Comparative risk assessment of severe accidents in the energy sector

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HIGHLIGHTS

- Accident risks are compared across a broad range of energy technologies.
- Analysis of historical experience was based on the comprehensive database ENSAD.
- OECD and EU 27 performed significantly better than non-OECD countries.
- External costs of accidents are very small, but impacts can still be enormous.
- No technology performs best for all risk indicators; thus tradeoffs are inevitable.

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ABSTRACT

Comparative assessment of accident risks in the energy sector is a key aspect in a comprehensive evaluation of sustainability and energy security concerns. Safety performance of energy systems can have important implications on the environmental, economic and social dimensions of sustainability as well as availability, acceptability and accessibility aspects of energy security. Therefore, this study provides a broad comparison of energy technologies based on the objective expression of accident risks for complete energy chains. For fossil chains and hydropower the extensive historical experience available in PSI’s Energy-related Severe Accident Database (ENSAD) is used, whereas for nuclear a simplified probabilistic safety assessment (PSA) is applied, and evaluations of new renewables are based on a combination of available data, modeling, and expert judgment. Generally, OECD and EU 27 countries perform better than non-OECD. Fatality rates are lowest for Western hydropower and nuclear as well as for new renewables. In contrast, maximum consequences can be by far highest for nuclear and hydro, intermediate for fossil, and very small for new renewables, which are less prone to severe accidents. Centralized, low-carbon technology options could generally contribute to achieve large reductions in CO2-emissions; however, the principal challenge for both fossil with Carbon Capture and Storage and nuclear is public acceptance. Although, external costs of severe accidents are significantly smaller than those caused by air pollution, accidents can have disastrous and long-term impacts. Overall, no technology performs best or worst in all respects, thus tradeoffs and priorities are needed to balance the conflicting objectives such as energy security, sustainability and risk aversion to support rationale decision making.

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1. Introduction

1.1. Scene setting

The origin of the term sustainability can be traced back to forestry in the 18th century when von Carlowitz (2000) in his book “Sylvi-cultura oeconomica” characterized a mode of cultivation, at which not more wood was used than could grow again. With the publication of the so-called Brundtland-Report “Our Common Future” of the World Commission on Environment and Development (WCED, 1987) the concept of sustainability or sustainable development became the focus of a major worldwide discussion, and since the 1990s it has become the dominant model of societal development (Noll, 2002).

The textual connotation of the concept is still controversially debated not only in politics but also in science, which is why there is no single, generally accepted definition of sustainability, although the one given by the “Brundtland Commission” is now generally recognized as a certain standard. Controversial topics include for example the equal...
treatment of the three pillars or dimensions of sustainability (Levett, 1998), the degree to which different types of capital can be substituted or not (Dietz and Neumayer, 2007; Hueting and Reijnders, 2004; Rapp Nilsen, 2010), and the time period of concern (Kates et al., 2005).

Concurrently to the intensified discussion on sustainable development, the importance of accurately assessing accident risks in the energy sector has been emphasized by different authors since the 1980s (Fritzsche, 1989; Inhaber, 2004; Rasmussen, 1981). Nevertheless, energy-related accidents were generally just addressed as part of technological accidents instead of a separate and in-depth analytical treatment (Fritzsche, 1992). To improve this situation and to establish a comprehensive and consistent framework for comparative risk assessment, the Paul Scherrer Institut (PSI) initiated in the early 1990s a long-term research activity, with the Energy-related Severe Accident Database (ENSAD) constituting its quantitative foundation (Hirschberg et al., 1998).

In recent years, the comparative assessment of accident risks has become an integral component within the broader context of energy security, sustainability and critical infrastructure protection (e.g., Cherp and Jewell, 2011; Chester, 2010; Johansson, 2013; Sovacool, 2013; von Hippel et al., 2011; Winzer, 2012; Yustaa et al., 2011). These overarching topical areas also comprise overlapping zones, which make them all relevant in a comparative evaluation of energy systems, and thus require strengthening of interfaces as well as choice of objective, transparent and adequate indicators to support informed decision making (Gray and Wiedemann, 1999; Jeswani et al., 2010; Johansen and Rausand, 2014; Musango and Brent, 2011; Singh et al., 2009). Furthermore, energy security is conceptually closely linked to the areas of resilience, vulnerability and risk governance (e.g., Coaffee, 2009). Moreover, energy security is conceptually closely linked to the areas of resilience, vulnerability and risk governance (e.g., Coaffee, 2009).

