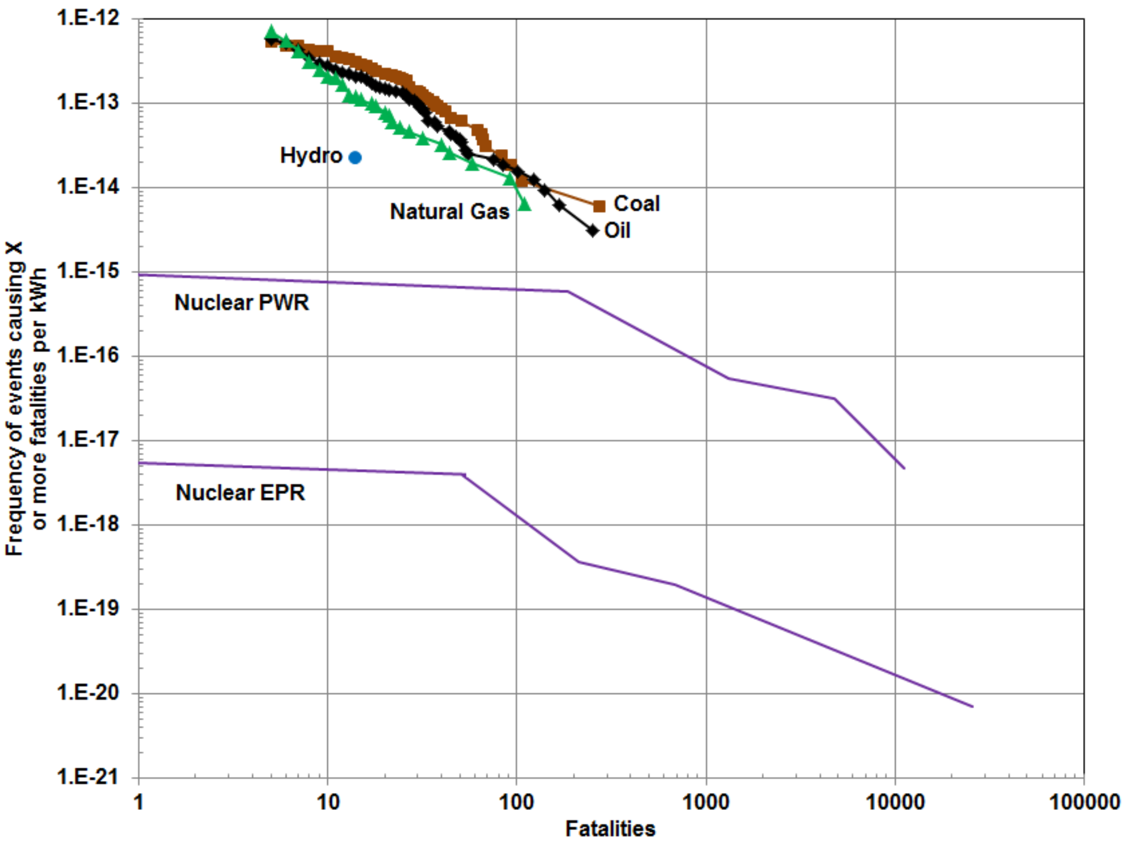
The results for fossil options are exclusively based on historical evidence according to ENSAD. The same applies to hydro with the exception of the high value of maximum consequences for OECD (red square point) corresponding to simulated consequences for a specific Swiss dam at a site characterized by relative ely high population density downstream from the dam. For nuclear energy a simplified Level III PSA was applied to a specific GEN II plant in Europe and to hypothetical GEN III plant in the same location; the maximum consequences include the dominant latent fatalities. For new renewables a combination of limited historical experience, literature data and expert judgment were used; the maximum credible consequences of accidents could in some cases (e.g. solar PV) be much higher than indicated. For further details on the methodological approach we refer to ([18]-[21]).

Non-OECD fatality rates are clearly higher than those for OECD. Fossil energy chains and non-OECD hydro have much higher fatality rates than the other options. Nuclear and hydro accidents may, however, have very large consequences. This is further illustrated by frequency-consequence curves below. The experience-based maximum consequences of accidents with new renewables are small. Further work exploring hypothetical accident scenarios for example in the manufacturing of solar cells are needed.

