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1 Introduction

Within the EU Integrated Project NEEDS (New Energy Externalities Developments for Sustainability), the objective of Research Stream RS2b “Energy Technology Roadmap and Stakeholder Perspectives” is to broaden the basis for decision support beyond the assessment of external costs and to extend the integration of the central analytical results generated by other Research Streams.

For the health and environmental set of indicators, system performance associated with normal operation is considered to be sufficiently well described by the burdens and impacts assessed within NEEDS. However, external inputs are needed for accident risks, not directly addressed by NEEDS. The results obtained by PSI and its partners for non-nuclear systems in the relevant task within the EU Project NewExt provided a good starting point for such an analysis. For nuclear systems the existing results were outdated. New results were needed to account for site dependence and use of advanced designs. For this purpose, results from publicly available Probabilistic Safety Assessments (PSA) were used for the relevant designs (subject to adjustments based on engineering judgement) and a simplified consequence analysis was conducted, based on the knowledge that few factors drive the results. Since a complete set of source terms will hardly be available for the selected advanced design(s) extrapolations based on engineering judgement will be employed. The results covering accident risks were also partially used to quantify risk aversion as one of the factors affecting acceptability. It should be noted that the accident issue is not only relevant for nuclear energy but concerns all major energy chains. Accident aspects belong to the central ones in the context of social acceptability.

The objective of WP7 is to estimate quantitative indicators for severe accident risks for a set of technologies in year 2050 considered within NEEDS. The definition of risk indicators (e.g., characteristics, units) has been done within the establishment of the whole indicator set within WP3. The expected output of this Work Package as well as interactions with other Work Packages of the Research Stream is summarized in Table 1.

Table 1 Expected output and interactions of the quantification of risk indicators performed in WP7 of RS2b.

| <i>Input into WP7</i> | | |
|-----------------------|---|---|
| | From | Description |
| internal | RS 2b WP 3: Establishment of full set of criteria and indicators | Full set of risk criteria and indicators to be quantified |
| internal | RS 2b WP 4: Extended technology characterisation and prospective advancements | Characteristics of additional technologies and, if possible, associated risk indicators; as a minimum qualitative influence factors |
| external | RS 1c: Externalities associated to the extraction and transport of energy | Oil spill data |

| <i>Output from WP7</i> | | |
|------------------------|---|---|
| | To | Description |
| internal | RS 2b WP 8: Quantification of social indicators | Risk indicators with social relevance |
| internal | RS 2b WP 10: Evaluations and analysis integration | Risk indicator values to be used in Multi-Criteria Analysis (MCA) |

Risk indicator results are based on PSI's severe accident database ENSAD (Energy-related Severe Accident Database), except for nuclear systems where predictive analyses were performed. The generated risk indicators serve as an input to the multi-criteria decision analysis in WP10. With regard to historical experience, a full update of the ENSAD database up to year 2005 was undertaken with focus on major fossil chains and hydropower, supplemented by the implementation of a simplified PSA approach for the nuclear chain. In contrast, consideration of new renewables was based on accident statistics, literature review and expert judgment because of limited or lacking historical experience.

It should be noted that some of the objective social indicators (WP8) related to health and environmental impacts due to accidents will be treated in this package. In addition, the accident risk results will partially be used to address terrorist threat and also risk aversion as one of the factors affecting social acceptability of the various technological options.

A complete overview of the criteria and indicator set developed and established within NEEDS is available in the following reports (Burgherr et al., 2008; Hirschberg et al., 2008). Risk relevant criteria and indicators were assigned to all three dimensions of sustainability. Those pertaining to accident risks and terrorist threat are marked in bold in the below list, and will be presented in this report.

Environmental Dimension:

- Climate change
- **Impacts on ecosystems**
 - o Normal operation
 - o **Severe accidents**

HYDROCARBONS: this indicator quantifies large accidental spills of hydrocarbons to the environment, which can potentially damage affected ecosystems. It considers severe accidents only, i.e. releases of at least 10000 tonnes. Unit: [t/GW_{eyr}] (metric tons per Gigawatt-electric-year).

LAND CONTAMINATION: This indicator quantifies land contaminated due to accidents releasing radioactive isotopes. The land area contaminated is estimated using Probabilistic Safety Analysis (PSA). Note that this indicator is restricted to the nuclear electricity generation technology chain. Unit: [km²/GW_{eyr}].

Economic Dimension:

- Autonomy of electricity generation
- Financial risks

Social Dimension:

- Political threats to continuity of energy service
- Potential of conflicts induced by energy systems
- **Social and individual risks**
 - o Expert-based risks of normal operation
 - o **Expert-based risks of severe accidents**

ACCIDENT MORTALITY: this indicator is based on the number of fatalities expected for each kWh of electricity that occur in severe accidents with 5 or more deaths per accident for a particular electricity generation technology chain. Unit: [Fatalities/GW_{eyr}].

MAXIMUM FATALITIES: this indicator is based on the maximum number of fatalities that are reasonably credible for a single accident for a particular electricity generation technology chain. Unit: [Fatalities/accident].

- Perceived risk
- **Terrorist threat**

TERROR-POTENTIAL: this indicator indicates the potential for a successful terrorist attack on a specific technology, based on its vulnerability, the potential damage and public perception of risk. Unit: [Ordinal scale].

TERROR-EFFECTS: this indicator concerns the potential likely consequences of a successful terrorist attack. The criterion implicitly addresses the aversion towards low-probability high-consequence accidents. Unit: [Expected number of fatalities].

PROLIFERATION: this indicator represents the potential for misuse of technologies or substances present in the nuclear electricity generation technology chain, based on both their presence and the risk of such misuse or diversion. Unit: [Ordinal scale].

2 Approach and methods

2.1 Severe accident database ENSAD

At an early stage of the development of ENSAD it was decided that building a severe accident database from the scratch would neither be feasible nor efficient, particularly given the actual time and resource constraints. The survey of the existing sources of information, carried out at the beginning of this effort showed that:

1. Numerous sources of information exist, but their availability, scope, development status and quality exhibit an enormous variation.
2. Commercial and non-commercial databases are available. They normally cover man-made accidents in a variety of sectors and in some cases also the natural disasters. Very few of the databases deal explicitly with energy-related accidents. If they do, the coverage concerns one specific energy carrier, for example offshore accidents. In most cases energy-related accidents constitute a not explicitly identified subset among other accidents.
3. None of the available individual databases has a satisfactory coverage to form alone a basis for the evaluation of severe accidents in the energy sector.
4. The information assembled in the available databases even if combined, would not be fully adequate for meeting the objectives of this work. It needs to be supplemented by additional sources in order to achieve reasonable completeness and quality.

Therefore, ENSAD uses a multitude of primary information sources whose contents are verified, harmonized and merged within the ENSAD framework. The advantages of such an approach are:

1. The substantial variation among individual databases in availability, scope, development status and quality can be balanced.
2. Commercial databases were also considered to gain access to proprietary data that are not fully contained in publicly available information sources.
3. The combined information available from a variety of sources results in a much broader coverage of severe accidents than any single database.

The actual process of database building and implementation has been described in detail earlier (Burgherr & Hirschberg, 2008a; Burgherr et al., 2004; Hirschberg et al., 1998), thus only a brief summary of the essential steps is given here:

1. Survey of available information sources and selection of relevant ones. Criteria for acquisition included that retrieved data were of sufficient quality in terms of detail and accuracy, and allowed a balanced coverage of different sectors, geographical area and time.
2. Raw information from the various sources was then merged, harmonized, checked for inconsistencies and verified before records were entered in ENSAD.
3. Each record was assigned to a disaster group (natural, man-made energy-related, man-made non-energy-related). Energy-related accidents were then allocated to specific fuel cycles and subsequently to specific stages within each fuel cycle.
4. After integration of the various information sources into ENSAD, the assembled data set was subjected to another cross-check. In those cases, for which discrepancies still remained, supplementary searches were performed to get access to additional information to resolve these conflicts.
5. Compilation of the “final” set of data and subsequent queries to generate data subsets for specific evaluations. In a first step, analyses are carried out for each energy carrier. Secondly, these results are then used for comparative evaluations between the various energy carriers.

2.2 Criteria and structure of ENSAD

2.2.1 Severe accident definition

In the literature no commonly accepted definition can be found of what constitutes a severe accident. Differences concern the actual damage types considered (e.g. fatalities, injured persons, evacuees or economic costs), use of loose categories such as “people affected”, and differences in damage thresholds to distinguish severe from smaller accidents.

This can be illustrated by the following examples. The “World-wide Offshore Accident Database” (WOAD) of the Det Norske Veritas (DNV, 1999) considers an accident as severe or major, if more than one fatality occurred or if the damaged unit (e.g., oil platform, drill ship or drill barge) experienced total loss. Glickman & Terry (1994) define a significant accident for technological hazard, if it resulted in at least five fatalities or if it involved the release of a chemical, petroleum product, hazardous waste or other hazardous material. The SIGMA publication series of Swiss Re Company (Swiss Re, 2001) and Rowe (1977) do not use the term “severe accidents”. However, they do investigate and collect data on catastrophic events.

Within the framework of PSI’s database ENSAD an accident is considered to be severe if it is characterized by one or several of the following consequences (Hirschberg et al., 1998):

1. at least 5 fatalities or
2. at least 10 injured or
3. at least 200 evacuees or
4. extensive ban on consumption of food or
5. releases of hydrocarbons exceeding 10'000 (metric) tones (t) or
6. enforced clean-up of land and water over an area of at least 25 km² or
7. economic loss of at least 5 million USD(2000)¹

Generally, fatalities comprise the most reliable indicator concerning completeness and accuracy of the data; superior to injured persons or evacuees. A typical problem in case of economic damages is that sources outside the insurance sector tend to mix the various types of economic damages (e.g., insured vs. total loss) or give no specification at all what type of damage is reported.

While insured losses provide a particularly suitable basis for analyses as they can be established precisely, economic damages can never be calculated exactly as they are determined in various ways, depending on the definition applied in each case, and are seldom fully and reliably established (e.g., Munich Re, 2001). Furthermore, they can consist of direct losses (immediately visible, countable losses), indirect losses (resulting from the physical destruction of assets) and secondary costs (costs that weaken the affected country’s economy); however, the components considered are often not clearly stated. The other consequence indicators are either relevant only for specific energy chains or ENSAD contains very few entries with adequate details of information (Burgherr et al., 2004; Hirschberg et al., 1998).

¹ Different currencies were all converted to USD values. To take account of inflation, specific amounts were extrapolated using the US Consumer Price Index (CPI) to obtain year 2000 values.

2.2.2 Milestones in the development of ENSAD

Although accidents in the energy sector have been shown to form the second largest group of man-made accidents (after transportation), their level of coverage and completeness was not satisfactory because they were commonly not surveyed and analyzed separately, but just as a part of technological accidents (Hirschberg et al., 1998).

In the 1990s the Paul Scherrer Institut (PSI) started a long-term research activity to close this gap and to enable a factual and appropriate treatment of accident risks in the energy sector. The analytical approach behind PSI's database ENSAD integrates historical accident data from a large variety of sources, encompassing fossil, hydro and nuclear energy chains because all of them entail some significant forms of health, environmental or socio-political risks. In the case of nuclear power, application of Probabilistic Safety Assessment (PSA) was mandatory (Hirschberg et al., 1998). Consequences of hypothetical nuclear accidents were analyzed using PSA techniques.

Consideration of complete energy chains is essential because accidents not only occur during actual energy production, but in every stage of a chain from exploration to extraction, refining, storage, distribution, and finally waste disposal. Severe accidents are most controversial in public perception and energy politics. Therefore they are the main focus of investigations, even when the total sum of the many small accidents with minor consequences is substantial.

A comprehensive and undistorted comparative assessment requires the objective expression of accidents and risks on the basis of extensive data collection and evaluation. Considerable difference in the magnitude, timing, and nature of associated risks can be expected among the various energy chains. It is this difference that allows a degree of choice in the decision-making process, with regard to selecting energy alternatives, decisions on energy policies and achieving safety goals. Custom-tailored information on energy-related accident risks can be useful to a variety of stakeholders ranging from industry and the services sector to national governments and national or international organizations and authorities that are engaged in emergency response, disaster relief and safety or law enforcement.

After its initial establishment (Burgherr & Hirschberg, 2008a; Burgherr et al., 2004; Hirschberg et al., 1998), the ENSAD database has been continuously updated to keep up with the growing historical experience. Furthermore, the analysis scope has been substantially extended to provide solutions to upcoming problems and to meet the specific needs of new users. Major advancements are attributable to several recently completed projects:

1. Within the China Energy Technology Program (CETP) access was obtained to previously restricted information on accidents in China; particularly detailed records on accidents in Chinese coal mines were practically unavailable in the past (Hirschberg et al., 2003a; Hirschberg et al., 2003b).
2. Within the EESD Energy Project New elements for the assessment of external costs from energy technologies (NewExt) for the first time a reasonably consistent and comprehensive assessment of externalities from major accidents in non-nuclear fuel chains was performed (Burgherr et al., 2004).
3. A study of natural gas accident risks for the Swiss Gas and Water Industry Association (SVGW) enabled further improvements based on detailed evaluations of natural gas accident statistics of Switzerland and Germany (Burgherr, 2005a; Burgherr, 2005b; Burgherr & Hirschberg, 2005).

Most recently, the database has been updated within the present Integrated Project “New Energy Externalities Developments for Sustainability” (NEEDS) of the EU 6th Framework Programme. For this purpose, the database content was first reviewed and consolidated as of year 2000, which corresponds to the starting point before the comprehensive update within the NEEDS project. In a second step, ENSAD was updated and extended to the year 2005. Data from 2006 onwards were not included in the current analysis because it is a known fact that there is a substantial time delay for

certain accidents until consolidated information and final reports become available, which can then be designated as a final record in ENSAD. Figure 1 provides a schematic overview of the main steps in the development and the increase in accident records stored in the ENSAD database.

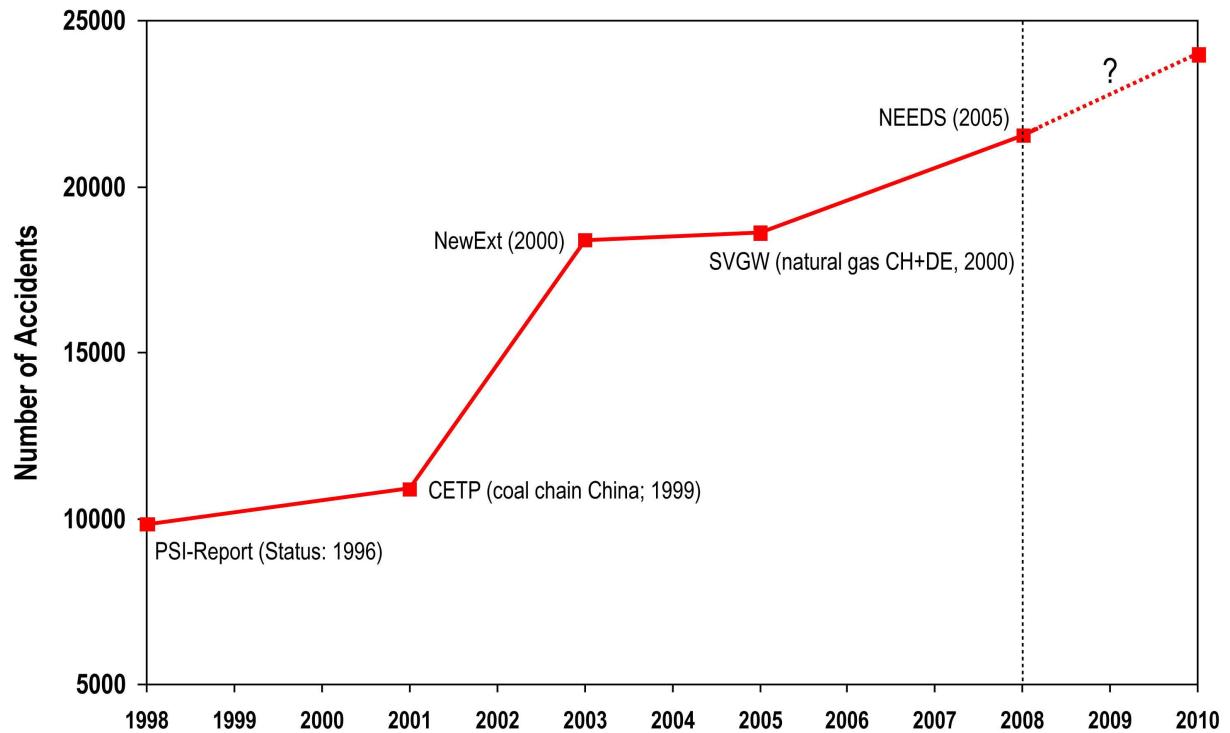


Figure 1 Major steps in the development, extension and update in contents of the ENSAD database. See text for Abbreviations.

2.2.3 Overview of information sources

In the past, significant efforts have been directed towards the development of databases for historical events with the purpose of understanding the potential hazards confronting industrial designers, insurance companies or decision makers. Efficient risk management and hazard control can be defined and implemented if lessons are learned from previous incidents and accidents (Baecher et al., 1980; Beek, 1994; Drogaris, 1983; ICOLD, 1974). The experience gained from the analysis of past accidents can be used to avoid design errors, to improve existing facilities, to develop emergency plans, to evaluate specific technologies, etc.

PSI's highly comprehensive database ENSAD utilizes merged and harmonized historical data from a large variety of information sources. Therefore, ENSAD can be considered superior compared to single database approaches that are also often limited concerning geographic area, time period, and energy chains included. Thus, the statistical evidence available for fossil systems is very extensive and can be regarded as quite satisfactory for comparative studies. Nevertheless, specific tasks were pursued aiming at extensions of the database and at creating a basis for evaluations consistent with the objectives of WP7 in RS2b of the NEEDS project.

Figure 2 shows the major commercial and freely available information sources used to document energy-related accidents included in ENSAD for the years 1969-2000. The four most common sources summed up to 48.5%, followed by seven other sources that cumulatively contributed 22.6%. Databases with a broad scope and a general coverage of technological accidents and natural disasters include MHIDAS, FACTS, HSELINE/LLP, Swiss Re (SIGMA) and EM-DAT. In addition a variety of databases were of critical importance. This applies in particular to databases covering specific energy chains and/or countries. For example, the China Coal Industry Yearbook (CCY) for the Chinese coal chain, MSHA for the US coal chain, WOAD for offshore gas and oil, ETC Tanker Spills

Database and Oil Spill Case Histories for oil spills, and ICOLD (International Committee on Large Dams) and “Bibliography of the History of Dam Failures” for dam accidents. The vast number of 172 sources subsumed under “Other Sources” amounted to about 28.9%. Their individual shares are smaller than 2%, and 153 of them contribute even less than 0.5%. However, many of these sources with small shares were of critical importance because they covered specific energy chains and/or countries, were useful to resolve contradicting statements, and provided supplementary information that would otherwise not be available.

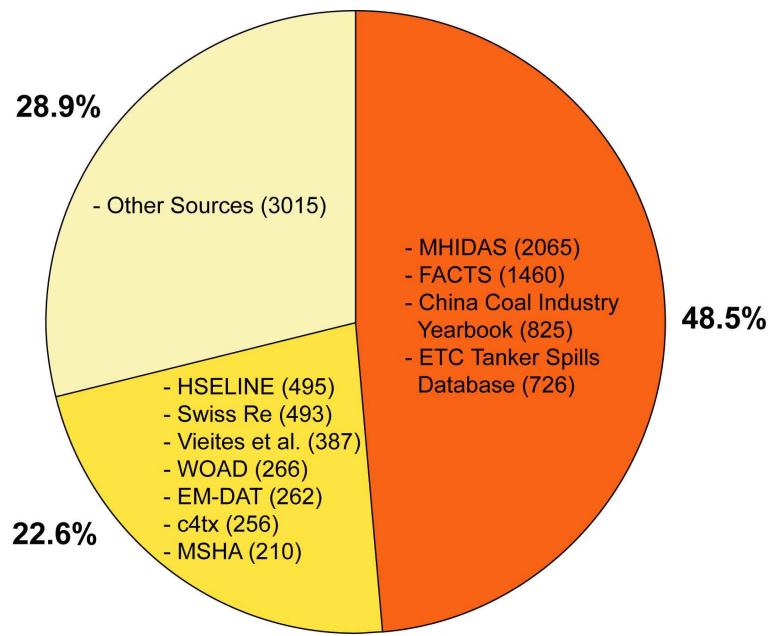


Figure 2 Contributions of major information sources to the total number of energy-related accidents stored in ENSAD for the years 1970-2005. Note that the total number of accident information sources (10460) sums up to more than the total number of accidents (6227) documented in ENSAD because a specific accident may be reported by several sources.