There is a broad range of low carbon energy technologies that could contribute towards a more sustainable energy future and mitigation of climate change effects. Several studies have looked at environmental, economic and social aspects of new renewables and nuclear technologies as well as decarbonizing fossil fuels by means of carbon capture and storage (e.g., Brook, 2012; Filippini and Silva, 2012; Kröger and Zio, 2011; Molyneaux et al., 2012; Renn et al., 2011). However, risks of severe accidents are generally not analyzed in a detailed and comprehensive manner, although their impacts can affect the environmental (e.g. land and water contamination), economic (e.g. damage and external costs) and social (e.g. human health and risk aversion) dimensions of sustainability, as well as the availability (e.g. supply disruption), acceptability (e.g. public perception) and accessibility (e.g. import dependency and transit) dimensions of energy security. Furthermore, consideration of accident risks is also important with regard to different time horizons because for example their consequences can be short (e.g. immediate fatalities) or long (e.g. latent fatalities, land and water contamination) term.

1.2. Comparative assessment of accident risks

Since its initial release (Hirschberg et al., 1998), PSI's database ENSAD and its associated framework for comparative risk assessment have been regularly extended and refined with respect to scope, coverage and content. New elements and methodological developments include:

- consideration of new primary information sources to constantly improve data quality and the level of completeness; for example coal China (Burgherr and Hirschberg, 2007; Hirschberg et al., 2003) and oil spills (Burgherr, 2007; Burgherr et al., 2012b),
- coupling of ENSAD with Geographic Information Systems (GIS) to enable geo-statistical analyses and risk mapping (Burgherr, 2009),
- application of a simplified level-3 Probabilistic Safety Assessment (PSA) for nuclear energy (Burgherr et al., 2008),
- estimation of external costs (Burgherr et al., 2004),
- evaluation of new renewable technologies (Burgherr, 2011),
- risk indicators for Multi-Criteria Decision Analysis (MCDA) (Eckle et al., 2011; Roth et al., 2009) and
- consideration of intentional attacks on energy infrastructure and terrorist threat (Burgherr and Hirschberg, 2009).

Due to the substantially growing interest for accident risks in the energy sector and its above described embedding within the broader context of sustainability and energy security, an increasing number of studies have been published addressing a variety of aspects. These include analyses of specific energy chains and/or infrastructure types such as coal mining (Chen et al., 2012; Maiti et al., 2009; Saleh and Cummings, 2011), oil spills (Kontovas et al., 2010; Psarros et al., 2011), offshore installations (Vinnem, 2011), refineries (Okoh and Haugen, in press; Szklo and Schaeffer, 2007), risks of new renewables (e.g. photovoltaics (Pfenakis and Kim, 2011), wind power (Mabel et al., 2010), and bioethanol (Delzeit and Holm-Müller, 2009)), and comparative studies (e.g., Colli et al., 2009; Sovacool, 2008). Finally, Felder (2009) compared PSI's database ENSAD (Hirschberg et al., 1998) with the Major Energy Accident (MEA) database (Sovacool, 2008) and also provided some recommendations for future energy accident research. However, in the case of ENSAD his analysis was based on the first release (Hirschberg et al., 1998), thus not taking into account any of the subsequent developments.

The main objectives of this article are the following: (1) to provide a detailed overview of the framework for comparative risk assessment based on ENSAD, (2) to present a range of risk measures covering the various consequences and impacts of energy-related accidents, (3) to compare in an objective and quantitative manner the strengths and weaknesses of a broad portfolio of energy technologies, and (4) to support decision making processes towards a more sustainable energy future.