In order to facilitate comparison of the estimates for normal operation and severe accidents, respectively, it is worth noting that one premature fatality caused by air pollution roughly corresponds to 10 (chronic) YOLLs.

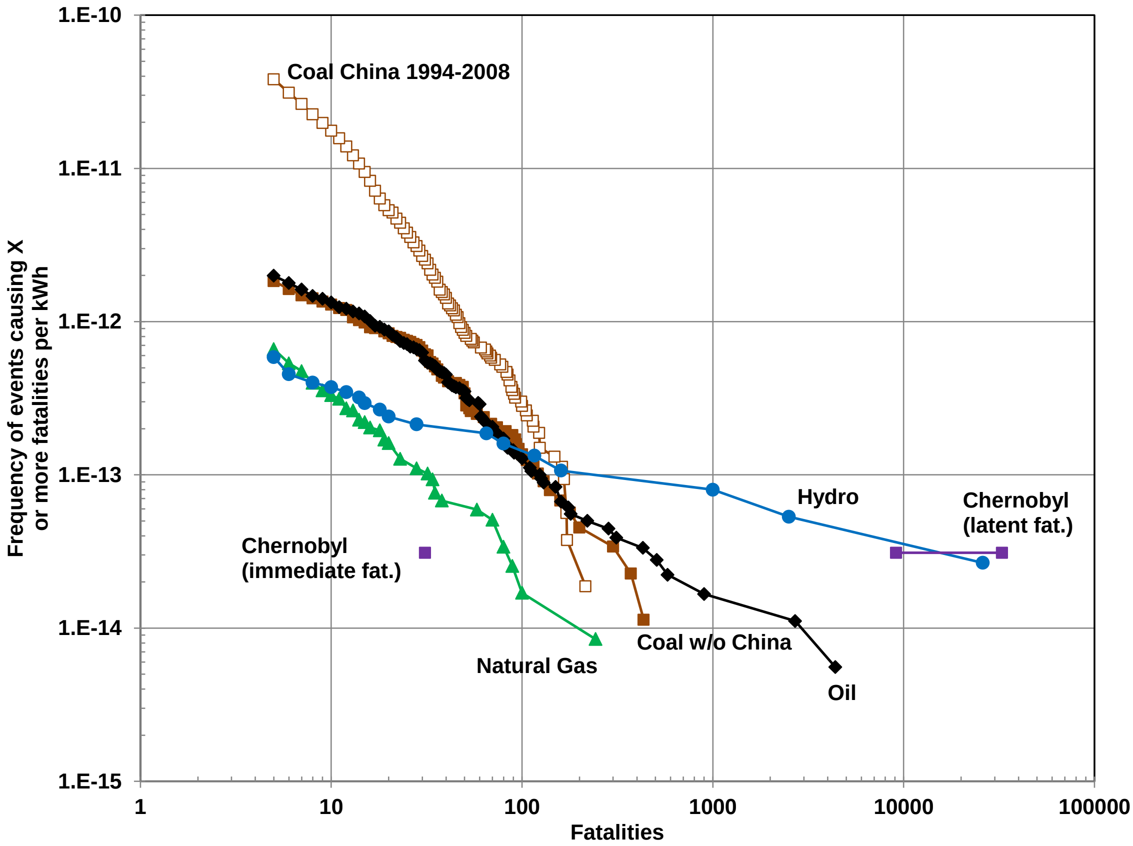
Figure 5 compares frequency-consequence curves for full energy chains in OECD countries for the period 1970 - 2008. The curves for coal, oil, natural gas and hydro are based on historical accidents and show immediate fatalities. For the nuclear chain, we extended Level II Probabilistic Safety Assessments (PSA) for a representative Generation II plant and a generation III plant (EPR) by conducting simplified Level III PSA; both immediate and latent fatalities are covered by these results. It should be noted that the Fukushima accident is not yet included since a reliable assessment of its consequences is still an open issue.

Figure 5 Comparison of frequency-consequence curves for full energy chains in OECD countries for the period 1970 - 2008 (after [20] and [21]).



Corresponding frequency-consequence curves for non-OECD countries are shown in Figure 6. The curves for coal, oil, natural gas and hydro are based on historical accidents and show immediate fatalities. For the nuclear chain, the results represent immediate and estimated range of latent fatalities caused by the Chernobyl accident.