Abbreviations: MHIDAS: Major Hazard Incident Data Service (UK Health & Safety Executive); FACTS: Failure and Accidents Technical Information System (TNO, Netherlands); HSELINE/LLP: Library and Information Services of the UK HSE (UK Health & Safety Executive); WOAD: World-wide Offshore Accident Database (DNV, Norway); EM-DAT: Emergency Disasters Data Base (OFDA/CRED International Disaster Database); c4tx: Center for Tankship Excellence (<http://www.c4tx.org/>); MSHA: US Department of Labor, Mine Safety and Health Administration (<http://www.msha.gov>); Other Sources: information sources with contributions less than 2%.

For the assessment of severe, energy-related accident risks within the NEEDS project, external database inputs relevant for ENSAD were reviewed with respect to suppliers, scope, update frequency, acquisition costs etc. Table 2 provides an overview of the primary information sources that have been considered for the ENSAD update within the NEEDS projects, covering the period 2001-2005. One should note that both freely available sources and commercial databases were taken into account because the latter may contain proprietary information not available at all or documented in a less detailed manner in non-commercial sources. Furthermore, several sources already surveyed earlier but with limited relevance for the NEEDS update or such that have not been updated or continued after year 2000, are not listed in Table 2. Nevertheless a total of about 30 primary information sources and more than 50 additional sources are being surveyed within the NEEDS update of ENSAD.

Table 2 Primary information sources used to update the ENSAD database within the NEEDS project. Abbreviations:
C = commercial database, F = freely available database.

| Database | Geographic area | Accident types |
|--|-------------------------|----------------------------------|
| MHIDAS (C) | Worldwide | Industry |
| HSELINE/LLP (C) | Worldwide | Industry |
| Swiss Re (C/F) | Worldwide | Natural & Man-made disasters |
| EM-DAT (F) | Worldwide | Natural & Man-made disasters |
| Hint (C) | Worldwide | Industry |
| Fireworld (F) | Worldwide | Industry |
| Lloyds Casualty Week (C) | Worldwide | Industry |
| Aria/Barpi (F) | Worldwide | Industry |
| MSHA (F) | USA | Coal |
| Newspapers / Internet (NZZ, BBC etc) (C/F) | Worldwide | Industry |
| US National Transportation Safety Board (NTSB) (F) | USA | Transport |
| US Department of Transportation, National Highway Traffic Safety Administration (NHTSA) (F) | USA | Transport |
| Australian Transport Safety Bureau (ATSB) (F) | Australia | Transport |
| US Office of Pipeline Safety (OPS) (F) | USA | Gas (Distribution, Transmission) |
| Centre de Documentation, de Recherche et d'Expérimentations sur les Pollutions Accidentielles des Eaux Cedre (CEDRE) (F) | Atlantic, Mediterranean | Oil Spills |
| International Tanker Owners Pollution Federation Ltd. (ITOPF) (C/F) | Worldwide | Oil Spills |
| The Center for Tankship Excellence (CTX) (F) | Worldwide | Oil Spills |
| Marinergroup (F) | Worldwide | Oil Spills |
| Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC) (F) | Mediterranean | Oil Spills |
| National Oceanic and Atmospheric Administration (NOAA), NOAA Incident News (F) | Mainly USA | Oil Spills |
| Helsinki Commission (HELCOM), Convention on the Protection of the Marine Environment of the Baltic Sea Area" (F) | Baltic | Oil Spills |
| International Oil Pollution Compensation Funds (IOPCF) (F) | Worldwide | Oil Spills |
| Australian Maritime Safety Authority (AMSA) (F) | Australia | Oil Spills |
| UK Maritime Accident Investigation Branch (MAIB) (F) | UK | Oil Spills |
| United States Mine Rescue Association (USMRA) (F) | USA, China | Coal |
| Disaster Database (F) | Worldwide | Industry |
| Dartmouth Flood Observatory (F) | Worldwide | Floods / Dams |
| Association of State Dam Safety Officials (ASDSO) (www.damsafety.org) (F) | USA | Dams |
| Munich Re (F) | Worldwide | Natural & Man-Made Disasters |
| Windpower databases (F) | Germany, Europe | Wind |
| Other sources (C/F), ca. 50 different sources | Worldwide | Various |

2.3 Principles, assumptions and methodology for evaluation

2.3.1 Energy chain stages

The risks to the public and the environment, associated with various energy systems, arise not only at the power plant stage but at all stages of energy chains. In general, an energy chain may comprise the following stages: exploration, extraction, transport, storage, power and/or heat generation, transmission, local distribution, waste treatment, and disposal. However, one should be aware that not all these stages are applicable to every energy chain. Figure 3 gives an overview of distinct stages for the major fossil (coal, oil, natural gas and liquefied petroleum gas (LPG)), hydro and nuclear chains.

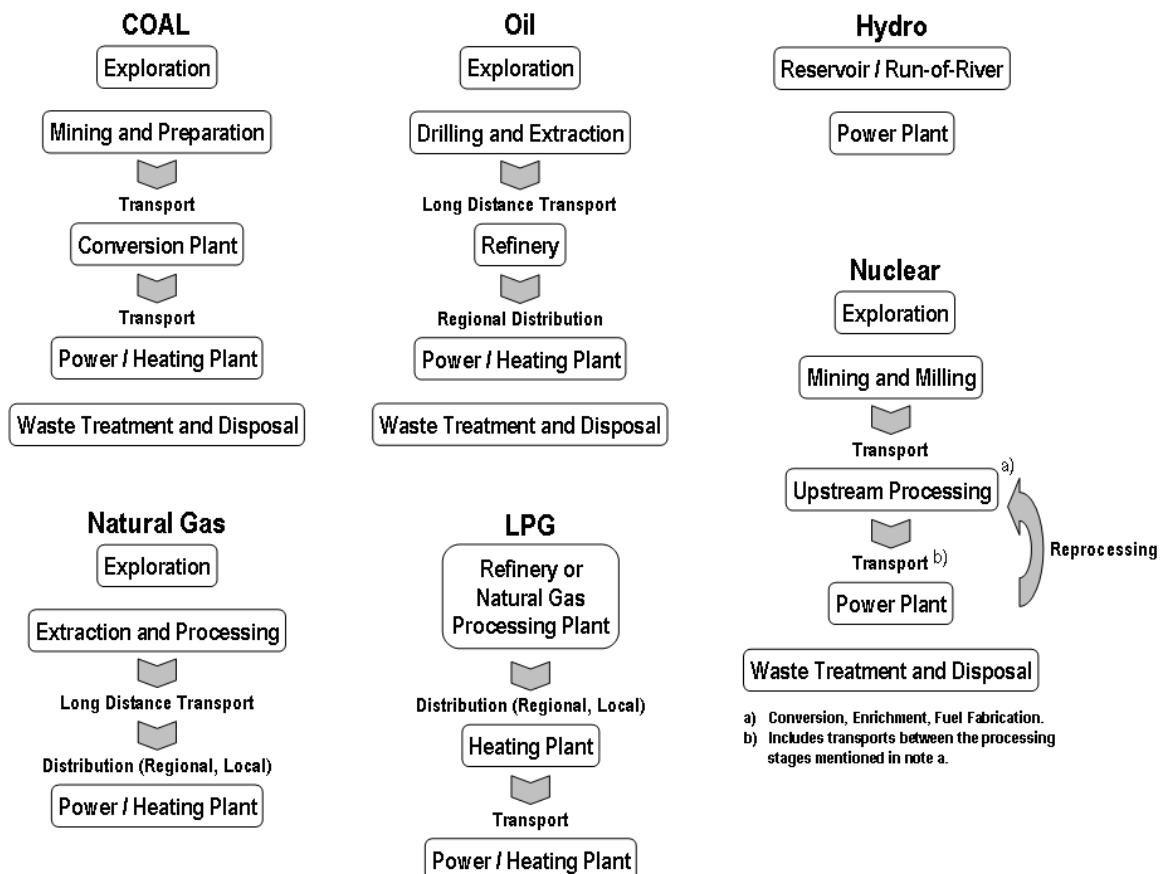


Figure 3 Main stages of different energy chains (modified from Hirschberg et al., 1998).

2.3.2 Historical experience and evaluation period

The ENSAD database allows carrying out comprehensive analyses of accident risks that are not limited to power plants but cover full energy chains. Such a broader perspective is essential because for the fossil chains accidents at power plants play a minor role compared to the other chain stages, i.e. analyses based on power plants only would radically underestimate the real situation (Hirschberg et al., 1998). Furthermore, identification of weak links in an energy chain, potential improvements and effective measures on the technical or regulatory levels require deep knowledge of events, their possible causes, dimensions and relationships (Burgherr & Hirschberg, 2008a; Burgherr & Hirschberg, 2008b).

Severe accidents in the energy sector are analyzed for the years 1970-2005. The starting year was chosen because energy-related severe accidents distinctively increased at the end of the 1960s, which is primarily due to the increase in the volume of activities (Hirschberg et al., 1998). Therefore, the selected period of observation covers more than three decades of historical experience, which allows evaluating temporal trends. Accidents further back in time were not taken into account because they may confound results since they are not comparable due to (1) less comprehensive coverage in past years; (2) improved reporting and documentation, particularly in the last five to ten years; and (3) changes over time (i.e., technological advancements, more strict safety regulations, etc.).

2.3.3 Comparative analyses: historical experience and allocation of damages

Comparisons of the various energy chains were based on data normalized to the unit of electricity production. For fossil energy chains the thermal energy was converted to an equivalent electrical output using a generic efficiency factor of 0.35. For nuclear and hydro power the normalization is straightforward since in both cases the generated product is electrical energy. The Gigawatt-electric-year (GW_eyr) was chosen because large individual plants have capacities in the neighborhood of 1 GW of electrical output (GW_e). This makes the GW_eyr a natural unit to use in discussions of total electricity production.

Results are provided separately for countries of the Organisation for Economic Co-operation and Development (OECD)² and states that are not OECD members (non-OECD) because of large differences in levels of technological development and safety performance. This distinction is also meaningful because of the substantial differences in management, regulatory frameworks and general safety culture between these two groups of countries (e.g., Burgherr & Hirschberg, 2008a; Burgherr et al., 2004; Hirschberg et al., 2004). Furthermore, it can be shown that within group variation is much larger for non-OECD compared to OECD countries (Burgherr & Hirschberg, 2008b). Finally, results were complemented by individual calculations for the EU 27³ and the Chinese coal chain. In the case of China, coal chain data were only analyzed for the years 1994-1999 when data from the China Coal Industry Yearbook were available, indicating that previous years were subject to substantial underreporting (Hirschberg et al., 2003a; Hirschberg et al., 2003b).

² The Organisation for Economic Co-operation and Development (OECD) was established in 1961 and currently consists of 30 member countries, which are: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, The Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States.

³ The European Union currently comprises 27 member states (EU 27). EU 15 (until April 2004) included Belgium, Germany, France, Italy, Luxembourg, The Netherlands, Denmark, United Kingdom, Ireland, Greece, Portugal, Spain, Austria, Finland, and Sweden. With the enlargement to EU 25 (until 2006) Czech Republic, Estonia, Cyprus, Latvia, Lithuania, Hungary, Malta, Poland, Slovenia, Slovak Republic joined. Most recently, Bulgaria and Romania became member states (EU 27 since 2007).

Aggregated indicators provide a direct comparison of severe accident consequences (e.g., fatalities) per unit of electricity produced (e.g., GW_eyr) between energy chains and country groups. A second set of values is also given, accounting for the fact that a large number of severe accidents occur in non-OECD countries at stages in the energy chain relevant for export to OECD countries. This can be incorporated in the calculations by adding the appropriate share of the consequences of accidents that occurred at such fuel cycle stages in non-OECD countries to the damages that physically occurred in OECD countries, i.e. OECD countries import fatalities with their fuel. The net amounts of energy carriers imported to OECD countries from non-OECD countries form the basis for this allocation procedure, which has been described in detail in Hirschberg et al. (1998). Aggregated indicators with allocation are particularly useful within a sustainable development perspective because they assume that the industrial OECD countries should bear a certain share of these damages (Burgherr & Hirschberg, 2008a).

The comparison of results can be expanded beyond the aggregated values obtained for specific energy chains. Frequency-consequence (F-N) curves display risks in the form of frequencies of exceeding a given number of fatalities on a double logarithmic scale, i.e. cumulative number of events are shown (Burgherr & Hirschberg, 2008a).

2.3.4 Simplified PSA-approach for the nuclear chain

A methodology for a simplified assessment of offsite consequences resulting from a severe accident is briefly described in this section, while more details can be found in previously published studies (e.g., Hirschberg et al., 2003b). The MACCS2 code is used for the calculations of inputs to the simplified model.

Offsite risk measures are calculated for the same LWR plant, with operating power equal to 3600 MWTh, for two hypothetical accidents, one with early containment rupture, and one with a late vented release. Data for two different sites is used for the dispersion and dose calculations, the first a European continental site with relatively large population density in the vicinity of the plant, and the other a US site with relatively low population density within the first ten km.

The calculations are performed for each of the nine normally defined (i.e., following PSA practices) radionuclide groups in turn, assuming that 100% of the group is released to the environment, without offsite countermeasures, and without cut-offs in effectiveness of doses in inducing cancers. The consequences are correlated then to the released activity, and factors (or effectiveness in causing consequences) are derived for each radionuclide group, i.e., consequences per Bq released. Consequences which were considered are early fatalities (i.e., deaths occurring because either inhalation or immersion in the passing cloud delivers doses larger than what is considered a lethal dose, or approximately 3 Gy), delayed cancer deaths due to doses from ingestion and inhalation while the cloud is passing, late cancer deaths due to doses incurred from ingestion of water and foodstuffs, and severely contaminated areas (which may be lost for up to 20 years or longer). Delayed cancer deaths together with late cancer deaths are normally called late fatalities, but due to the different pathways for exposure, they must be accounted for separately. Note that, consequences from the release of 100% of some groups may be enormous, and especially for early fatalities, these correlation coefficients may be overestimated due to non linear effects.

The calculations show that the Xe group (noble gases) has essentially no influence on offsite consequences, with the exception of a background effect in late cancer fatalities (i.e., only released aerosol shows appreciable consequences). Moreover, the effect of the time of release (from scram, and start of radioactive decay) appears to have little influence on delayed health effects. This is because the calculations show that only long-lived radionuclides are relevant for late health effects. Surprisingly, it was found that severe land contamination appears to be due only to the Cs and Sr groups, while the Ce group (which includes Pu) has no effect. Early health effects, on the other hand, are dominated by the I and Te groups, which include for the most part short-lived radionuclides.

In addition, the calculations show that health effects are strongly correlated to the total population that can be affected, while the variability in weather from site to site appears to play a secondary role (on this, it must be remembered that MACCS is a probabilistic tool, and calculations of cloud dispersion in first approximation do not include wind direction, because the wind rose is rotated in all direction for every hour of the year, regardless of the actual data in the weather data base). In particular, the coefficients derived from the calculations (i.e., effects per Bq released) appear to be approximately in the ratio of populations and land fractions.

In particular, early fatalities can be extrapolated from one site to another from the ratio of population within 8 to 10 km. This is because the radioactive content in a passing cloud is effectively dispersed over a very large volume very quickly (the MACCS2 code uses a Gaussian dispersion model), and the MACCS2 calculations show that mortality distance does not exceed 20 km under the worst possible weather conditions (i.e., with very small probability).

Delayed cancer deaths are found to be strongly correlated to the total population within 80 to 120 km. The MACCS2 calculations show that only a small background of delayed fatalities may occur beyond this distance. This, again, is due to cloud dispersion and dilution of activities, since the dose must be incurred via inhalation or submersion in the passing cloud. Cancer deaths occurring from ingestion (late deaths) are found to be correlated to the total population in the site considered. For both sites, a maximum distance of 800 km was considered, therefore, late deaths are considered proportional to the ratio of populations within 800 km. The calculations for the US site were later extended to 1600 km, and the results in this case differ only by fractions of 1% with respect to the results to 800 km.

Finally land contamination is assumed to be correlated to the ratio of land fractions to 120 km, even though the correlation was found to be weaker than the ones found for health effects. A distance of 120 km is assumed for this type of calculations, because the MACCS2 results show that the maximum distance where land can be severely contaminated does not exceed 120 km for any of the radionuclide groups.

In conclusion, this investigation is highly suggestive that offsite consequences may be calculated approximately using activity of releases, as provided by Level-2 PSAs for the relevant source terms, and the ratios which are discussed above. For the assessment of early fatalities, the ratios for the early release sequence should be used, since they provide more conservative figures (as mentioned, early fatalities are due mostly to short-lived radionuclides).

It should be emphasized that the results which may be obtained using this simplified methodology should be viewed as order-of-magnitude results. On the other hand, uncertainties in probabilistic calculations themselves are normally very large, especially due to weather variability.

Further information on the details of the pre-assessment calculations is briefly summarized below. The MACCS2 version of the USNRC consequence code system MELCOR/MACCS has been released to the PSI in late 2004. The new version of the code incorporates many modifications and corrections with respect to the now obsolete version used for earlier simplified assessments which used MACCS, among which a much more detailed assessment of ingestion doses, and therefore long term health risks.

In order to verify the appropriateness of the simplified methodology, with respect to full MACCS2 calculations, a comparison has been performed for the risks of six hypothetical accidents (source terms) for a specific operating power plant, using both MACCS2 (with site specific population data and weather) and the simplified methodology.

Results show that the simplified methodology provides conservative results for immediate health effects (due to the assumptions of early and fast releases used in the calculations of the risk coefficients), and fairly good agreement for the other risk measures. This proves that, once the data is developed for one site, it can be used for all assessments pertaining to accidents in that site, without the need to rerun MACCS2 or to develop new detailed inputs. Appropriateness of extrapolation to different sites may be harder to prove, however, the results appear to agree within the bounds of uncertainties in transport, deposition and health effects models.

2.3.5 Risk indicators

For the NEEDS Multi-Criteria Analysis (MCA) a database comprising a set of 36 separate indicators for 26 future electricity generation technologies (in the year 2050) in four countries (i.e. France, Germany, Italy and Switzerland) has been established (Schenler et al., 2008). For the risk indicators the following country differentiations apply:

- For the calculation of indicators for the nuclear chain a more specific site definition was required so that indicators like potential fatalities from an accident could be calculated.
- Some technologies were eliminated from the technology set in certain countries because they were not considered viable alternatives due to resource limitations. This applies to lignite (Italy and Switzerland), solar thermal (Germany and Switzerland) and offshore wind (Switzerland).
- Due to high summer temperatures, thermal efficiency was assumed 3% lower in Italy, as compared to the three other countries. This affected the results for hard coal and centralized natural gas technologies.

Note that no country differentiation was used for indicators related to the criterion “terrorist threat”. The following sections describe how indicators related to severe accident risks and the terrorist threat were established, calculated and evaluated.

2.3.5.1 Risk indicators addressing environmental impacts of severe accidents

Within the environmental dimension of the NEEDS criteria and indicator set, two indicators address ecosystem impacts in the event of severe accidents.

Hydrocarbons:

This indicator quantifies large accidental spills of hydrocarbons to the environment, which can potentially damage affected ecosystems. It considers severe accidents only, i.e. releases of at least 10000 tonnes. The applicability of this indicator is restricted to the oil chain. However, in the final NEEDS technology set no technology using oil as fuel was considered. Therefore, this indicator is of no actual relevance, but it was still calculated within WP 7.

Unit: [t/GW_{eyr}]; Best value: minimum.

Method: The ENSAD database has been queried for tanker oil spills of at least 700 tonnes (t) in the period 1970-2004. This lower threshold compared to the severe accident definition given for ENSAD in section 2.2.1 has been chosen to allow for a substantially larger spill data set for analysis, while at the same time a high completeness and quality of the data could be ensured (Burgherr, 2007; Burgherr & Hirschberg, 2008c). Aggregated tanker spill rates for the period of observation were expressed as tonnes per GW_{eyr} for OECD and non-OECD countries. Future values (year 2050) were estimated in MS Excel® using an exponential regression model:

$$y = a \times b^x \text{ and its logarithmic equivalent } \log(y) = \log(a) + x \times \log(b)$$

y = cumulated spill rate; x = year; a = intercept; b = slope.