2. Methodology

2.1. Overview of methodological framework

Fig. 1 provides an overview of PSI's comprehensive and integrated framework for comparative risk assessment, at the center of which is PSI's Energy-related Severe Accident Database (ENSAD). While the initial scope was limited to technological accidents, more recently also accidents triggered by natural hazards, and intentional attacks on energy infrastructure including terrorist threat were included (Burgherr et al., 2011, 2008; Burgherr and Hirschberg, 2009). For fossil energy chains and hydropower extensive empirical evidence from actual accidents contained in ENSAD is used; however, in the case of hydropower the analysis is complemented by site-specific consequence modeling. For nuclear power a site-specific level-3 Probabilistic Safety Assessment (PSA) is applied to estimate accident consequences. For new renewable technologies a so-called “hybrid” approach is utilized, which combines available accident data (mostly relatively scarce due to limited historical experience) with chain-specific modeling and expert judgment. Comparative evaluations of energy technologies encompass a broad range of analytical methods, including:

- various consequence indicators (see also severe accident definition in Section 2.2),
- frequency-consequence (F–N) curves,
2.2. Boundary conditions and main assumptions

To ensure that the above described framework can be applied consistently to a broad range of energy technologies, a number of assumptions and boundary conditions need to be defined in a clear and transparent manner.

2.2.1. Severe accident

In the literature no common definition of the term severe accident exists, i.e. different databases may differ with respect to their specific scope and purpose (Burgherr and Hirschberg, 2008a). ENSAD clearly focuses on severe accidents because industry, decision makers, regulators and the general public are most concerned about these. Furthermore, a much higher level of completeness and accuracy in accident reporting among countries can be assured, which is a necessary prerequisite for worldwide comparisons. Within ENSAD the following seven criteria and thresholds are used to define a severe accident:

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 tons 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\(_{2000}\).

The completeness, accuracy and robustness of the different consequence indicators has been presented before (e.g., Burgherr and Hirschberg, 2008a; Burgherr et al., 2008, 2004; Hirschberg et al., 2004)

It should be mentioned that ENSAD also contains accidents with smaller consequences, but these are not collected with the same rigor and effort, and differences among countries are potentially larger because of considerable differences in reporting.

2.2.2. Complete energy chains

When comparing risks among different energy chains, it is pivotal that one looks at the complete chains because the risks to human health, the environment and society do not only arise from the actual power and/or heat production, but all stages of the chain (Burgherr and Hirschberg, 2008a; Hirschberg et al., 2004). For example, in the coal chain accidents in the mines are prevailing, for oil it is resource extraction and transportation of crude and products, and in the case of hydropower accidents are practically limited to dam failures during operation as well as construction (Burgherr and Hirschberg, 2008a, b). In general, an energy chain may comprise the following stages: exploration, extraction, processing and storage, long distance transport, regional and local distribution, power and/or heat generation, waste treatment, and disposal. However, one should be aware that not all these stages are applicable to every energy chain.

2.2.3. Evaluation period

In this study, severe accidents in the energy sector are analyzed for the period 1970–2008. The start year was chosen because energy-related severe (≥5 fatalities) accidents distinctively increased at the end of the 1960s, which is primarily due to the higher volume of activities (Hirschberg et al., 1998), whereas the end year corresponds to the consolidated database status at the end of the European Union project SECURE (Burgherr et al., 2011). Thus the selected period of observation covers more than three decades of historical experience.

2.2.4. Data normalization

Energy chain comparisons should be based on understandable and meaningful risk indicators that cover a broad range of aspects. Direct comparisons among energy chains can be facilitated by normalized indicators. Therefore, indicator values are normally expressed per unit of electricity production. For fossil energy chains the thermal energy is converted to an equivalent electrical output using a generic efficiency factor of 0.35, but depending on the technology portfolio and study objectives one may also use technology-specific efficiencies. For nuclear and hydro power the normalization is straightforward since in both cases the generated product is electrical energy. The Gigawatt-electric-year (GWeyr) was chosen because large individual plants have capacities in the neighborhood of 1 GW of electrical output (GWe), which makes it a natural unit to compare technologies on a common basis (Hirschberg et al., 1998).