Figure 6 Comparison of frequency-consequence curves for full energy chains in non-OECD countries for the period 1970 - 2008 (after [20] and [21]).



4. HEALTH IMPACTS OF HYPOTHETICAL TERRORIST THREAT

Within the EU-project SECURE [22] we developed, implemented and applied a novel methodology for the analysis of terrorism threat to energy infrastructure facilities with the potential for catastrophic consequences following a terrorist attack [23]. The targets include oil refineries, liquefied natural gas (LNG) terminals, hydropower dams and different types of nuclear power plants that rely on current (EPR) as well as future technologies (HTR – High Temperature Reactor; LMR – Liquid Metal-cooled Reactor). For each type of energy installation a specific location in China, Europe and the US was defined, where possible representing a real facility.

The developed framework allows integration of diverse expertise ranging from political sciences and intelligence on the motivation of terrorists to military knowledge on scenario planning to physical assessment of consequences. The framework also addresses the challenge of the large differences in the reliability of information in the different areas. While consequences can be modeled with relatively high confidence, the motivations of terrorists can be judged only within large error limits. The resulting large variation of uncertainty in the quantification of those aspects is addressed through a consistent treatment of uncertainty through all steps in the model.

The risk is calculated based on three factors:

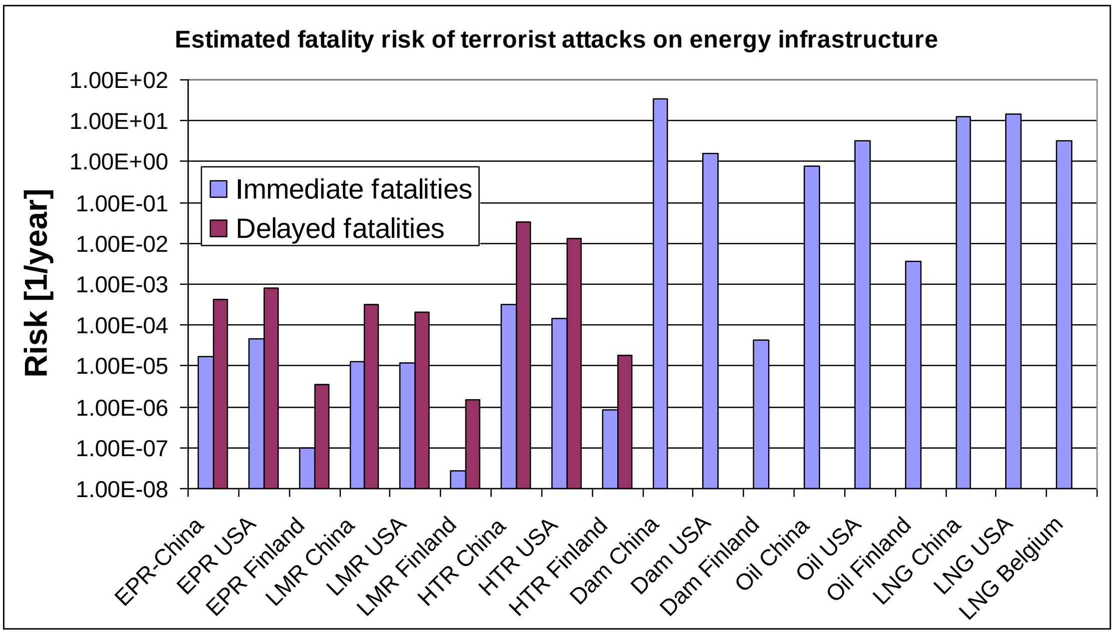
- The probability that an attack is planned based on historical evidence of attractiveness of a target and evidence of terrorist activity in the considered country
- The probability that a certain scenario can be implemented based on the necessary resources, time, know-how and countermeasures in place
- The consequences in terms of fatalities, injured and land contamination.

The reasoning behind this approach is that a terrorist will, more or less formally, follow the same evaluation: consequences of an attack should be maximized, but this aim has to be weighted against the success probability, the planning effort and the financial and personnel means available.