Land contamination: This indicator quantifies land contaminated due to accidents releasing radioactive isotopes. The land area contaminated is estimated using Probabilistic Safety Analysis (PSA). Note that this indicator is restricted to the nuclear electricity generation technology chain.

Unit: [km²/GW_{eyr}]; Best value: minimum.

Method: The Simplified Probabilistic Safety Assessment (PSA) applied to the nuclear chain has already been described in section 2.3.4.

2.3.5.2 Risk indicators addressing fatal consequences of severe accidents

Within the social dimension of the NEEDS criteria and indicator set, there are two indicators assessing the risk from severe accidents and three indicators estimating the risk of terrorism.

Accident mortality: This indicator is based on the number of fatalities expected for each kWh of electricity that occur in severe accidents with 5 or more deaths per accident for a particular electricity generation technology chain.

Unit: [fatalities/GW_{yr}]; Best value: minimum.

Method: For technologies using fossil fuels (hard coal, lignite, natural gas) the ENSAD database has been used to compile the respective historical experience of severe accident records for the period 1970-2005. Evaluation of the nuclear chain was based on simplified PSA. For new renewables available historical experience was less extensive, this is why it had to be supplemented by expert judgment.

Maximum fatalities: This indicator is based on the maximum number of fatalities that are reasonably credible for a single accident for a particular electricity generation technology chain.

Unit: [fatalities/accident]; Best value: minimum.

Method: Maximum consequences have been determined based on historical experience for technologies using fossil fuels (hard coal, lignite, natural gas), simplified PSA for nuclear technologies, and a mixture of limited available historical experience and expert judgment for new renewables (wood gas, short rotation poplar, straw from wheat, PV, solar thermal, and wind).

Generic results for major current technologies (see sections 2.3.1 – 2.3.3) are based on the period 1970-2005 for fossil chains and hydropower, and PSA for nuclear. In contrast, calculations for the NEEDS set of future technologies were based on specific characteristics and assumptions that are summarized in Table 3. Extrapolations of mortality rates for 2050 were based on historical experience of full energy chains (coal, lignite, natural gas) and relevant chain stages (cogeneration using natural gas or biomass) for the period 1980-2005, if not otherwise stated. This shorter time period was chosen because fatality rates for the 1970s were generally substantially different, and thus may constrain forecasting results. Future values (year 2050) were estimated in MS Excel® using an exponential regression model:

$$y = a \times b^x \text{ and its logarithmic equivalent } \log(y) = \log(a) + x \times \log(b)$$

y = cumulated fatality rate; *x* = year; *a* = intercept; *b* = slope.

Additionally, technology specific fuel contributions from OECD and non-OECD countries as well as electric efficiency factors were considered. Maximum consequences correspond to the most deadly accident that occurred in the period of observation.

Carbon Capture and Storage (CCS) is considered a viable technology to mitigate large quantities of CO₂ (Damen et al., 2003; Holloway, 2005; IEA, 2007; IRGC, 2007). However, it is difficult to accurately quantify likelihoods and consequences of accidental events associated to CCS because directly relevant leak experience is very limited (Vendrig et al., 2003) and natural emissions of CO₂ such as the limnic eruptions in Lake Nyos and Lake Monoun are considered extremely unlikely to happen at a properly operated CCS site (Holloway et al., 2007). Furthermore, CO₂-pipeline incidents in the USA for the period 1990-2001 resulted in only ten incidents with no fatalities (Gale & Davison, 2004). Therefore, we only used natural gas well-blowouts (in exploration and extraction chain stages) with at least 5 fatalities in OECD (1980-2005) as a rather coarse surrogate for CCS accident risks.

Results for nuclear are based on simplified PSA, and for new renewables limited historical experience was supplemented by expert judgement. For a full description of individual technologies and their characteristics analyzed within the NEEDS project compare the report on “Quantification of environmental indicators” (Simons et al., 2008).

One should note that the risk indicators “accident mortality” and “maximum fatalities” for future technologies (year 2050) were generated in view of their use within Multi-Criteria Analysis (MCA). Indicator values for fossil and nuclear technologies are based on ENSAD and PSA, respectively, and are thus accurate and robust both in absolute and relative terms. Estimates for new renewables are

exposed to a higher degree of uncertainty and less robust, i.e. their relative ranking position within the NEEDS technology set is still sufficient, but individual indicator values should not be used for absolute comparisons outside an MCA-context.

Table 3 Summary of applied methodologies and main assumptions that were used to forecast technology specific risk indicators for severe accidents.

| Technology (Abbreviation) Method / Assumptions |
|--|
| NUCLEAR |
| European Pressurised Reactor (EPR) – Generation III - simplified PSA (section 2.3.4) |
| European Fast Reactor (EFR) – Generation IV - simplified PSA (section 2.3.4) |
| COAL |
| Pulverised Coal (PC) - data source: ENSAD - time period: OECD and non-OECD w/o China (1980-2005); China (1994-2005) because previous data are highly incomplete (Burgherr & Hirschberg, 2007; Hirschberg et al., 2003a; Hirschberg et al., 2003b) - forecasting model: exponential regression - fuel origin: 61% OECD, 34% non-OECD w/o China, 5% China - electric plant efficiency: 0.54 |
| Pulverised Coal with post combustion Carbon Capture and Storage (PC-post CSS) - same as for PC, except - electric plant efficiency: 0.49 - consideration of CCS |
| Pulverised Coal with oxyfuel combustion and Carbon Capture and Storage (PC-oxyfuel CCS) - same as for PC, except - electric plant efficiency: 0.47 - consideration of CCS |
| Integrated Gasification Combined Cycle coal (IGCC-coal) - same as for PC, except - electric plant efficiency: 0.545 |
| Integrated Gasification Combined Cycle coal with Carbon Capture and Storage (IGCC-coal CCS) - same as for PC, except - electric plant efficiency: 0.485 - consideration of CCS |
| LIGNITE |
| Pulverised Lignite (PL) - data source: ENSAD - time period: OECD (1980-2005); non-OECD not considered since lignite is not transported over long distances, i.e. plants are rather close to mining areas - forecasting model: exponential regression - fuel origin: 100% OECD - electric plant efficiency: 0.54 |
| Pulverised Lignite with post combustion Carbon Capture and Storage (PL-post CCS) - same as for PL, except - electric plant efficiency: 0.49 - consideration of CCS |
| Pulverised Lignite with oxyfuel combustion and Carbon Capture and Storage (PL-oxyfuel CCS) - same as for PL, except - electric plant efficiency: 0.47 - consideration of CCS |

Integrated Gasification Combined Cycle lignite (IGCC-lignite)

- same as for PL, except
 - electric plant efficiency: 0.525
-

Integrated Gasification Combined Cycle lignite with Carbon Capture and Storage (IGCC-lignite CCS)

- same as for PL, except
 - electric plant efficiency: 0.465
 - consideration of CCS
-

NATURAL GAS (CENTRALIZED)

Gas Turbine Combined Cycle (GTCC)

- data source: ENSAD
 - time period: OECD (1980-2005); non-OECD (1985-2005; previous years strongly affected overall trend)
 - forecasting model: exponential regression
 - fuel origin: 15.1% OECD, 84.9% non-OECD
 - electric plant efficiency: 0.65
-

Gas Turbine Combined Cycle with Carbon Capture and Storage (GTCC CCS)

- same as GTCC, except
 - electric plant efficiency: 0.61
 - consideration of CCS
-

NATURAL GAS COGENERATION

Internal Combustion Combined Heat and Power (IC CHP)

- same as GTCC, except
 - electric plant efficiency: 0.44
-

Molten Carbonate Fuel Cells using Natural Gas 2MW (MCFC NG 2MW)

- same as GTCC, except
 - electric plant efficiency: 0.55
-

Molten Carbonate Fuel Cells using Natural Gas 0.25 MW (MCFC NG 0.25MW)

- same as GTCC, except
 - electric plant efficiency: 0.50
-

Solid Oxide Fuel Cells using Natural Gas 0.3 MW (SOFC NG)

- same as GTCC, except
 - electric plant efficiency: 0.58
-

BIO MASS

Molten Carbonate Fuel Cell using wood derived gas 0.25 MW (MCFC wood gas)

- data source: ENSAD
 - time period: OECD (1980-2005); non-OECD not considered since wood is not transported over long distances
 - natural gas chain from distribution stage as surrogate
 - forecasting model: exponential regression
 - fuel origin: 100% OECD
 - electric plant efficiency: 0.50
-

Combined Heat and Power using short rotation coppiced poplar (CHP poplar)

- data source: ENSAD
 - time period: OECD (1980-2005); non-OECD not considered since poplar is not transported over long distances
 - natural gas chain from local distribution as surrogate
 - forecasting model: exponential regression
 - fuel origin: 100% OECD
 - electric plant efficiency: 0.30
-

Combined Heat and Power using straw (CHP straw)

- same as CHP Poplar
 - electric plant efficiency: 0.30
-

SOLAR

Photovoltaic, ribbon crystalline Silicon - power plant (PV-Si plant)

- expert judgement based on literature data (e.g., Fthenakis et al., 2006; Ungers et al., 1982)
-

Photovoltaic, ribbon crystalline Silicon - building integrated (PV-Si building)

- same as PV-Si plant

Photovoltaic Cadmium Telluride – building integrated (PV-CdTe building)

- same as PV-Si plant

Concentrating thermal – power plant (Solar thermal)

- similar approximative approach as for PV

WIND

Offshore Wind (Wind offshore)

- data from Wind Watch: Wind Turbine Accident Data (<http://www.wind-watch.org>) and Windpower Death Database from Wind-Works.org (<http://www.wind-works.org/index.html>)
- Estimations based on EU 27 data for 1994-2006

2.3.5.3 Risk indicators addressing the terrorist threat of energy infrastructure

Terror potential: This indicator estimates the potential for a successful terrorist attack on a specific technology, based on its vulnerability, the potential damage and public perception of risk.

Unit: [ordinal scale] (1-10); Best value: minimum.

Terror effects: This indicator concerns the potential likely consequences of a successful terrorist attack. The criterion implicitly addresses the aversion towards low-probability high-consequence accidents.

Unit: [ordinal scale] (1-10); Best value: minimum.

Proliferation: This indicator represents the potential for misuse of technologies or substances present in the nuclear electricity generation technology chain, based on both their presence and the risk of such misuse or diversion.

Unit: [nominal scale] (0,1); Best value: 0 = no proliferation.

Method: The methodological approach for the three terrorism indicators is described in section 3.3.6.

2.3.6 Evaluation of terrorist threat

For the evaluation and ranking of possible terrorist attacks on technology-specific infrastructure elements in the energy sector, three indicators have been established under the criterion “terrorist threat”, namely terror potential, terror effects and proliferation. Subsequently, qualitative procedures have been developed to provide a ranking and relative importance of terrorist threats on energy related technologies and systems.

The evaluation is performed by assigning three indicators to each technology:

1. Potential of attack
2. Likely potential effects of a successful attack: expected number of fatalities (on- and off-site)
3. Proliferation: potential for misuse of technologies and substances (within the nuclear chain)

The third indicator is defined as 1 (for nuclear technologies) and 0 (non-nuclear technologies). To each of the other two indicators values ranging from zero to ten are assigned, following the rule that the larger the assigned value, the larger the potential.

In detail, the following reasoning rules have been established:

Potential of attack: In order to assess the indicator for the potential of attack, four elements have been introduced:

1. Attractiveness of the target
2. Resources needed to perform the attack

3. Potential for unsuccessful countermeasures

4. Ease of execution

As for the two main indicators, each element is graded from 1 to 10, the value being larger if the attack is viewed as developing in a favorable manner (e.g., “resources” is rated 1 if a very large number of resources and time are needed for planning and execution, 10 if the resources etc. are minimal).

With regard to the attractiveness of a target, it is assumed, as supported by current publicly available data bases on terrorism (e.g., USA FBI files are available on Internet), that the major goal of terrorist attacks is to cause as many fatalities as possible and not economic disruption. There is to date very little evidence that other specific goals are in the mind of terrorist groups than the chain “demonstrative actions - extensive loss of civilian life - political consequences”.

The indicator for “execution” is proportional to the chances that the goal (maximum credible effects) will be reached. However, maximum effects are the hardest to achieve, thus successful execution and this sub-indicator are inversely correlated with the main indicator 2 “effects”.

Further, a weight is assigned to each element, so that the sum of all four can be normalized to 1. At the end, the values obtained will be renormalized to the largest value for all technologies, so that the overall ranking returns to lie in the range from 1 to 10.

Clearly, there are other correlations between these components and the indicator “potential effects”, and correlations among the individual elements, but this will not be explored or quantified further. Moreover, since the element “attractiveness” would be the prevailing motivator for planning and execution, a larger weight is assigned to this component (0.5). To “resources” and “countermeasures a weight of 0.2 is assigned, while “execution” is deemed the least important component to the entire process (0.1), since if the planning stage is completed, resources availability is assured and countermeasures are bypassed, execution will always follow.

In Table 4, the detailed data for three technologies is shown as an example.

Table 4 Example of “potential of attack” for three different technologies.

| Element (weight) / Technology | Advanced Nuclear, EPR | Natural Gas CCS | Coal systems |
|---------------------------------|-----------------------|-----------------|--------------|
| Attractiveness (0.5) | 10 | 6 | 1 |
| Resources (0.2) | 1 | 8 | 9 |
| Countermeasures (0.2) | 5 | 8 | 9 |
| Execution (0.1) | 3 | 7 | 8 |
| Total Weighted / (renormalized) | 6.5 / (9) | 6.9 / (10) | 4.9 / (7) |

Likely potential effects: The expected number of fatalities (workers and public) following a successful attack are defined for each technology on the basis of the most likely type of attack. For instance, for a threat to a nuclear installation, the most likely type of attack that could have a very good chance of success is the destruction of a plant switch-yard and transformers, causing a loss of power to the plant, and uncontrolled shutdown of the installation. The only credible type of accident resulting from this scenario is a core melt down with a small failure of the containment in both types of technologies considered (new generation LWR and LMFBR). The assessed number of fatalities from this accident ranges between 300 and 1000. Since these figures are the largest expected from any of the systems considered for this task, a value of 10 is assigned to the indicator for nuclear technologies.

At the other end of the spectrum, the solar and offshore wind systems would not cause threats to the public, if attacked, and only some workers may be affected. Thus a value of 1 is assigned to the indicator for these systems. For the technologies where some threat could be expected to the public, a value between 1 and 10 is assigned, in first approximation logarithmically (normalized so that 10 corresponds to the number of fatalities expected in the attack to the nuclear installations), according to the number of expected or possible fatalities.

Some variations are given within the sub-type of technology involved. The values thus arrived at are the following:

| | |
|-------------------|-----|
| Nuclear | 10 |
| Advanced fossil | 2-6 |
| Fuel cells | 3-5 |
| CHP steam turbine | 1 |
| Photovoltaic | 2-3 |
| Solar | 1 |
| Offshore wind | 2 |

The detailed results for all technologies are incorporated and shown in the general summary table for individual indicators for all technologies in section 5.

3 Current status of ENSAD

The ENSAD database currently contains 21550 accident records (Figure 4), of which 90.2% occurred in the years 1970-2005. Within this period, 14815 were man-made accidents, of which 8688 were attributable to the energy sector and 27.3% (2371) of them resulted in five or more fatalities.

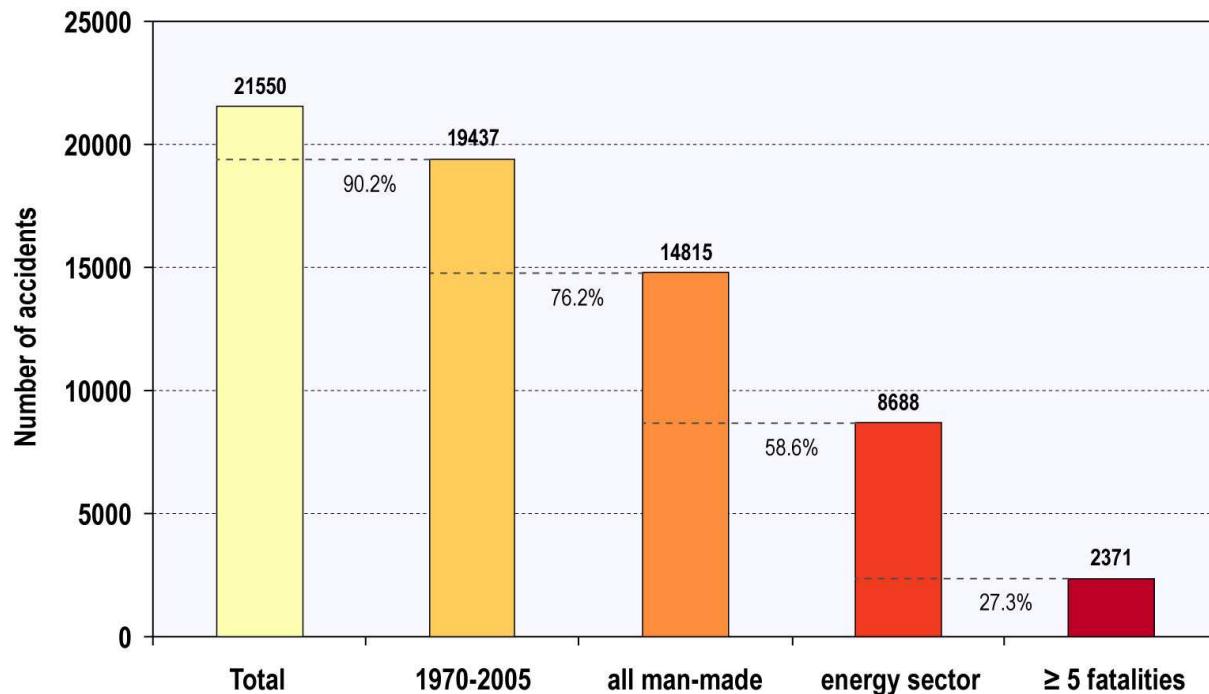


Figure 4 Number of accident records contained in ENSAD and respective shares for specific categories.

Figure 5 shows fatalities in all categories of severe (≥ 5 fatalities) man-made accidents and natural disasters from 1970-2005, amounting to about 3.3 million fatalities. Of these victims, more than 90% were due to natural catastrophes and only about 10 % due to severe man-made accidents; 34 % of the latter were killed in energy-related accidents.

The largest natural disasters include a storm and flood catastrophe in Bangladesh in 1970 (300'000 fatalities), the Tangshan earthquake in China in 1976 (290'000), and a drought and civil strife in Sudan in 1983 (250'000). In the 21st century, the December 2004 Indian Ocean seaquake (magnitude of 9.1 to 9.3 on the Richter scale) triggered a series of devastating tsunamis. Initial estimates put the death toll in the range of 300'000, but recent analyses reduced it to about 220'000 (e.g., Swiss Re, 2006). Nevertheless, this catastrophe is one of the deadliest disasters in modern history.

In contrast, the largest man-made accidents resulted in fatalities one to two orders of magnitude lower. The top-ranked energy-related accidents include the Banqiao/Shimantan dam failure in China in 1975 (26'000 fatalities), the collision of the tanker “Victor” with the Ferry “Dona Paz” off the Philippines in 1987 (4386), and a tank truck collision with another vehicle in the Salang tunnel in Afghanistan’s Parvan province in 1982 (2700). Large non-energy-related severe accidents include the accident at a pesticide plant in Bhopal in India in 1984 (5000 fatalities), the sinking of the ferry “Neptune” near the coast of Haiti in 1993 (1800) and the failure of the Gouhou dam (primary purpose: irrigation and water supply) in China in 1993 (1250).

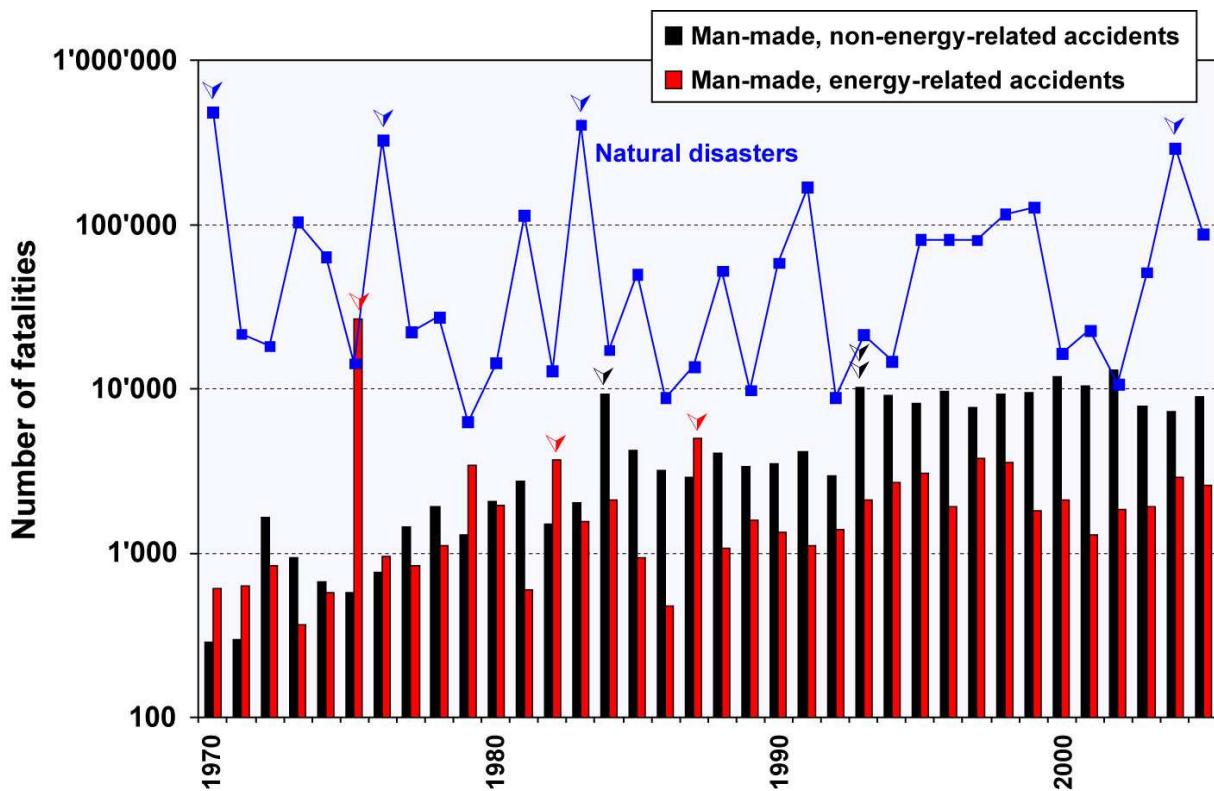


Figure 5 Number of fatalities for severe (≥ 5 fatalities) accidents that occurred due to natural disasters and man-made accidents in the period 1970-2005. Years marked by an arrow indicate accidents that are discussed in the text.

Although the number of natural catastrophes and man-made accidents has increased strongly in the last three decades, it is very difficult to associate how this increase may be related to the observed climate warming on the basis of individual events. But it is clear that the ever denser population of areas exposed to risks (e.g. floods, storms and seismic activities) plays an important role. Economic damage has similarly increased, with total damages of 147.6 billion USD in the 1970's growing to 703.6 billion USD in the 1990's. In comparison, total insured damages grew more strongly, from 13.7 billion USD to 132.2 billion USD (Munich Re, 2005), reflecting the fact that in the industrialized countries a significant share of damages is insured, which is not true in the less developed countries.

The ENSAD database at PSI includes 2368 severe accidents for the various energy chains in the period 1970-2005, amounting to 90'374 immediate fatalities⁴ (Table 5). The coal chain accounted for 67.1% of all accidents, with oil a distant 2nd at 20.3%. Contributions by the natural gas (6.9%) and LPG (5.1%) chains were much smaller, while both hydro (0.55%) and nuclear (0.05%) have negligible shares. This dominance of coal-chain accidents is fully attributable to the release of detailed accident statistics by China's coal industry, data that were not previously publicly available (Burgherr & Hirschberg, 2007; Hirschberg et al., 2003a; Hirschberg et al., 2003b). Altogether, 818 of the 1363 accidents collected for the Chinese coal chain occurred in the years 1994-1999, implying substantial under-reporting prior to the release of the annual editions of the China Coal Industry Yearbook.

⁴ Latent fatalities associated with nuclear accidents are treated separately in section 4. The reason for this is that historically they occurred only in one accident in non-OECD (Chernobyl). Furthermore, the number of latent fatalities cannot be solely based on their historical occurrence, as is the case with immediate fatalities, but is subject to extrapolations to the future.

Fatalities were clearly dominated by the Banqiao/Shimantan dam failures, which together resulted in 26'000 deaths. As a consequence, the hydro chain accounts for 33.2% of all fatalities. Among the fossil chains, coal accounted for most fatalities, followed by oil, LPG and natural gas.

Table 5 Summary of severe accidents with at least 5 immediate fatalities that occurred in fossil, hydro and nuclear energy chains in the period 1970-2005. Accident statistics are given for the categories OECD, EU 27, and non-OECD. For the coal chain, non-OECD w/o China and China alone are given separately.

| Energy chain | OECD | | EU 27 | | Non-OECD | | World Total | |
|--------------------|-----------|------------|-----------|------------|-----------|--------------|-------------|------------|
| | Accidents | Fatalities | Accidents | Fatalities | Accidents | Fatalities | Accidents | Fatalities |
| Coal | 81 | 2123 | 41 | 942 | 144 | 5360 | 1588 | 31939 |
| | | | | | 1363 | 24'456 | | |
| | | | | | (818) (a) | (11'302) (a) | | |
| Oil | 174 | 3338 | 64 | 1236 | 308 | 17'990 | 482 | 21328 |
| Natural Gas | 103 | 1204 | 33 | 337 | 61 | 1366 | 164 | 2570 |
| LPG | 59 | 1875 | 20 | 559 | 61 | 2610 | 120 | 4485 |
| Hydro | 1 | 14 | 1 | 116 (b) | 12 | 30'007 (c) | 13 | 30021 |
| Nuclear | -- | -- | -- | -- | 1 | 31 (d) | 1 | 31 |
| Total | 418 | 8554 | 159 | 3190 | 1950 | 81'820 | 2368 | 90374 |

(a) First line: Coal non-OECD w/o China; second and third line: Coal China 1970-2005, and in parentheses 1994-1999. Note that only data for 1994-1999 are representative because of substantial underreporting in earlier years (Burgherr & Hirschberg, 2007; Hirschberg et al., 2003a; Hirschberg et al., 2003b).

(b) Belci dam failure (Romania, 1991)

(c) Banqiao/Shimantan dam failures (China, 1975) together caused 26'000 fatalities

(d) Only immediate fatalities. In the case of Chernobyl estimates for latent fatalities range from about 9000 for Ukraine, Russia and Belarus to about 33'000 for the whole northern hemisphere in the next 70 years Hirschberg et al., 1998. According to a recent study (Chernobyl Forum, 2005) by numerous United Nations organizations (IAEA, WHO, UNDP, FAO, UNEP, UN-OCHA and UNSCEAR) up to 4000 persons could die due to radiation exposure in the most contaminated areas. This estimate is substantially lower than the upper limit of the PSI interval, which, however, was not restricted to the most contaminated areas.

Total fatalities for cumulated as well as for individual fossil and hyrdo energy chains per country were plotted on a world map to visualize spatial distribution patterns of severe accident consequences (Figures 6-11). Cumulated fatalities for all chains are given in Figure 6. When looking at the top ten countries in terms of fatalities, seven of them were non-OECD countries and only three belonged to the OECD. However, Mexico and South Korea gained OECD membership only around the mid 1990s (1994 and 1996, respectively), whereas the USA has been a member since OECD's foundation in 1961. China was the most accident-prone country with 51'976 fatalities. Of these 24'456 fatalities occurred in 1363 accidents attributable to the coal chain, but only 15 of these resulted in 100 or more fatalities. Another 26'000 people were killed in the Banqiao/Shimantan dam failure (1975), whereas oil, natural gas and LPG chains contribute only little to the total number of fatalities in China. In contrast, the cumulated fatalities of India, the Philippines, Nigeria, Afghanistan, Russia, Mexico, Colombia and Turkey were strongly dominated by a few very large accidents that contributed a substantial share of the total. The USA exhibited a distinctly different pattern compared to the other countries with no extremely large accidents (only three out of 149 with more than 50 fatalities), and 76% of accidents and 70% of associated fatalities taking place in the oil and gas chains.

When comparing the top ten countries for the total number of accidents, seven out of the ten most fatality-prone countries also appear in this ranking, but Japan (27 accidents), Pakistan (24) and Ukraine (32) replace Afghanistan, Colombia and the Philippines (compare Figure 6). In China 95% of all 1431 accidents recorded took place in the coal chain. Nigeria (95% for oil) and Ukraine (94% for coal) showed a similar dominance by single energy chains. In India and Japan oil chain accidents ranked first followed by coal, whereas it was reversed for Pakistan, Russia and Turkey. Contributions from the oil and natural gas chains dominated in Mexico (12/12 accidents) and the USA (65/48).

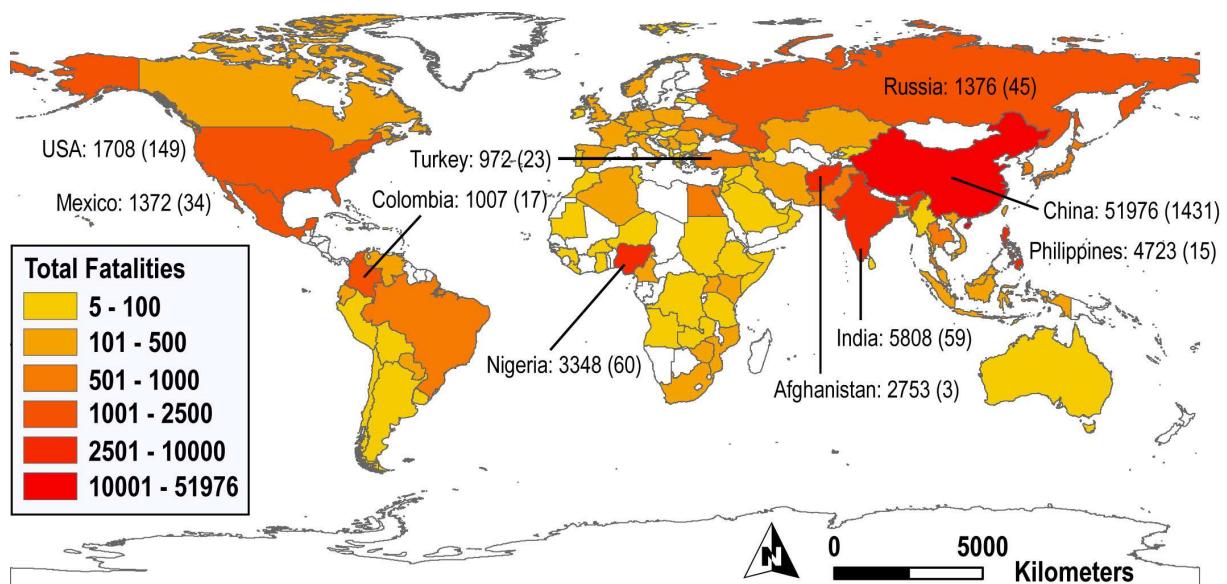


Figure 6 Individual countries are shaded according to their total numbers of severe (≥ 5 fatalities) accident fatalities in fossil (coal, oil, natural gas, LPG) and hydro energy chains for the period 1970-2005. The top ten countries in terms of cumulated fatalities are also indicated, with total number of accidents in parentheses.

Figures 7-11 show total fatalities per country as well as the five most deadly accidents for individual energy chains. Among accidental events with very high death tolls only few occurred in OECD or EU 27, namely in Turkey (coal), Japan and South Korea (natural gas), Spain (LPG), and Romania (Hydro).

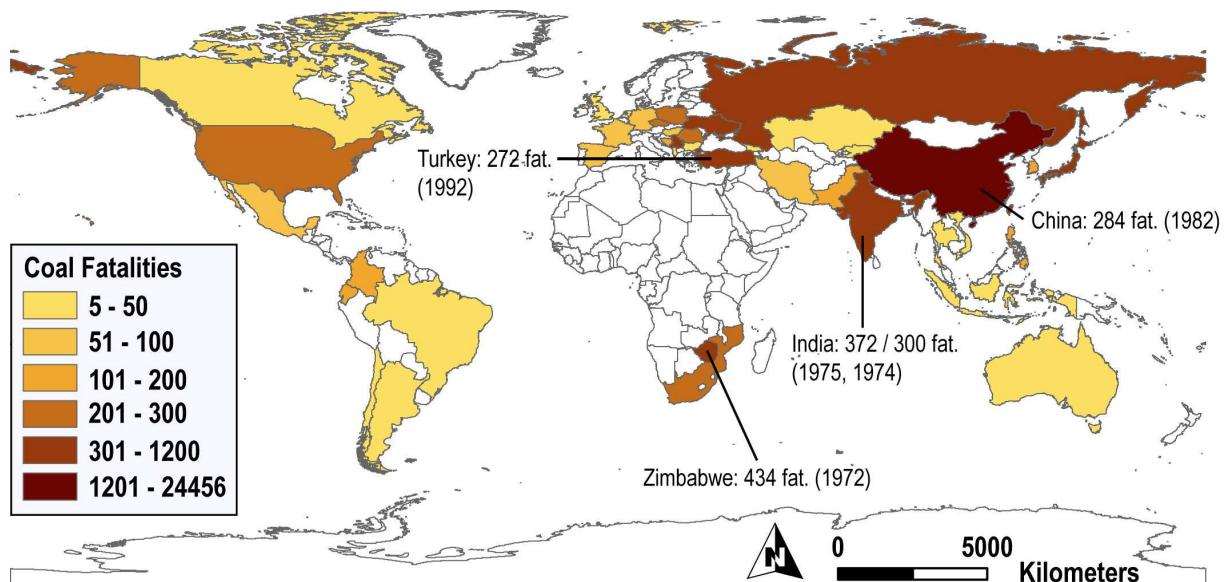


Figure 7 Number of cumulated fatalities per country for severe (≥ 5 fatalities) accidents in the coal chain that occurred in the period 1970-2005. The five most deadly accidents are also shown.

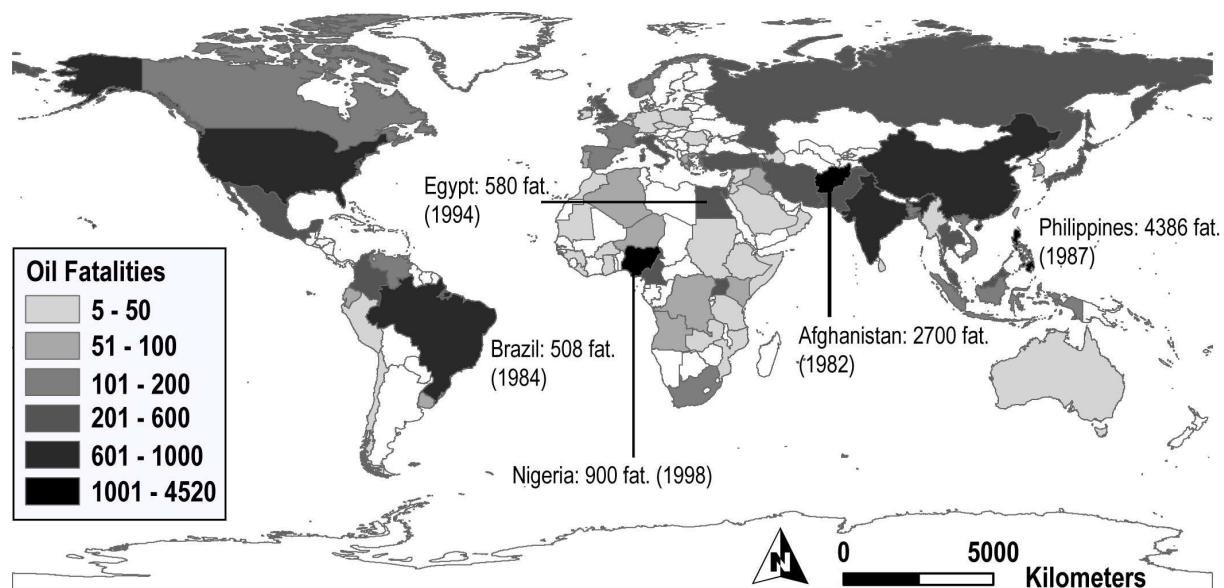


Figure 8 Number of cumulated fatalities per country for severe (≥ 5 fatalities) accidents in the oil chain that occurred in the period 1970-2005. The five most deadly accidents are also shown.

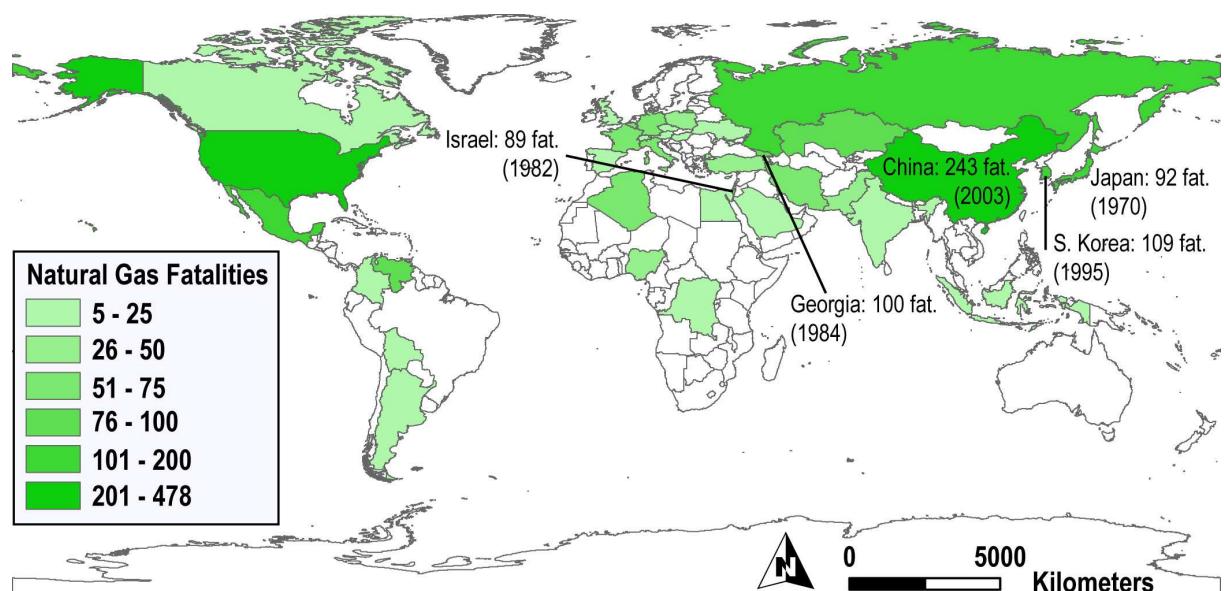


Figure 9 Number of cumulated fatalities per country for severe (≥ 5 fatalities) accidents in the natural gas chain that occurred in the period 1970-2005. The five most deadly accidents are also shown.