Several different concepts were integrated into the framework: The scenario quantification is based on fault/event tree logic. The “initiator frequency” of terrorist attacks, i.e. the probability that a given target is chosen per year is treated with Bayesian frequency updating. Uncertainties in the quantification process are addressed by using fuzzy logic, i.e. uncertainty functions that are evaluated by Monte Carlo analysis. This allows the systematic and formalized integration of expert judgment with a physical analysis of the consequences and attack scenarios to generate a complete picture of the probability that an attack can be successfully executed and of the likely resulting consequences.

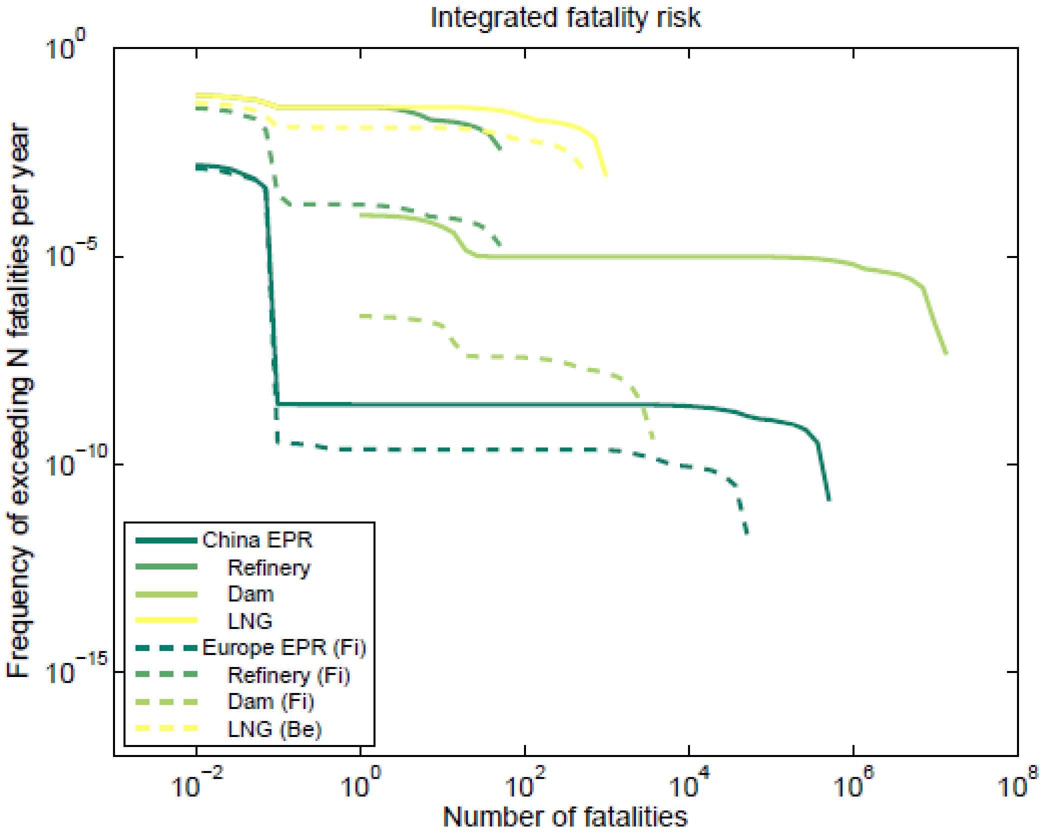
Figure 7 and 8 show respectively the estimated fatality risks and frequency-consequence curves for the analyzed energy infrastructure.

Figure 7 Risk of immediate and delayed fatalities due to hypothetical terrorist attacks [23].



The results are strongly technology-, country- and site-specific. The risk to oil refineries and LNG terminals may be substantial though maximum consequences are much more limited than for hydro and nuclear. Countermeasures on site may reduce the impact of a terrorist attack but will not ensure the total elimination of threats. Risks from attacks to dams are potentially very large in cases with high density of population down-stream from the plant (China). It should be noted that the analyzed Chinese dam is the largest world-wide electricity generation plant. However, the chance that a catastrophic accident can be induced by a terrorist attack is much smaller than for oil and LNG installations. Finally, the chance that a terrorist attack would cause very large consequences at the examined nuclear installations is extremely small, and comparable to the corresponding hypothetical risks associated with random severe accidents at these plants.

Figure 8 Frequency-consequence curves for hypothetical terrorist attacks on energy infrastructure [23].