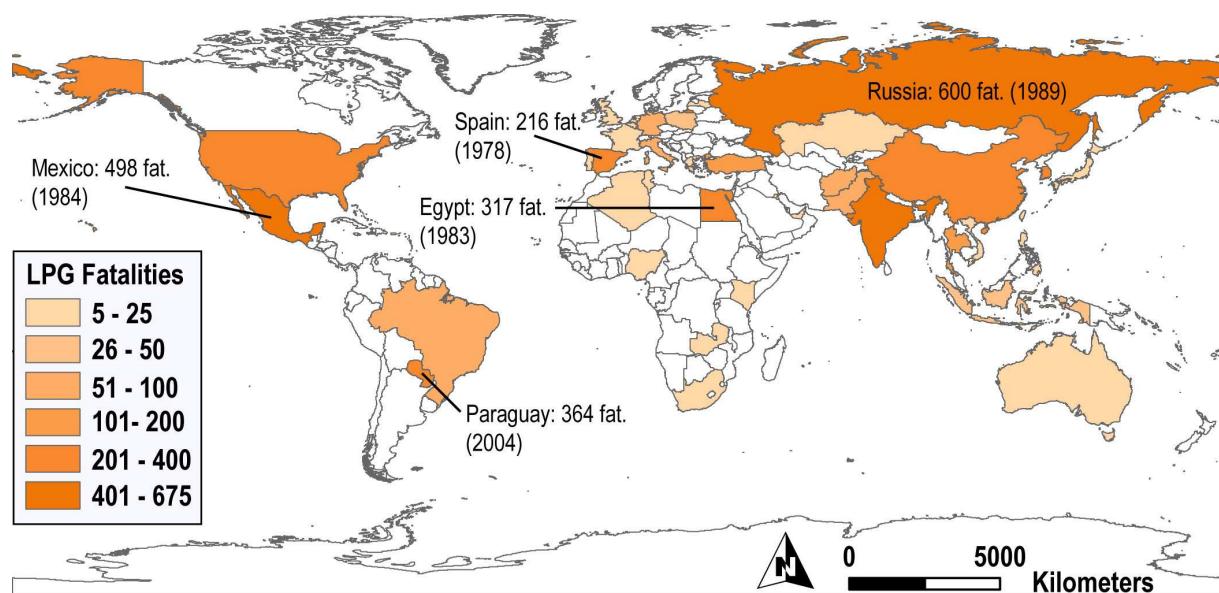


Figure 10 Number of cumulated fatalities per country for severe (≥ 5 fatalities) accidents in the LPG chain that occurred in the period 1970-2005. The five most deadly accidents are also shown.

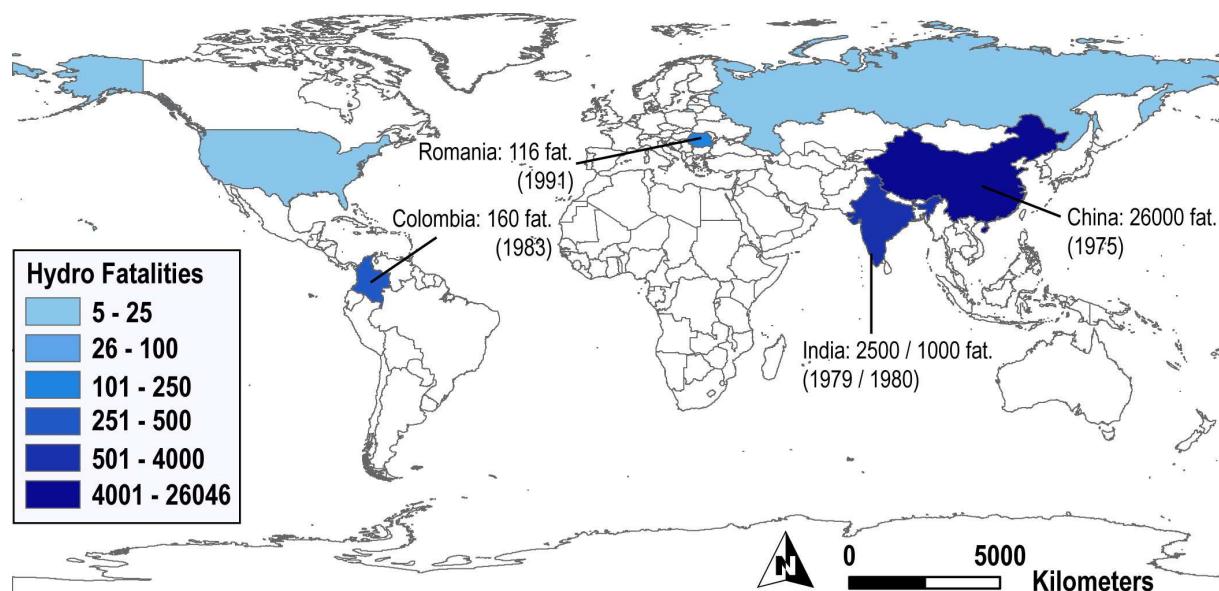


Figure 11 Number of cumulated fatalities per country for severe (≥ 5 fatalities) accidents in the hydro chain that occurred in the period 1970-2005. The five most deadly accidents are also shown.

4 Comparative analyses for major energy chains

4.1 Weak-point analysis of energy chains

Figure 12 shows the percent shares of fatalities in severe accidents (≥ 5 fatalities) for different energy chain stages in fossil chains of OECD and non-OECD countries. The Figure clearly depicts that the majority of accidents do not occur in power plants, but rather in other stages in the energy chains.

Over 95% of the victims in the coal chain lose their lives in mines, primarily due to gas explosions. With oil, the transportation to the refinery (long distance) and regional/local distribution are the most accident prone stages; most frequent are tanker accidents at sea and street accidents involving tank trucks. Transportation is also the weak stage in the gas chain, which is dominated by pipeline accidents in transmission (long-distance) and distribution (regional/local) networks. However, in non-OECD countries contributions of exploration/extraction and power/heat generation are much larger at the expense of transportation stages. In the LPG chain fatalities occurring in transportation stages were most prominent too, followed by accidents in power/heat generation. The much larger contribution of long distance transport in non-OECD is fully attributable to a single pipeline accident transporting LPG to refineries (Russia, 1989) that resulted in 600 fatalities alone. While coal chain victims are almost exclusively work-related, gas and oil accidents involve a significant number of innocent bystanders as victims.

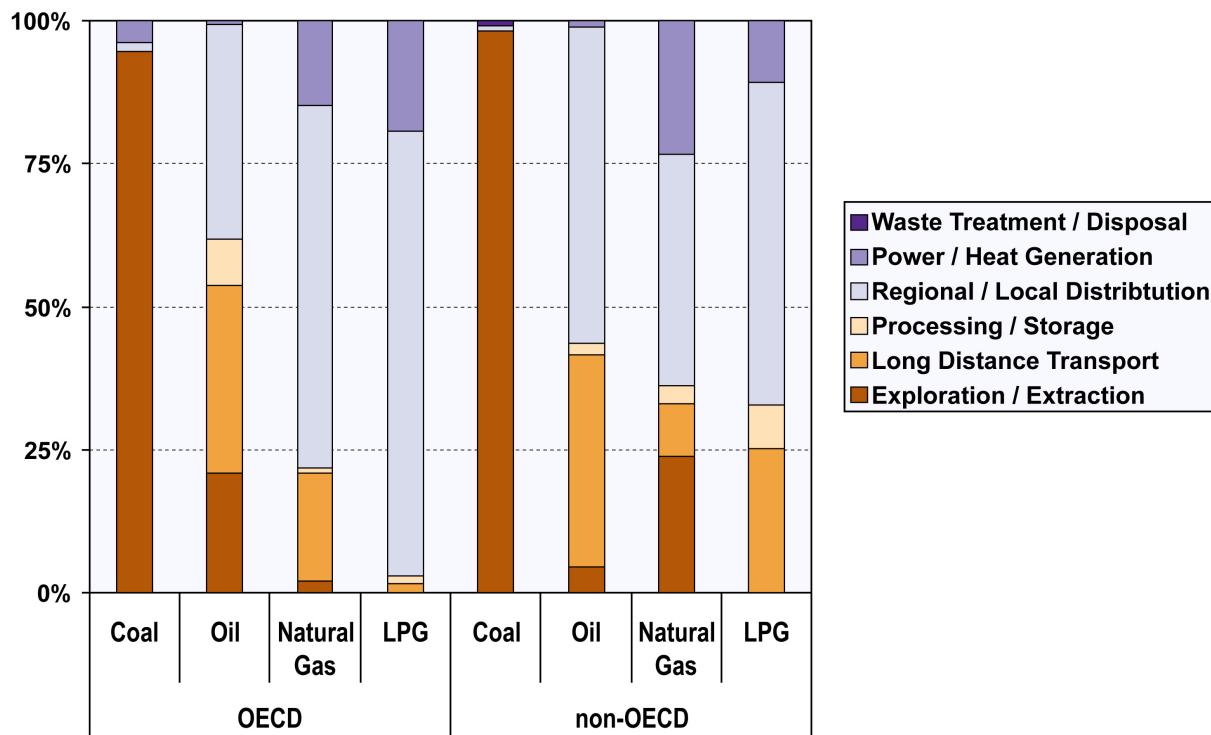


Figure 12 Percentage shares of accidental fatalities in the different stages of fossil energy chains for the period 1970-2005.

For hydro and nuclear power (not shown in Figure 12) the situation is rather different. Severe accidents in the hydro chain are generally occurring at the dam/reservoir site, but the general populace is almost exclusively affected, with the exception of the dam operators. However, there are some well documented accidents during construction. For example, the Mattmark dam (Switzerland) in 1965 when an ice-avalanche catastrophe caused the death of 88 workers, or the Guavio dam (Colombia) in 1983 when torrential rains lead to mudslides burying and killing 160 workers changing shifts at the dam construction site (Burgherr & Hirschberg, 2008b). Dam failures in non-OECD countries can result in thousands of victims, whereas in OECD no such accident has occurred since 1963 (Vajont,

Italy; 1917 fatalities). Nuclear power plant accidents may also lead to immediate fatalities, but here the deaths are dominated by latent fatalities (see section 4.3) due to eventual cases of cancer.

4.2 Aggregated indicators

Aggregated indicators are calculated as fatalities per $\text{GW}_{\text{e}}\text{yr}$, differentiating between OECD, EU 27 and non-OECD countries. It should be noted that the statistical basis for the indicators for individual energy chains may differ radically. For example, there are 1588 severe accidents worldwide with at least five fatalities in the coal chain and only one in the nuclear chain (Chernobyl) (see Table 5).

Figure 13 shows that significant differences exist between the aggregated damage rates assessed for the various energy chains. However, from an absolute point of view the damage rates for fatalities of fossil sources are much smaller than the corresponding rates associated with health impacts of normal operation (Burgherr & Hirschberg, 2008a). Therefore, the evaluation focuses here on the relative differences between the various energy carriers.

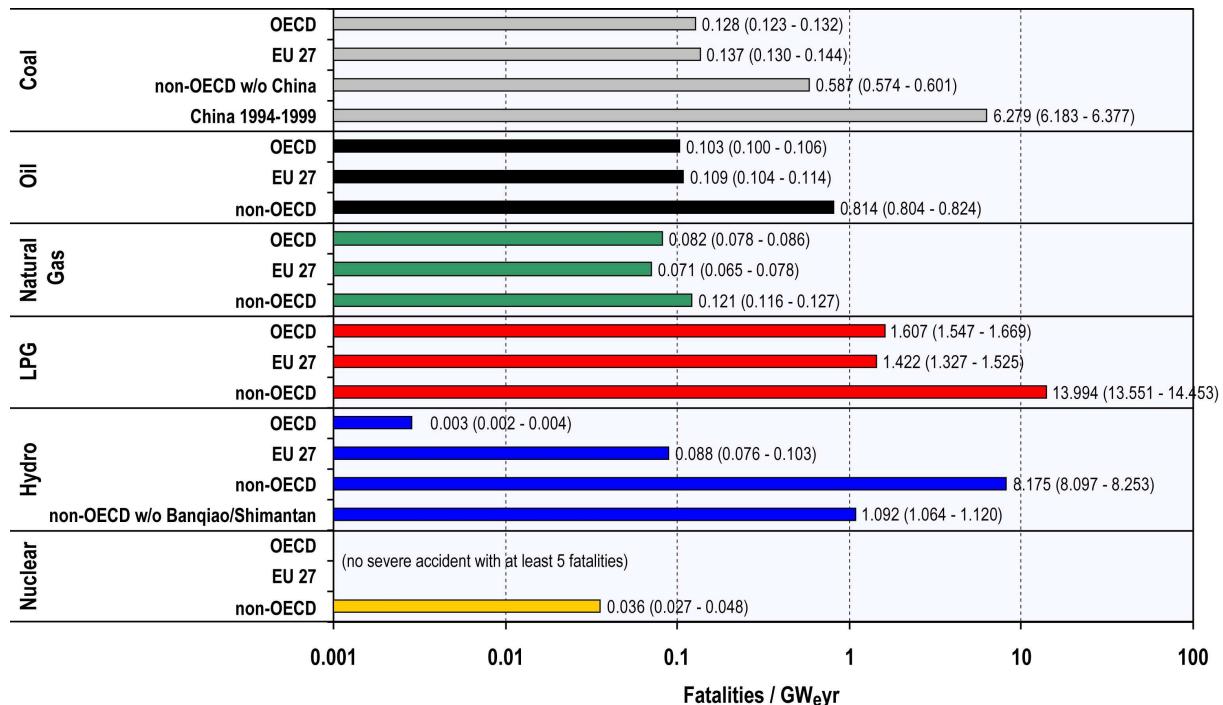


Figure 13 Comparison of aggregated, normalized, energy-related fatality rates, based on historical experience of severe accidents that occurred in OECD, EU 27 and non-OECD countries in the period 1970-2005, except for coal China where complete data from the China Coal Industry Yearbook were only available for the years 1994-1999. Note that only immediate fatalities were considered; latent fatalities, of particular relevance for the nuclear chain, are commented separately in the text. The exact values for each bar are shown in the figure, with values for 5% and 95% confidence intervals in parentheses.

Generally, OECD and EU 27 countries exhibit significantly lower fatality rates than those for non-OECD countries. However, all three country groups show similar rankings of fossil chains, i.e. LPG is most accident-prone, followed by coal and oil, whereas natural gas performs best. For non-OECD countries the corresponding rate is higher for oil than for coal without China. The coal fatality rate for non-OECD including China amounts to 1.747, about three times the non-OECD w/o China value, demonstrating that the Chinese coal chain should be analyzed separately to avoid a substantial bias in the comparative results (Burgherr & Hirschberg, 2007; Hirschberg et al., 2003a; Hirschberg et al., 2003b). Furthermore, it can be shown that the accident record completeness for China is strongly depending on available primary information sources. Full coverage of the Chinese coal chain can only be achieved when annual editions of the China Coal Industry Yearbook (CCY) are available (6.279

fatalites per GW_eyr for China 1994-99), compared to 4.609 fatalities per GW_eyr for China 1994-2005 (additional China-specific information sources surveyed after 1999, but no CCIY) and 3.079 fatalities per GW_eyr for China 1970-2005. The clear underreporting for the Chinese coal chain has been recognized earlier by Hirschberg et al. (1998), and since then could be significantly improved (Burgherr & Hirschberg, 2007; Burgherr & Hirschberg, 2008a). Western style nuclear and hydropower plants have the lowest fatality rates. The recent experience with hydro in OECD countries points to very low fatality rates, comparable to the representative PSA-based nuclear power plants investigated in NEEDS, whereas in non-OECD countries dam failures can claim large numbers of victims.

The above discussion was restricted to immediate fatalities, however in the case of the nuclear chain latent fatalities dominate total fatalities. When one reviews these latent fatalities for the only severe (≥ 5 fatalities) nuclear accident with an impact on human health (Chernobyl), then estimates of latent deaths would range from 13.9 to 51.2 deaths per GW_eyr (for non-OECD countries). However extending these risks for nuclear energy to current OECD countries is not appropriate, because OECD plants use other, safer technologies. This is also predominantly true for the current situation in non-OECD countries. Results for PSA-based latent fatalities in four countries (France, Germany, Italy and Switzerland) are shown in sections 4.3, 4.4 and 5.

4.3 Frequency-consequence curves

Frequency-consequence (F-N) curves retain the ranking of energy chains derived from aggregated indicators, but provide additional insight on chain-specific maximum damages and on the probability of an accident exceeding a specified consequence threshold (e.g. number of fatalities).

Figure 14 shows F-N curves for severe accidents with at least 5 fatalities in OECD and EU 27. Fossil energy chains clearly exhibited higher frequencies of severe accidents than hydro and nuclear. Among fossil chains, LPG exhibits the worst performance and natural gas the best, whereas coal and oil chains are ranked in between. Looking at maximum consequences allows for some interesting comparisons, both among energy chains and between OECD and EU 27. Maximum values of fossil chains for OECD are between 1.5 and 4.2 times greater than for EU 27. The impact of hydro is minimal for OECD (Teton dam failure, USA, 1976, 14 fatalities), but an accident in EU 27 resulted in 116 fatalities (Belci Dam, Romania, 1991), which is in the same range as the most deadly natural gas accident in OCED.

For non-OECD countries (Figure 15), the ranking of F-N curves was comparable to the OECD, except for the Chinese coal chain that showed a significantly worse performance than other non-OECD countries. Furthermore, frequencies at corresponding numbers of fatalities were generally higher for non-OECD compared to OECD, and for LPG and Coal China (1994-99) chain frequencies at lower death tolls were even greater than 10^{-1} (Figures 14 and 15). Regarding chain-specific maxima, non-OECD values of fossil chains were substantially higher than the corresponding OECD values, except Coal China, for which only 15 out of 1363 accidents in the period 1970-2005 resulted in 100 or more fatalites (1 in the years 1994-1999, 5 before and 9 after). Additionally, the range in observed maximum fatalities among individual chains was larger in non-OECD, particularly because the oil chain can reach maximum numbers up to one order of magnitude higher than other fossil chains.

For nuclear energy immediate fatalities play a minor role, whereas latent fatalities clearly dominate. Expectation values for severe accident fatality rates associated with the nuclear chain (Chernobyl) are relatively low, but the maximum credible consequences may be very large due to the dominance of expected latent fatalities, i.e. comparable to the Banqiao/Shimantan dam accident that occurred in China in 1975. Results concerning Chernobyl were published in Hirschberg et al. (1998). Studies by EC/IAEA/WHO and UNSCEAR formed the main basis for the numerical estimates of total latent fatalities associated with Chernobyl, supported by numerous sources including the Russian ones. Estimated latent fatalities due to delayed cancers range from 9000 (Ukraine, the Russian Federation and Belarus) to 33'000 (entire northern hemisphere) over the next 70 years (Hirschberg et al., 1998), indicating that the upper range in PSI's estimate is conservative (as intended) because it was not

limited to the most contaminated areas. In September 2005 a new report on the consequences of the Chernobyl accident was released by a Forum consisting of a number of professional organizations of the United Nations (IAEA, WHO, UNDP, FAO, UNEP, UN-OCHA and UNSCEAR) as well as the World Bank and the governments of the Russian Federation, Belarus and Ukraine (Chernobyl Forum, 2005). This report reflects the findings of a large team of natural scientists, economists and health specialists. One of the conclusions of the report is that in the areas with high contamination up to 4000 people could eventually die due to radiation doses from the Chernobyl accident, most of them among the so called "liquidators". This is significantly lower compared to the previously mentioned PSI values because of the more limited area considered.

Finally, the large differences between Chernobyl-based estimates and probabilistic plant-specific estimates for a Swiss nuclear power plant (Figures 14 and 15) illustrate the limitations in applying past accident data to cases that are radically different in terms of technology and operating environment. To obtain realistic calculations for Western plants, results of full scope Probabilistic Safety Assessment (PSA) should constitute the relevant reference. Therefore, risk indicators for the nuclear chain presented in the following chapter are based on a simplified PSA approach for specific sites in France, Germany, Italy and Switzerland (see section 4.4).

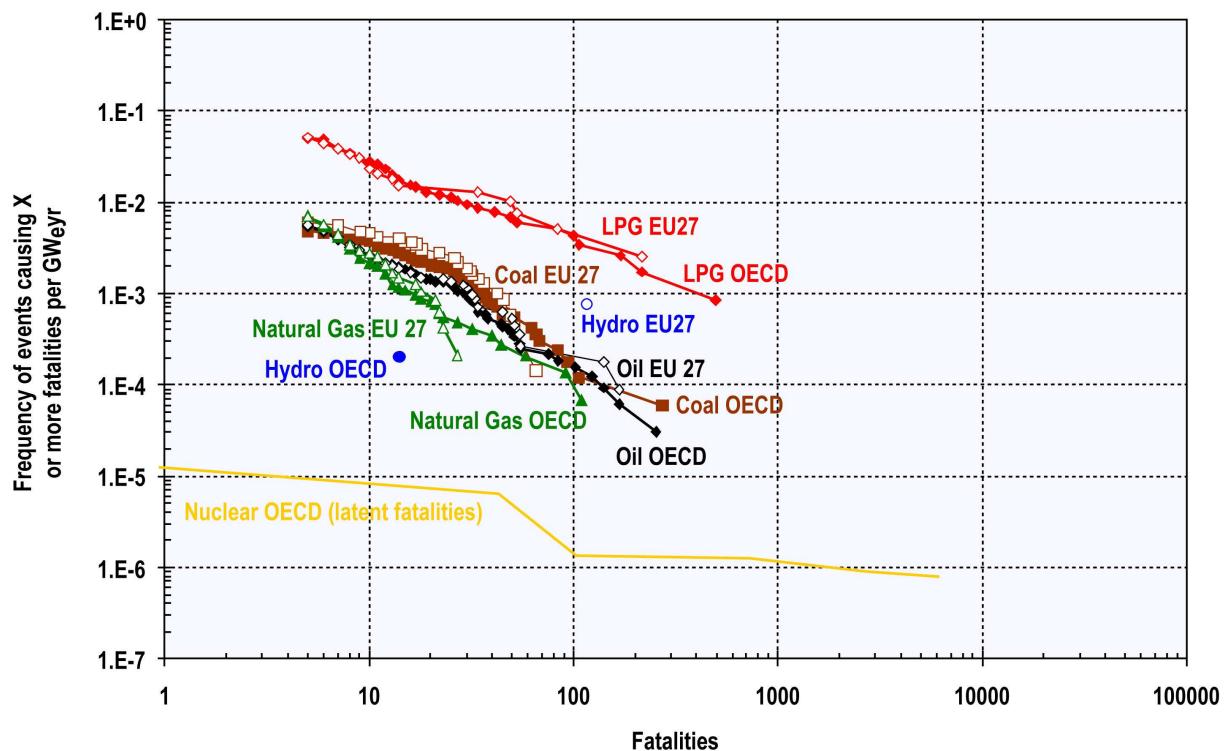


Figure 14 Comparison of frequency-consequence curves for full energy chains, based on historical experience of severe accidents in OECD (filled symbols) and EU 27 (open symbols) countries for the period 1970-2005.

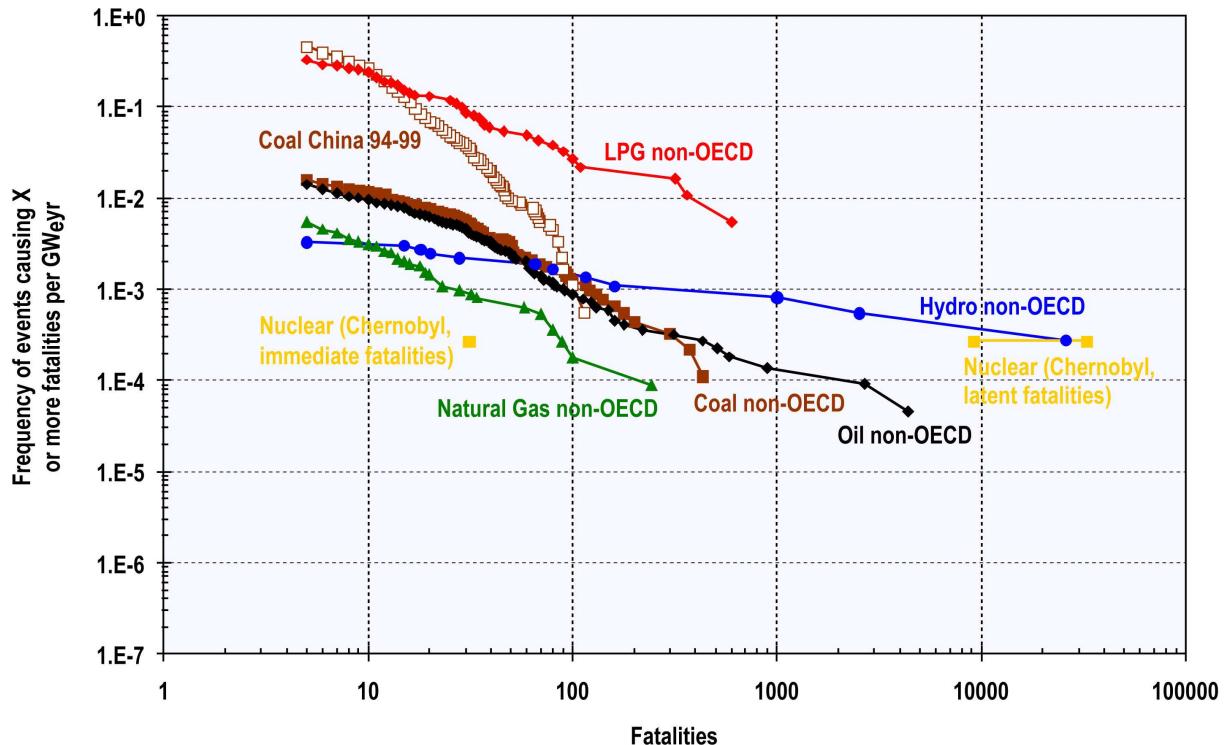


Figure 15 Comparison of frequency-consequence curves for full energy chains, based on historical experience of severe accidents in non-OECD countries for the period 1970-2005, except for coal China 1994-99 (compare text).

4.4 Results for the nuclear chain based on simplified PSA

The work has focused on the assessment of radioactive releases and associated frequencies for the two reference advanced designs to provide inputs for the risk indicator calculations.

EPR

At least 6 events which could be considered as severe accidents have occurred in about 12000 years of commercial operations (namely, in order of decreasing severity, Chernobyl 4, TMI 2, Saint Laurent, Atucha, Vandellós, Leningrad, or 2 in RBMKs, 3 in PWRs, and 1 in PHWRs). Nevertheless, the technology has benefited from “lessons learned” and clearly has improved in design and reliability, at least in the area of accident prevention. The Generation 3 (or 3+) designs, in addition, have incorporated additional features for accident mitigation. In this respect, designs such as the EPR, the AP-600 and AP-1000 can be considered as having reached the optimum and safest level of operation among PWRs.

One European Pressurized Water Reactor (EPR) unit, of Framatome Advanced Nuclear Power (FANP) design, has been accepted in Finland for construction at the Teollisuuden Voima Oy (TVO) site near Rauma (designated as TVO-3) in the Southwest of Finland, and the plant safety has been under scrutiny by the Finnish authority STUK. FANP has performed a PSA specific for the site (i.e., for the plant as commissioned, but not yet built and operating), and understandably all the details of the PSA are not available.

The EPR is a 1600 MWe Generation 3 (or 3+) PWR with advanced features, especially with respect to Severe Accident Management active and passive systems. Much information on the plant layout, systems, severe accident protection and mitigation, etc., relevant for this work, is publicly available on internet either from FANP or through public reports on the plant design. For accident specific data (release rates from fuel, for instance, aerosol retention in systems and containment, types of

accidents), publicly available information from the most recent state-of-the-art PSAs for Siemens Generation 2 PWRs can be used by similarity of design.

STUK has rejected the FANP PSA and the work is currently under revision. Main reasons for the rejection are overly conservative assumptions in the evaluation of frequencies (both in Level 1 and 2) and unrealistic or not defensible source terms. For reasons given below, it is believed that the present assessment provides a reasonable and realistic estimate of frequencies and source terms, and that the published FANP results could be considered as the 95th percentile of realistic estimates.

The plant is of a Generation 2+ (or 3+) design, and will operate with a power output of about 1600 MWe, but with very high efficiency turbines (hence thermal power and radioactive core inventories are slightly lower than in comparable LWRs of previous generations). The main safety-augmenting differences with the Generation 1+ and 2 designs, from the point of view of severe accidents, are as follows:

More redundancies in primary systems (4 steam generating loops instead of 2 or 3).

Some diversification in primary systems.

As a result of these and other improvements in design, core damage frequency from internal initiators (**only**) “shall not exceed 10^{-7} per reactor year” (FANP statement), as compared to the order of 10^{-5} per reactor year, typical for the currently operating plants in the EU (and Switzerland).

In-containment emergency water tank (Internal Refuelling Water Service Tank, IRWST).

Provisions for avoiding containment basemat melt-through (core spreading-cooling systems).

Containment shield to mitigate impact of aircraft crashes.

In other safety- and risk-relevant aspects, the two designs show similarities, or the EPR design is slightly disfavoured. These may include, for instance:

Individual unit power is very high as compared to most operating installations, hence radioactive inventories, and potential for accidental releases, are proportionally higher, despite the high efficiency turbines.

Containment size may not be larger proportionally to power, to accommodate the potentially higher loads.

Containment strength for an EPR is assumed to be between 10 and 12 bar-abs, compared to that of most operating PWRs, assessed at between 5.3 and 9 bar-abs; i.e., containment strength is not proportionally larger.

The main high risk PWR vulnerabilities (SGTRs, IS-LOCAs) are “generic”, i.e., the frequencies of the initiator events cannot be ruled out for the EPR, and should be similar for the two designs. In fact, for SGTR there is a considerable history of vulnerability of the steam generator tubes in the operating PWRs (nearing one single tube rupture per year for all PWRs). Assessed core melt frequency for these sequences may be lower than for current plants, due to more modern materials, design, and accident diagnostic systems, however, the potential frequencies for these severe accidents is not zero.

Frequencies and source terms are then calculated, using the relevant public information previously summarized, accepted PSA practices and accepted PSA tools, for best estimate and 95th percentile. In particular, source terms are calculated using NUREG-1150 parametric models as follows:

Release to environment = release from primary system / retentions flow rates to environment.

All parameters are evaluated from generic PWR data and adapted to the EPR known plant data (including containment systems).

Six hypothetical accidental releases are defined for the present work as for older PWRs, which are:

| | |
|----------------|---|
| RC1/EPR | Accidents where the containment function is preserved and radioactivity is dispersed to the environment via a small assumed leak (a design basis leak of less than 0.05 containment volume per day%, as specified by FANP, and a small leak from the secondary isolated containment, RC1). |
| RC2/EPR | Accidents where the containment is vented by the operators at least 12 hours after accident initiation (it is assumed that the Swiss authorities would require this system, as was done for all other Swiss plants; alternatively, the containment may fail in these accidents after at least 24 hours, with very similar offsite consequences, RC2). |
| RC3/EPR | Accidents where the containment fails within 12 hours from the start, resulting in a leak through the primary containment, the filtered ventilation system of the secondary containment, to the environment (RC3). |
| RC4/EPR | Accidents where containment isolation fails from the beginning and a small leak occurs via pipings directly to the environment (RC4). |
| RC5/EPR | Accidents initiated by an un-isolated SGTR or small IS-LOCAs (RC5). |
| RC6/EPR | Accidents involving large IS-LOCAs (RC6). |

Note that, for the last two release types, very little mitigation, if any, is possible or can be assumed by design. In addition, accidents with late failure of the containment are not included, because failure by hydrogen combustion is almost precluded, due to the presence of Passive Autocatalytic Recombiners (PARs), or because the core debris is very likely cooled by the combination of passive core catcher systems.

The following overview in Table 6 shows the estimated source terms.

Table 6 Source terms and frequencies of accidents for EPR.

| Release class(es) | Xe | I | Cs | Te | Sr-Ba | Ru | La | Ce | Frequency (/Ry) |
|---|------|------|------|-------|-------|-------|-------|-------|-----------------|
| RC1/EPR Containment Integrity or BMT | 7E-5 | 5E-9 | 4E-9 | 9E-10 | 8E-10 | 1E-11 | 1E-11 | 1E-9 | 6E-8 |
| RC2/EPR Containment Vented | 0.80 | 2E-7 | 2E-8 | 9E-8 | 2E-8 | 6E-10 | 6E-10 | 6E-10 | 5E-8 |
| RC3/EPR ECF | 0.90 | 3E-3 | 3E-3 | 8E-4 | 8E-4 | 1E-5 | 2E-5 | 1E-5 | 1E-9 |
| RC4/EPR Isolation Failure | 0.45 | 4E-4 | 3E-4 | 9E-5 | 9E-5 | 1E-7 | 1E-7 | 1E-7 | 2.3E-9 |
| RC5/EPR Small Bypass | 0.90 | 0.02 | 0.01 | 0.003 | 0.003 | 4E-5 | 4E-5 | 4E-5 | 2.7E-9 |
| RC6/EPR Large Bypass | 0.99 | 0.60 | 0.50 | 0.13 | 0.10 | 0.002 | 0.002 | 0.002 | 1E-10 |

Issue of EPR source terms and frequencies

In 2005 FANP made public at the Beijing ICONE 2005 conference more details on the Level 2 study for the EPR, than were known from publicly available information before. As mentioned, a regulatory review of the study has rejected these results and therefore is still not definitely completed.

In particular, the results show that not only, as noted previously, the magnitude of the source terms is for the most part not realistic, the analysis admittedly having used conservative assumptions for the evaluation of large source terms, such as not crediting realistic mitigative features. But, in addition, that the frequency of each source term is assessed to be at least one order of magnitude higher than what could be expected, based on simple considerations of systems configuration as compared to various operating plants. The following list shows a comparison with the results of other recent, state of the art PSAs for PWRs (in parentheses, year of start of operations):

Gösgen, three loops KWU (1982), total CDF internal plus external $< 3 \times 10^{-6} / \text{Ry}$;

Paluel, four loops FANP 1300 (1986), total internal plus LPSPSA $\sim 1 \times 10^{-5} / \text{Ry}$, currently revisited by EDF and estimated at $< 8 \times 10^{-6} / \text{Ry}$.

One Konvoi plant, Siemens four loop, operative since late 1980s, total CDF (without LPSPSA) $6 \times 10^{-7} / \text{Ry}$.

All these plants are at least one to two generations removed from the EPR, and especially if the result reported by FANP is compared with that for Gösgen, it is extremely surprising that the assessed frequency for EPR internal CDF alone is $> 1 \times 10^{-6} / \text{Ry}$, while for Gösgen it is also $\sim 1 \times 10^{-6} / \text{Ry}$. The two plants differ in number of redundancies (4 instead of 3 loops), and especially in diversification of systems (e.g., 2 different types of pumps in the feedwater trains in the EPR, with consequent reduction of CCF frequencies).

This is a strong indication that, as STUK affirmed without giving details, the study had to be performed in a very conservative manner due to lack of specific historic data on component failures, for instance, and initiator frequencies. It is therefore to be expected that much of the assessed frequencies will be reduced, once the plant (and similar units) is in operation.

Moreover, much of the residual risk in the current FANP assessment comes from accidents at shutdown, with bypass of the containment (with an estimated frequency $>> 1 \times 10^{-7} / \text{Ry}$). This is because very likely Siemens did not yet develop Severe Accident Management Guidelines for shutdown periods, since these are largely site dependent, and can be assessed only after the plant is in operation.

Two important points, on the other hand, can be made from the reported results to confirm the assessment performed for this work:

- 1 Accidents with releases needing offsite intervention cannot be excluded for the EPR.
- 2 The FANP reported frequencies and source terms are close to the 95th percentile used in the present assessment.

Frequencies and Source Terms for a Na- Cooled Fast Reactor ⁵

Sodium cooled fast breeder reactors had been extensively investigated in the period 1970-1984, and several prototypes of different designs had been operating, (current total operating experience is about 300 reactor years). But the largest model (Super Phenix) was shut down due to safety concerns. In addition, at least one severe accident has occurred in an experimental breeder reactor (the EBR).

The interest for these reactors has been revived during the push for Generation IV plants, due to expected smaller consequences from severe accidents than for LWRs, and some studies have been

⁵ Note that for reasons of consistency in terminology with other WPs of RS 2b the abbreviation EFR (European Fast Reactor) is also used in this deliverable

conducted including attempts to Level 2 PSA by INEEL, ORNL, and the Japanese concern CRIEPI. A large amount of information can be found in Internet, and some of the most significant data is given in the Attachments, including the specific sources and references. However it must be cautioned that the safety analyses efforts so far have been very primitive and limited, hence the information found in the open must be interpreted very conservatively.

A summary of a joint effort by ORNL and CRIEPI (Toshiba-Hitachi, 2005) is the most interesting document, and the present estimates are extracted from that publication. CRIEPI shows the preliminary results for a Level 2 PSA conducted for a Small Breeder Reactor (SBR) which appears to be in operation. The reactor power can be extended to 1500 MWTh (500-600 MWe, depending on turbine efficiency, not yet specified), and the fuel can be exchanged to conventional LWR MOX fuel. A commercial power plant may likely operate with MOX fuel like an LWR.

Therefore, for the remainder of the discussion, it is assumed that the plant would be MOX-fueled, making it for easier comparisons to LWRs. It should be noted that, if non-MOX fuel were to be used, the main differences would be a longer time for progression to core damage, but a possibly much higher inventory of long-lived elements such as Cs₁₃₇, hence in the end safety concerns balance each other out.

The CRIEPI analysis is very incomplete, and takes into consideration only internal initiating events, and moreover it would appear that not all accident sequences have been analyzed. In particular, results (very abbreviated) are shown for three sequences, Protected Loss of Heat Sink (PLOHS), Unprotected Loss of Heat Sink (ULOHS), and Transient Over Power (TOP). The first two presumably refer to loss of heat exchangers, and/or steam generators capabilities, the last to transients with power increase, which would include ATWSs. Primary system LOCAs and Loss of Power events appear not to be considered and ATWS may thus not be completely covered in TOP.

For these scenarios, frequencies and source terms are provided for what appear to be six release categories, for one radionuclide group only (presumably I-Cs). Table 7 below shows the data which can be extracted from the information given by CRIEPI. Release classes are not specified but from the magnitude of releases it can be guessed that they correspond to the following LWR classes:

- RC1: Intact containment
- RC2, RC3: Two different scenarios with late containment failure
- RC4, RC5: Two different scenarios with early containment failure
- RC6: Containment function impaired from the start of the accident

Accident frequencies have been corrected, assuming that the analysis is incomplete (i.e., assuming conservatively that all missing scenarios behave as the worst scenario ULOHS), and further assuming that the frequency of external and area events contributes about one third of the total CDF for states at power (as for most LWRs), and that shutdown states also contribute an additional 50% of the total CDF at power (as is the case for the EPR plant). Source terms for groups other than I and Cs are extrapolated from typical LWR analyses, which is reasonable for a MOX core.

Table 7 Estimated source terms and frequencies, reconstructed from CRIEPI (Toshiba) preliminary work on S4 project in Japan (2005), corrected for external and area events and shutdown states.

| Release class | Frequency (/Ry) | Xe | I | Cs | Te | Sr | Ru | La | Ce | Ba |
|---------------|-----------------|------|------|------|------|------|------|------|------|------|
| RC1/FBR | 5.9e-7 | 0.1 | 1e-4 | 1e-4 | 5e-5 | 2e-5 | 2e-6 | 5e-6 | 1e-7 | 2e-5 |
| RC2/FBR | 2.7e-7 | 0.98 | 9e-4 | 9e-4 | 4e-4 | 2e-4 | 2e-5 | 6e-5 | 2e-8 | 2e-4 |
| RC3/FBR | 1.6e-7 | 0.98 | 8e-3 | 8e-3 | 6e-3 | 3e-3 | 3e-4 | 6e-4 | 3e-6 | 3e-3 |
| RC4/FBR | 7.0e-8 | 0.98 | 0.01 | 0.01 | 6E-3 | 4E-3 | 3e-4 | 5e-4 | 1e-5 | 4E-3 |
| RC5/FBR | 1.4e-9 | 0.98 | 0.07 | 0.07 | 0.04 | 0.02 | 2e-3 | 4e-3 | 2e-4 | 0.02 |
| RC6/FBR | 2.5e-12 | 1.00 | 0.10 | 0.10 | 0.05 | 0.03 | 3E-3 | 7E-3 | 3e-4 | 0.03 |

The total CDF would be about 1.1×10^{-6} , which is consistent with earlier estimates from a more complete PSA published in 1991 and consistent with CDF for Generation 3 plants. It is to be said that the results should be taken with much caution, because the PSA here discussed appears to be not only very incomplete, but also rather primitive in the Level 2 treatment, especially in the very coarse estimate of source term classes and releases.