5. CONCLUSIONS

Health effects of normal operation are estimated using detailed Life Cycle Assessment (LCA), Impact Pathway Approach (IPA) allowing accounting for site-specific effects, and combination of these two methods. The LCA part is supported by the ecoinvent database, the largest and most detailed LCA database, developed and operated by us and our research partners.

Estimation of health effects caused by severe accidents is based on historical experience as represented in our ENergy-related Severe Accidents Database (ENSAD), the most comprehensive database world-wide covering accidents in the energy sector. This is supplemented by the results of full scope Probabilistic Safety Assessments. Specifically for new renewables we use a hybrid approach including statistics (e. g. for wind), modeling (e. g. for solar PV), proxies (e. g. partially for geothermal, biogas) and expert judgment (e. g. for solar thermal or wave and tide).

A novel approach to the analysis of terrorist threat against energy infrastructure was developed, implemented and applied to selected energy facilities in various locations. It considers a number of factors including: attractiveness of specific objects as targets for an attack, implementation scenarios depending on resources, time, know-how and countermeasures, and estimation of consequences.

On the basis of our work employing the above approaches and carried out during the last 20 years a number of conclusions can be drawn with regard to the various types of risks associated with the energy supply. This paper focused on health risks represented by mortality.

Our work demonstrates that both in the context of normal operation and severe accidents it is highly essential to cover the full energy chains.

The contributions to health risks other than those caused by direct emissions from the operation of power plants, may in some cases be dominant but the relative shares vary a lot between the different options. For the normal operation such contributions (e.g. burdens related to material inputs and component manufacturing), are particularly important for solar PV, solar thermal, wind and hydro options. The rest of the energy chains along with the construction of power plants can also have quite high significance for specific burdens associated with fossil and nuclear fuel chains as well as the production of biomass.

The two approaches used for the estimation of health impacts from normal operation are much different both in terms of scope and the underlying methodology. While there are large numerical differences between the technology-specific estimates obtained using the two approaches, there are also some parallels in terms of technology ranking. Thus, renewables (with the exception of biogas) and nuclear mostly exhibit very good performance with hydro being the best option; coal ranks mostly worst while performance of natural gas is mixed.

In the context of severe accidents the fuel extraction, processing and transports within the fossil energy chains and hydro in non-OECD countries are most accident prone. The lowest fatality rates apply to hydro and nuclear in OECD countries though in both cases events with very low frequency can lead to quite extreme consequences. Generally, the fatality rates due to accidents in non-OECD countries are substantially higher than in OECD-countries and exhibit a number of accidents with very large consequences not experienced within OECD.

Overall, the fatality rates due to normal operation are much higher than the corresponding rates due to severe accidents.

In spite of large uncertainties the first-of-its-kind analysis of the terrorist threat indicates that the frequency of a successful terrorist attack with very large consequences is of the same order of magnitude as can be expected for a disastrous accident in the respective energy chain. This is primarily due to the fact that centralized large energy installations are hard targets and relatively easy to protect, requiring sophisticated attack scenarios to cause significant damage and lasting impacts. Historic preference of terrorists for fatalities implies lower risk compared to soft targets, which are much more vulnerable and do not necessitate mobilization of very large resources by the terrorists.

Further work on health effects associated with energy technologies should strive for dealing with limitations of the current work thus reducing the uncertainties. There is a need to improve the consistency of the analysis by fully consequent choice of reference technologies and the associated fuel cycles when carrying out the various types of analysis presented here. The analysis scope should be extended both geographically and in terms of covering future technologies. Novel approaches to the treatment of spatial dependencies in LCIA should be considered along with accounting for health effects associated with climate change when using IPA.

In the treatment of severe accidents it is desirable to extend the use of PSA to better reflect the quite heterogeneous safety performance of nuclear and hydro by extended use of PSA. More extensive analysis is needed for renewables handling large amounts of toxic materials, in particular solar PV.

The main merit of the current exploratory study is that it provides a structured methodology for quantitative assessment of terrorist threats against energy infrastructure. Such a framework has not been available until now. The framework was implemented and applied to selected facilities in specific locations. The numerical results should be seen as indications and depend on the judgments made by risk analysts engaged in the project. Full scale implementation would call for engagement of a variety of intelligence and technology specialists to provide more robust judgments and address the credibility of the postulated scenarios.

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