In a comparison with LWR results, it is seen that the frequency of accident sequences leading to large consequences ($>> 1\%$ of the Cs inventory released to the environment) is very small, and especially limiting events involving more than 10% of the inventories are of remote probability. However, large releases still cannot be excluded. The limiting sequences appear to involve a partial bypass of the primary system and/or containment, due unidentified mechanisms; most likely, given the magnitude of the source terms, early failure of the containment due to over-pressure or over-temperature. On the other hand, due to design, accidents with potentially very large releases (such as from the accident at Chernobyl) appear completely excluded. Certainly, the design is a-priori not susceptible to Interfacing Systems LOCA.

Figure 16 shows a comparison of frequency of exceedance for Cs releases for the two plant types; also preliminary HTGR estimates are included for comparison. In order to properly compare the data, the releases for the FBR have been normalized to the EPR core inventory, and for the EPR the very conservative provisional assessment by AREVA is also shown. In the figure are also shown two severe accident safety criteria, the first used by the Finnish authority (the limit of acceptable releases is 100 TBq of Cs-137 equivalent), the second proposed by the USNRC (related to the release of Iodine). Since releases of iodine and Cs are almost 100% correlated, the limit also applies to Cs releases.

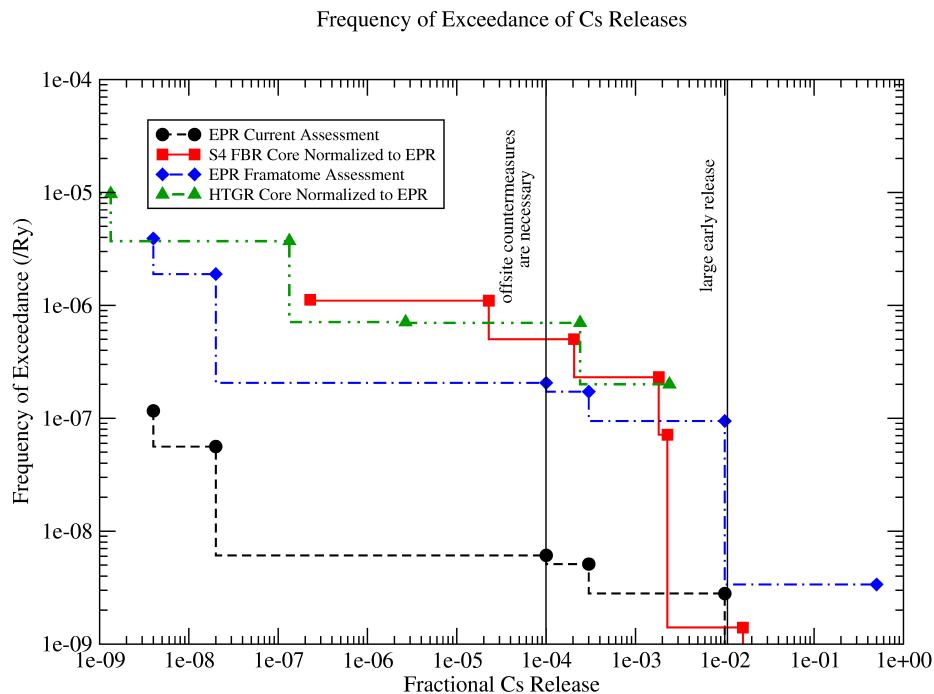


Figure 16 Frequency of exceedance for Cs releases: a comparison between EPR, the S4 FBR and an HTGR.

The two criteria define different types of absolutely necessary offsite countermeasures. The one used in Finland is related to aggressive long term interventions, i.e., if Cs release exceeds 100TBq, relocation, land interdiction and condemnation, disposal of crops and livestock would all be necessary to some extent. The one proposed by the USNRC is related to immediate countermeasures, i.e., if Iodine and Cs releases exceed about 2-3% of total core inventory (for the EPR core), evacuation or equivalent protective actions would have to be initiated immediately to prevent prompt fatalities.

For the EPR, it may be argued that the frequency of releases exceeding the criterion is extremely small. Acceptance of both plants according to the Finnish criterion again may be supported on the basis of small frequencies (compare Tables 6 and 7, and associated texts).

A comparison of the estimated Cs releases as fractions of core inventories and frequencies for the plant types included in the present assessment is shown in Figure 16. The release limits which would certainly trigger long term or immediate offsite countermeasures are also provided.

Finally, Figures 17 to 19 show frequency-consequence (F-N) curves for early fatalities, latent fatalities and land contamination of future (year 2050) EPR and EFR technologies sited in France, Germany, Italy and Switzerland, as defined within the NEEDS technology set. For each of the considered aspects, maximum consequences are substantially lower for EFR, however frequencies are higher for small and medium sized consequences compared to EPR. Both for EPR and EFR the F-N curves are depending on the severity of consequences about one to three orders of magnitude below the corresponding curves for Generation 2 reactors.

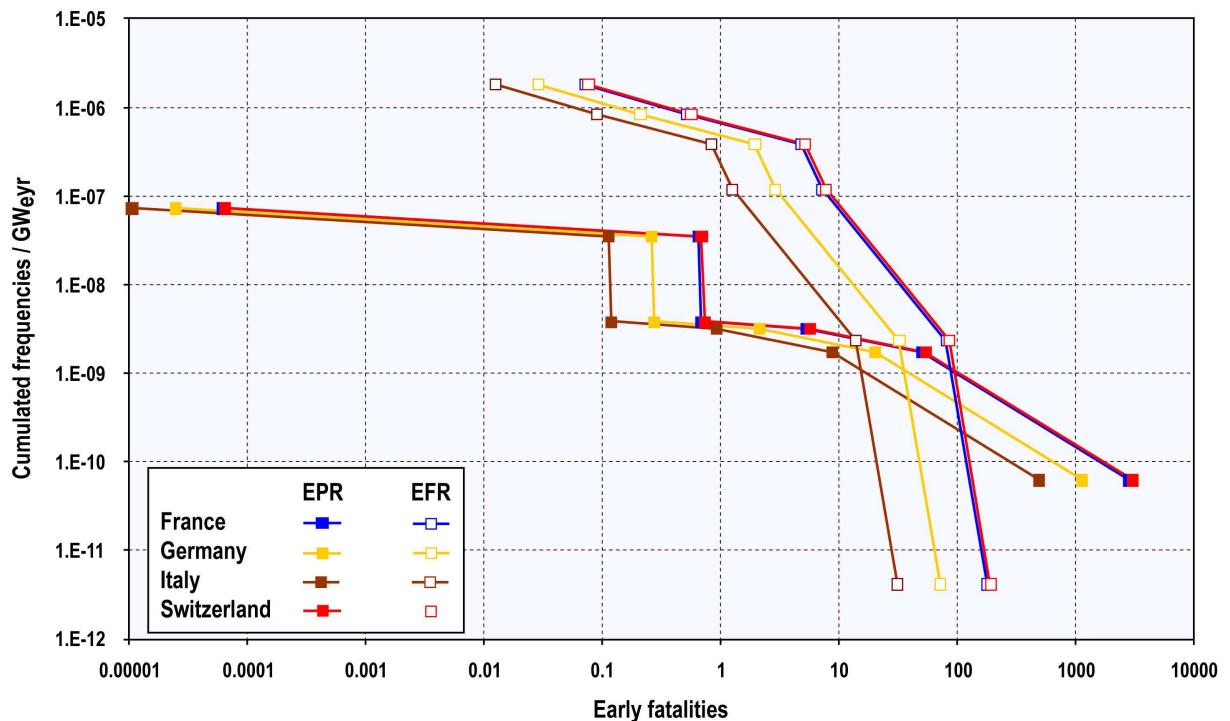


Figure 17 Frequency-consequence curves for early fatalities of EPR and EFR technologies in four countries as defined in the NEEDS technology set (year 2050).

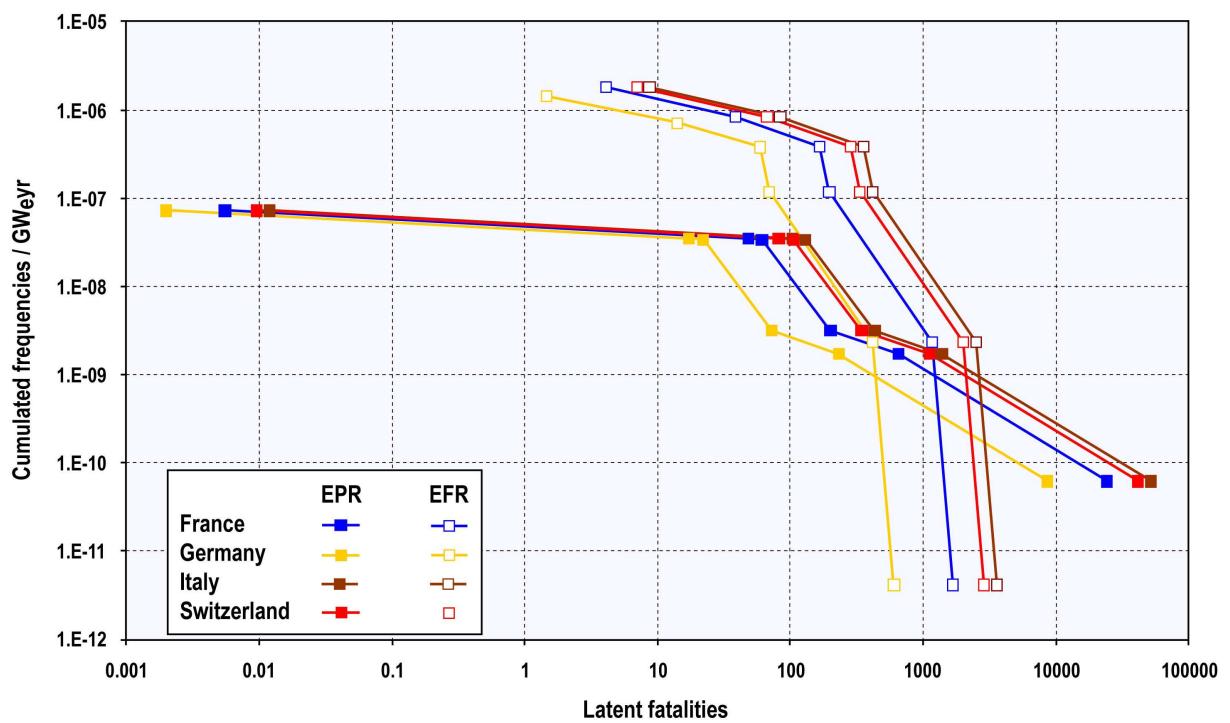


Figure 18 Frequency-consequence curves for latent fatalities of EPR and EFR technologies in four countries as defined in the NEEDS technology set (year 2050).

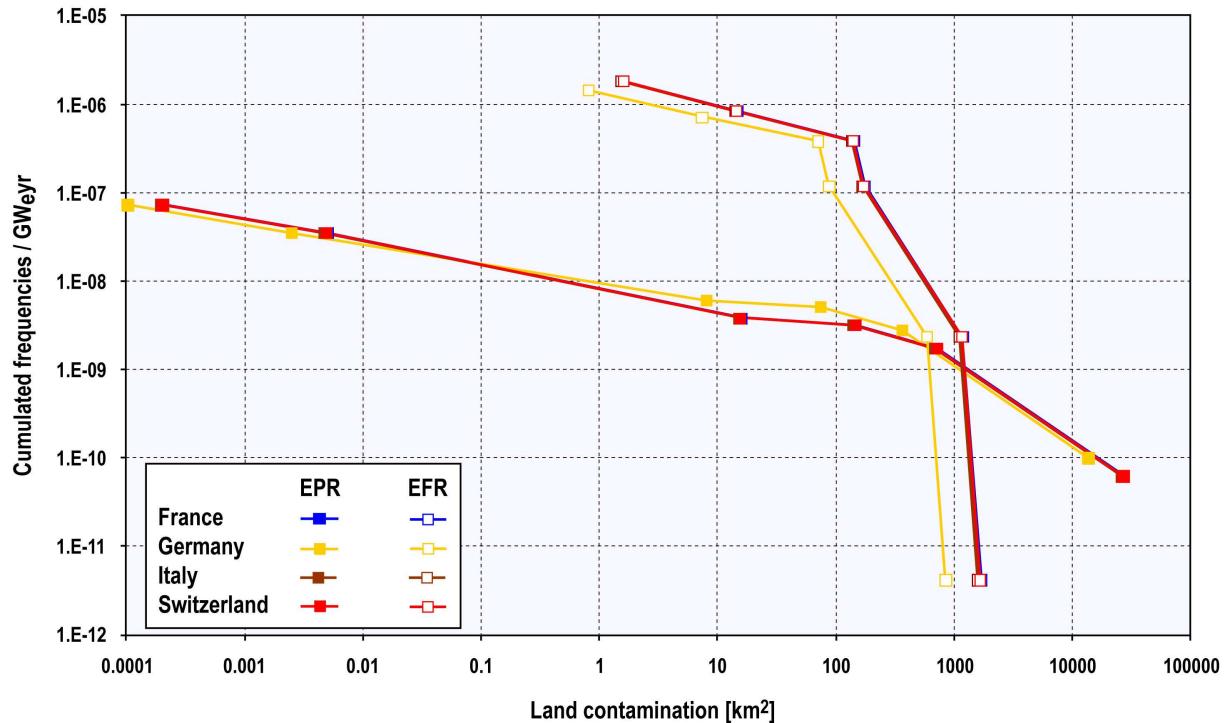


Figure 19 Frequency-consequence curves for land contamination of EPR and EFR technologies in four countries as defined in the NEEDS technology set (year 2050).

5 Risk indicator results

Figures 20 to 24 show the numerical results for the different risk and terrorist threat indicators calculated for the NEEDS set of advanced technologies in the year 2050. The indicator for accidental spill of hydrocarbons is not shown because no oil-based technology is considered in the NEEDS set. Land contamination due to the release of radioactive isotopes (Figure 20) is only relevant for the nuclear technologies.

Fatality rates (Figure 21) are lowest for nuclear, intermediate for new renewables and highest for fossil technologies, whereas for maximum consequences (Figure 22) nuclear and new renewables are reversed, while fossil technologies remain intermediate. Lower results for lignite compared to hard coal are predominantly attributable to its rather local use, i.e. imports from more accident-prone non-OECD countries do not apply, and thus do not enter the calculations. For the same reason natural gas has somewhat higher values than lignite, but clearly performs better than hard coal. Concerning fatality rates biomass technologies are closest to natural gas, whereas wind offshore and solar technologies show fatality rates that are about one and two orders of magnitude lower, respectively. Maximum consequences of new renewables are very limited, except for MCFC wood gas because its chains have certain similarities to the natural gas chain.

For nuclear energy the source terms are based on published results, which however were modified to better reflect emerging insights for best estimates. The estimated source terms for future EFR should be considered as rough since the details of the future design are not known at this stage. The results indicate that the expected risks for EPR and EFR are very low in the absolute sense. In relative terms, EPR shows lower expected risks. On the other hand, EFR exhibits substantially lower maximum credible consequences of hypothetical accidents, which is a positive feature in the context of public acceptance. The current estimates of nuclear risks, particularly for EFR, should be seen as explanatory. Further more detailed analyses are recommended.

Although the attractiveness of a terrorist attack on a nuclear power plant may appear highest, it only ranks second after combined cycle natural gas because for the latter the elements resources needed, implemented countermeasures and ease of execution are considered more favourable, resulting in a higher potential for a terrorist attack (Figure 23). Results for the other technologies are based on similar reflections. Potential effects of a terrorist attack (Figure 24) show a quite similar technology ranking to maximum consequences, however one has to be aware that effects of the most likely type of attack are considered and not the most severe one. Nuclear ranks first because the only credible type of accident would result in a core melt down with a small failure of the containment, causing 300 to 1000 fatalities, which are clearly higher than for the other technologies considered. Effects of natural gas technologies are considered greater than hard coal or lignite because credible scenarios during transportation, storage and at the plant site may result in more victims. Fossil technologies using CCS were assigned a higher value because the additional transport and disposal of CO₂ provides an increased risk. Effects of new renewables are generally at the lower end of the spectrum, although MCFC wood gas and PV-CdTe building because of some natural gas like properties and some assumed toxicity effects, respectively. Finally, the proliferation indicator is only applicable to the nuclear energy chain with no distinction being made here between EPR and EFR, i.e. the two nuclear technologies have been assigned a value of 1 and all other technologies a value of 0. It would be desirable to differentiate between the two associated fuel cycles what concerns proliferation potential. This would require a dedicated study, which was outside of the scope of the current project.

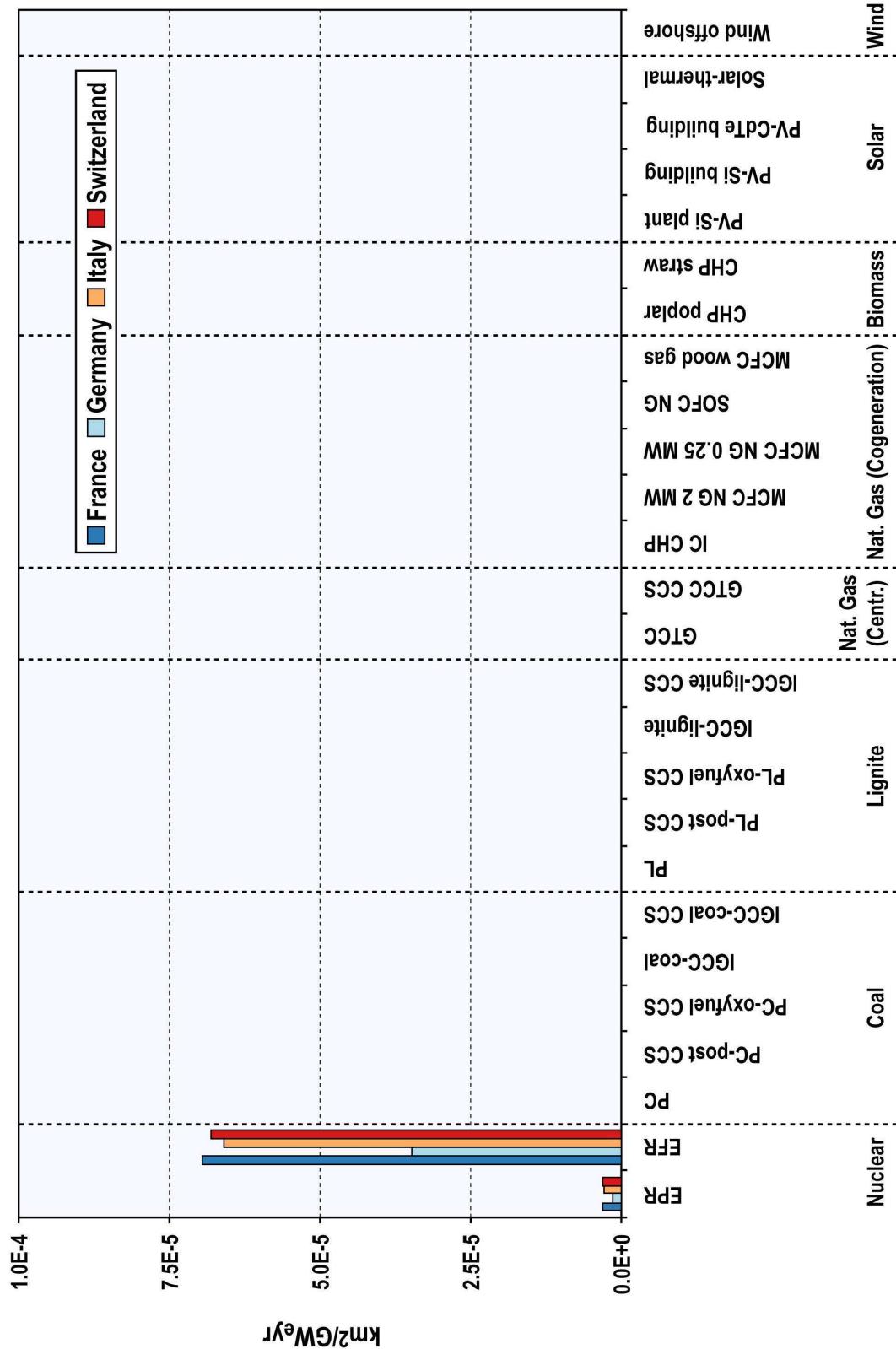


Figure 20 Land contamination due to the release of radioactive isotopes for the NEEDS set of advanced technologies in 2050. For technology names and their abbreviations see Table 3.

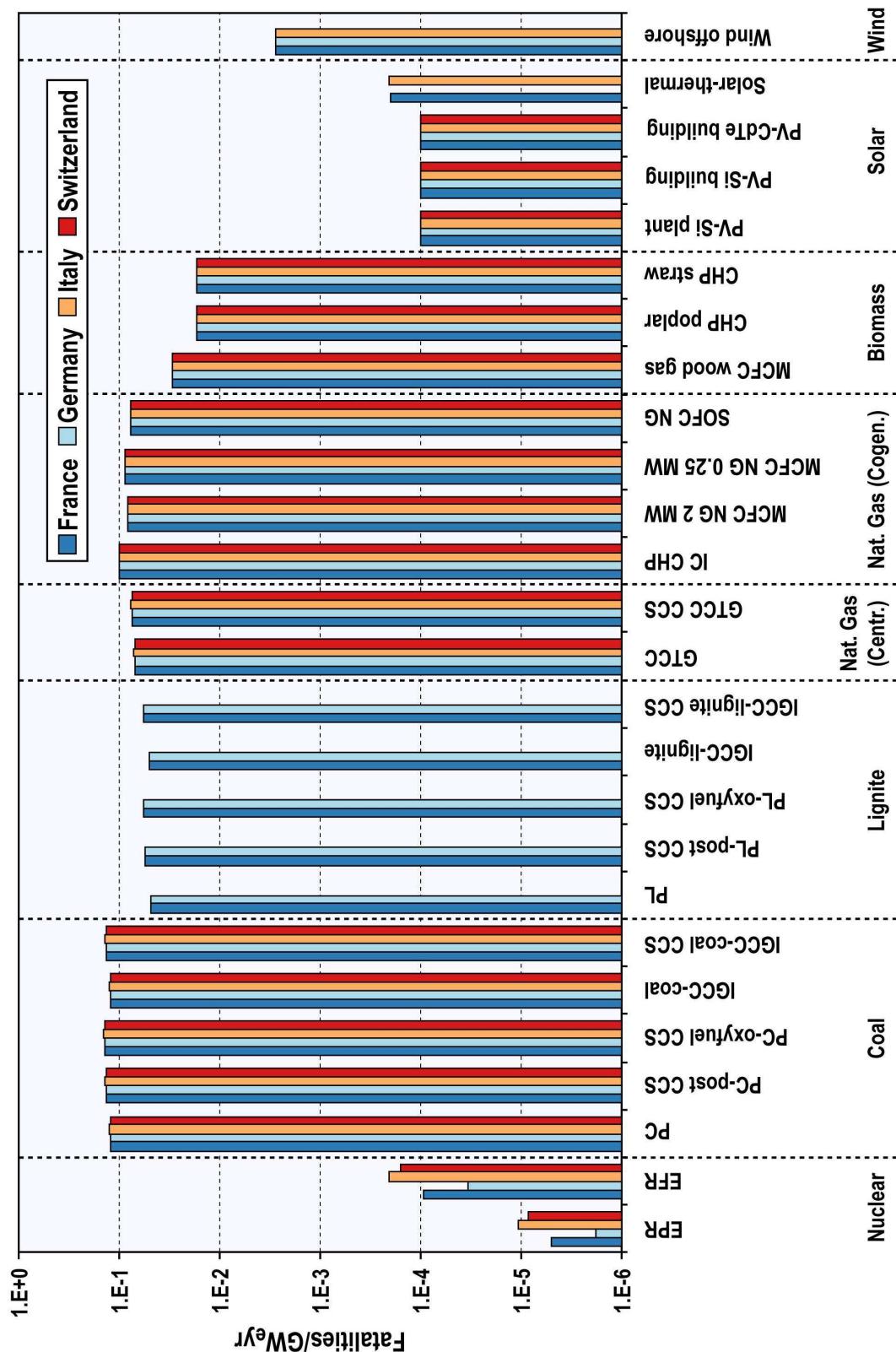


Figure 21 Accident mortality based on expected fatality rates for the NEEDS set of advanced technologies in 2050. For technology names and their abbreviations see Table 3.

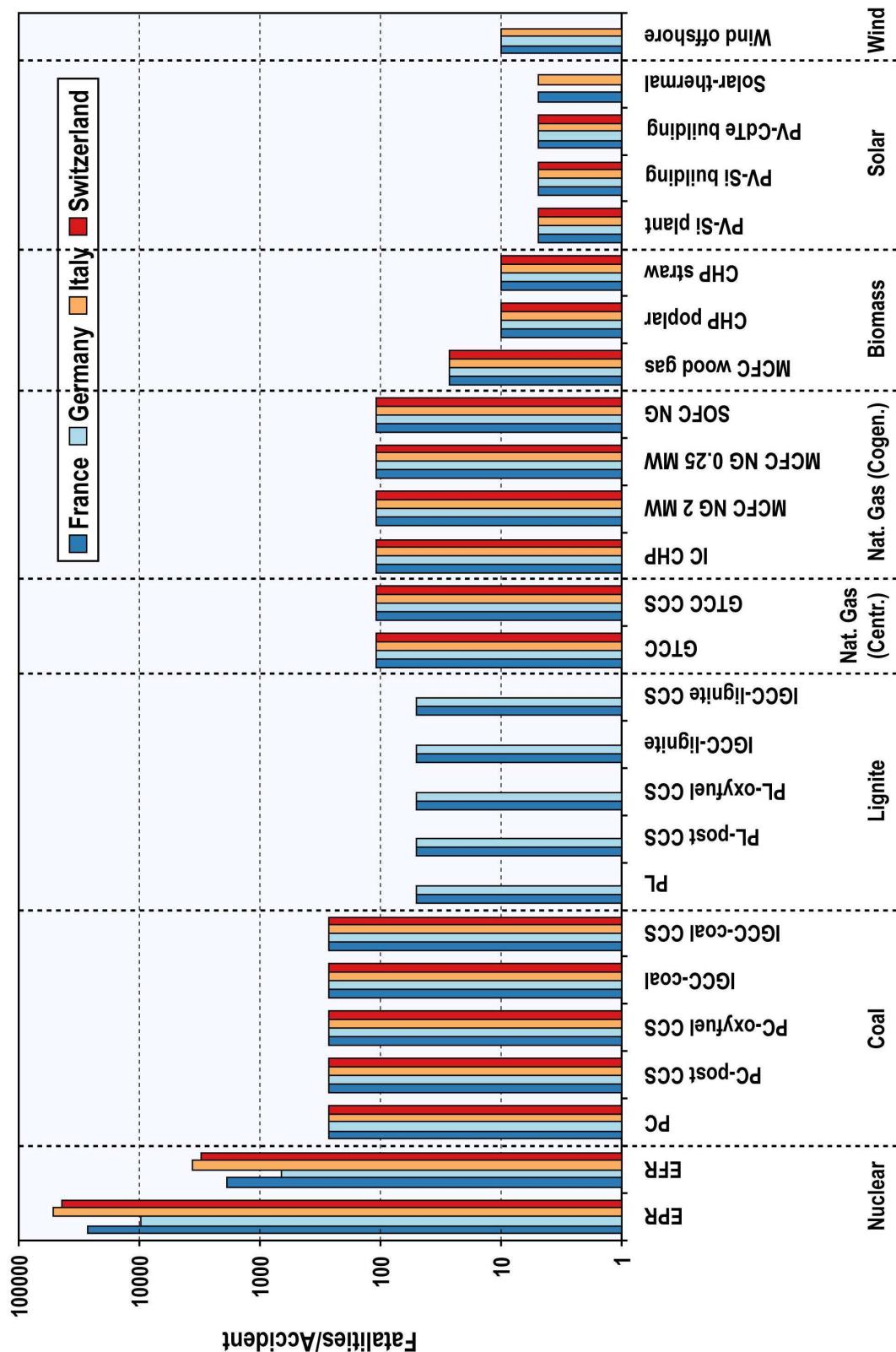


Figure 22 Maximum accidental consequences for the NEEDS set of advanced technologies in 2050. For technology names and their abbreviations see Table 3.

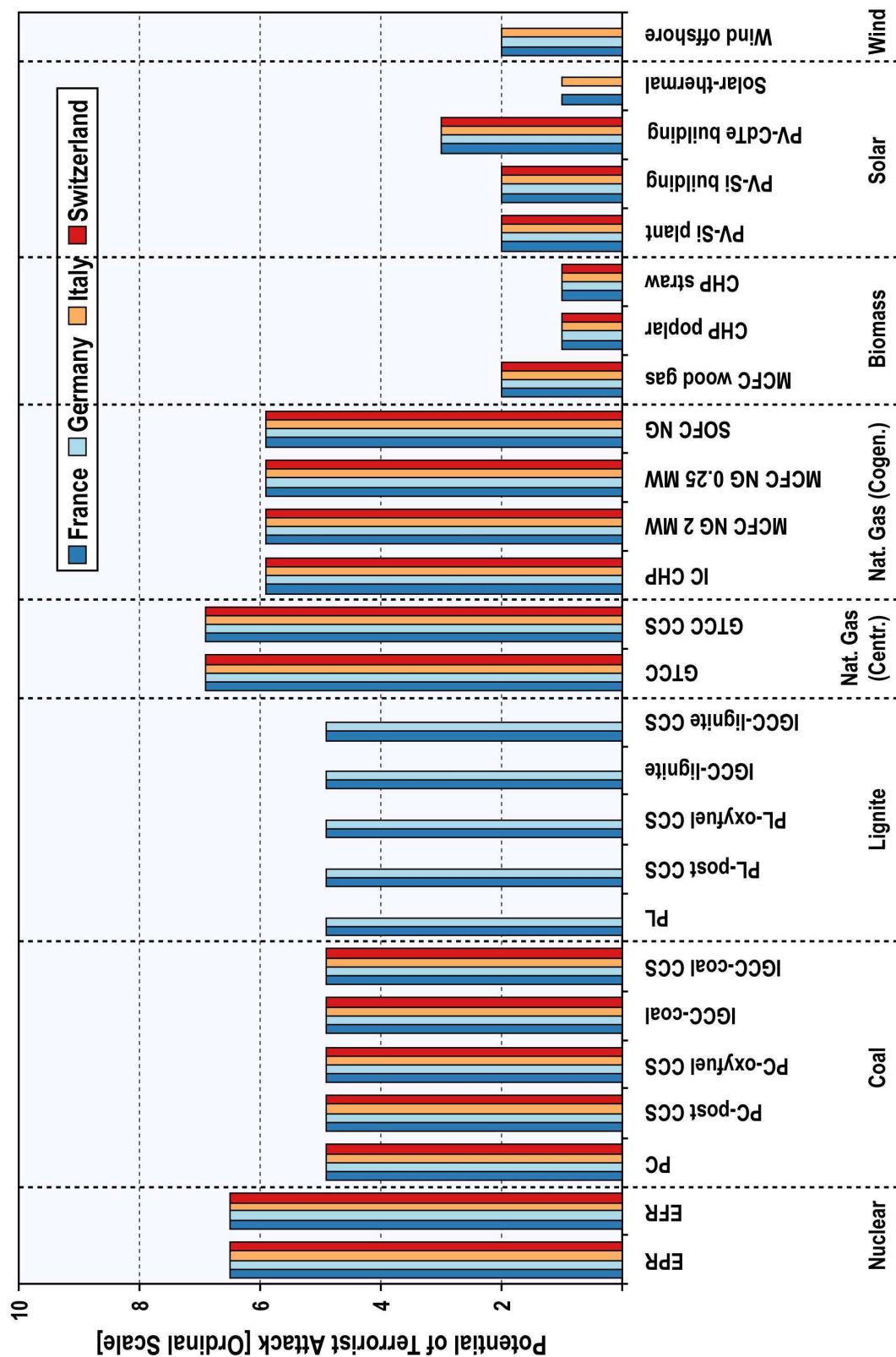


Figure 23 Potential for a successful terrorist attack for the NEEDS set of advanced technologies in 2050. For technology names and their abbreviations see Table 3.

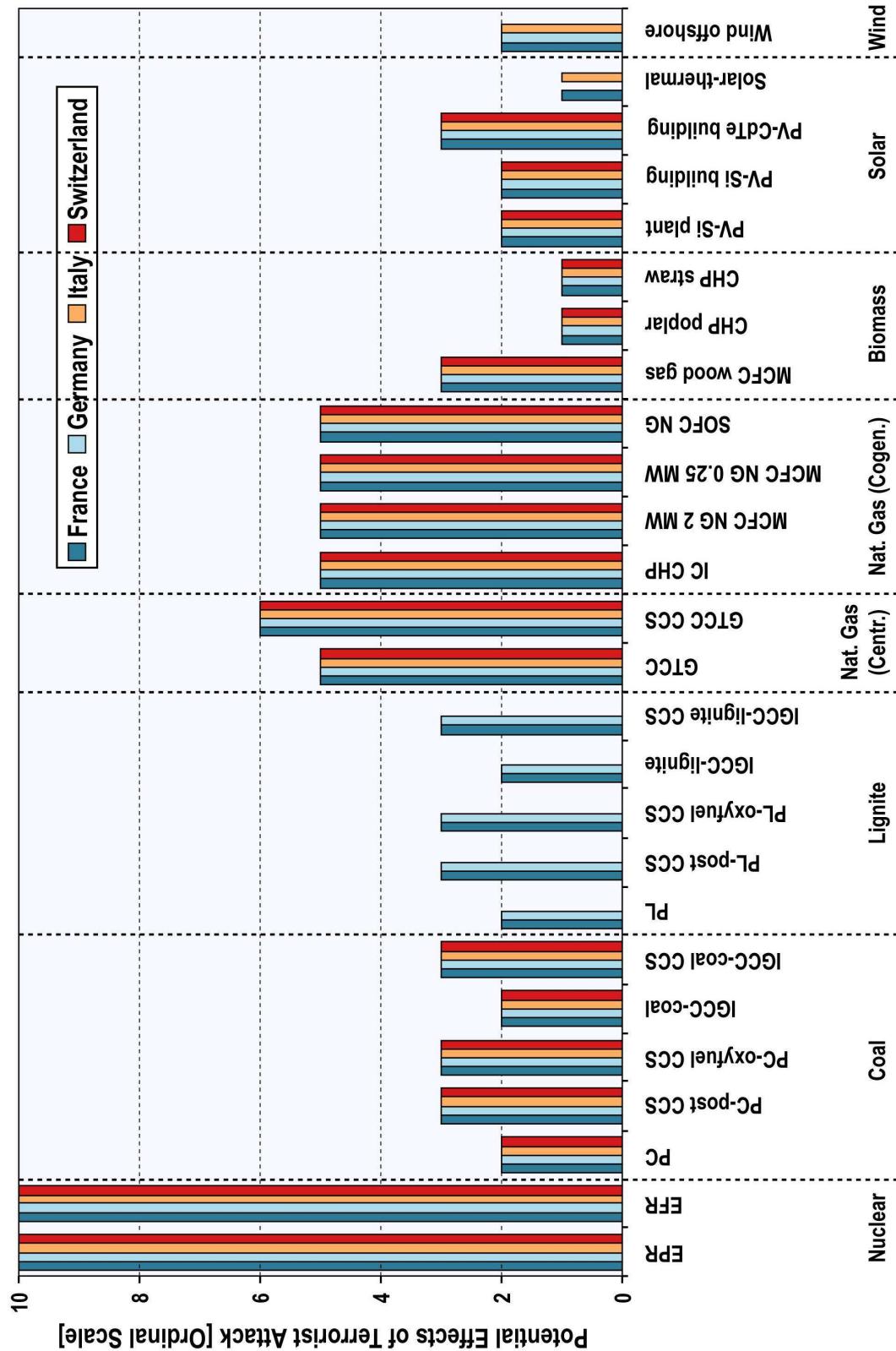


Figure 24 Potential likely consequences of a successful terrorist attack for the NEEDS set of advanced technologies in 2050. For technology names and their abbreviations see Table 3.

6 Conclusions

The ENSAD database contains comprehensive historical experience of severe accidents in the energy sector allowing for detailed and quantitative technical comparisons of a wide range of aspects of severe accident risks. ENSAD is (1) continuously maintained to ensure accurate functionality and proper operation, (2) regularly updated to keep up with the demand for timely availability of growing historical experience, and (3) extended in scope to broaden its range of application and to enable tailored studies for a variety of stakeholder groups and their specific needs. Therefore, the use of ENSAD is not restricted to purely scientific evaluations, but can contribute to manifold activities such as decision-making processes for energy policies, the realization of safety goals, and improved technology transfer to other countries. In addition a simplified PSA was used for nuclear where full chain risks are dominated by the power plant stage and the availability of historical experience is strongly limited, as it is the case for western nuclear power plants. Historical experience was also rather limited for some new renewable technologies, so that evaluations had to be complemented by expert judgment when necessary.

Within the NEEDS project a total of 3024 new accident records for the period 2001-2005 have been added to ENSAD. Of these 2601 were attributable to the energy sector, of which 508 resulted in five or more fatalities. Additionally, significant improvements were achieved in (1) the acquisition of new information sources, (2) data transfer from primary information sources to ENSAD, (3) database architecture, (4) coupling of ENSAD with geographic information systems (GIS) to analyze spatially discontinuous distributions and to identify, analyze and visualize spatial patterns by means of geo-statistical tools and multivariate statistics, (5) consistent calculation of technology-specific risk indicators, (6) development and implementation of an assessment procedure to qualitatively estimate indicators that describe the susceptibility of specific technologies towards the terrorist threat, and (7) application of risk and terrorist threat indicators to current and future technologies.

Chain-specific analyses were used to identify the most accident-prone stages in different major energy chains, which were fuel extraction, refining and transportation in fossil energy chains, as well as hydropower in the less developed (non-OECD) countries.

Comparative evaluations showed substantial numerical differences between the different energy chains and country groups analyzed. Expected fatality rates were lowest for western hydropower and nuclear power plants. Among fossil chains, natural gas exhibited the lowest risks followed by coal and oil, whereas LPG performed worst. When comparing country groups, energy-related accident risks are distinctly lower in the OECD and EU 27 countries than in non-OECD countries. Differences between OECD and EU 27 are mostly quite small, thus the more statistically robust estimates obtained for OECD countries can also be considered representative for the EU 27. Results for maximum consequences showed that low very low accident frequencies can be associated with very large numbers of fatalities, as it is the case for hydropower in non-OECD countries and for hypothetical nuclear power plant accidents based on site-specific, simplified PSA.

Regarding the simplified PSA approach for nuclear, a number of developments were achieved within NEEDS. Inventories were established for EPR and EFR that enabled the calculation of consequences of hypothetical accidents at specific nuclear power plant sites in France, Germany, Italy and Switzerland.

To provide a coherent and transparent decision base, the different aspects of severe accident risks need to be considered and expressed whenever possible in quantitative terms or at least in a comprehensible qualitative manner. For this purpose clearly defined risk indicators were calculated on the basis of ENSAD and PSA, with supplementary expert judgment for few new renewables. The terrorist threat was assessed using a rather crude and qualitative methodological procedure that built on applicable and understandable rules and took into account the most important, result-driving elements for each indicator. However this approach is currently refined and substantially extended within the EU-project SECURE to provide more systematic and robust estimates that build upon a

less expert-dependent methodology, include quantitative elements to the extent feasible, and are applicable to various energy infrastructures.

Calculated risk indicators in WP7 included large accidental spills of hydrocarbons (oil chain), land contamination due to the release of radioactive isotopes (nuclear chain), accident mortality based on expected fatality rates (all chains), and maximum consequences based on the most deadly accident (all chains). For the terrorist threat three indicators were estimated, namely the potential for a successful attack (all chains), the potential likely consequences of a successful attack (all chains), and the proliferation of technologies or substances present in the nuclear electricity generation chain.

Risk indicators led to valuable insights and conclusions, but above all they provided essential input to the NEEDS MCA for the sustainability assessment of a defined, future (year 2050) set of electricity generation technologies. Within MCA actual indicator values are combined with stakeholder preferences resulting in a technology ranking, which in an iterative process can be modified by balancing tradeoffs and compromises between risk indicators and in relation to all other sustainability indicators, as well as among the three sustainability dimensions. The MCA results can support stakeholders assess and understand the sustainability performance of current and/or future energy supply technologies, and they can also contribute to decisions on / formulation of energy policies at different spatial scales (local/regional, national, supranational) and for different technology portfolios.

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