2.2.5. Regional aggregation

Indicator results can be calculated at different spatial scales, e.g. worldwide, country groups, individual countries or country sub-divisions. However, the level of resolution is normally determined by the amount of data. Therefore, often the intermediate level of country groups is chosen because it allows for differentiation between well-defined entities. Generally, indicators are provided separately for three major country groups, namely the Organisation for Economic Co-operation and Development (OECD), the European Union (EU 27), and states that are not OECD members (non-OECD). It should be noted that some countries are members in both OECD and EU 27, thus creating some partial overlap, which is considered acceptable because both country groups are essential.
at a global scale. While OECD and EU 27 are comprised of mostly highly developed countries, non-OECD is considered a more heterogeneous mix of emerging and developing countries. This categorization is also meaningful because of the substantial differences in management, regulatory frameworks and general safety culture between countries (e.g., Burgherr and Hirschberg, 2008a; Hirschberg et al., 2004). In the case of the Chinese coal chain it has been previously shown that a separate treatment is necessary because it performs significantly different from the other non-OECD countries (Burgherr and Hirschberg, 2007; Hirschberg et al., 2003). Lastly, it should be mentioned that assignment of countries to groups can also be done in a more sophisticated manner to elaborate further on differences between the above mentioned main groups (Burgherr et al., 2012a). In the case of nuclear, site-specific results using a simplified level-3 PSA are used. For renewable energy technologies except large hydropower, estimates can be considered representative for developed countries (e.g., OECD and EU 27). Calculations for new renewables are based on the methodology described in Burgherr (2011); however, in the case of wind updated data for the years 2000–2012 were used.

2.3. Statistical analyses

First, an overview of the available ENSAD data (1970–2008) for the various energy chains and country groups (OECD, EU 27, non-OECD) is given, considering severe accidents that resulted in at least five fatalities or ten injured persons, although in subsequent analyses the focus is on fatalities only.

Second, severe (≥ 5 fatalities) accidents in fossil energy chains (coal, oil, and natural gas) are analyzed, for which extensive historical data is available in the ENSAD database, including:

a. Investigation of the distribution of accidents across energy chain stages and description of major accident causes to identify chain-specific risks.

b. Calculation of cumulative curves of individual country shares to total numbers of accidents and fatalities to examine country-specific patterns.

c. For each fossil energy chain a country comparison based on the three risk indicators accident rate, fatality rate and maximum consequences of a single accident was performed. For this, principal component analysis (PCA) was used, which has been first introduced by Pearson (1901) and Hotelling (1933), but see Jolliffe (2002) for a detailed overview. In a nutshell, PCA is a mathematical procedure that transforms a set of possibly correlated variables, the so-called principal components (PC). Computations were done with the ADE-4 software (Chessel and Dolédec 1996; Thioulouse et al. 1997).

d. Based on country data, average normalized accident (AR) and fatality (FR) rates (per GWeyr) as well as confidence intervals (5% and 95%) were calculated for OECD and non-OECD countries.

It should be noted that for the analyses in c and d those non-OECD countries were excluded whose AR and/or FR values were at least one order of magnitude higher than the for the other non-OECD countries, i.e. 3 were eliminated for coal, 11 for oil, and 1 for natural gas.

Third, fatality rates and maximum consequences were compared across a broad range of fossil, nuclear, hydropower and new renewable technologies.

Fourth, external costs of severe (≥ 5 fatalities) accidents were estimated for fossil and hydropower chains, and compared to own and other literature values for nuclear. Assumptions for external cost calculation were based on the results of the EU project NewExt (for details see, Burgherr et al., 2004), i.e. EUR 1,045,000 for the value of statistical life (VSL), and degrees of internalization were 0.8 (OECD, EU 27) and 0.5 (non-OECD) for occupational fatalities, vs. 0.5 and 0.2 for public fatalities.

3. Results and discussion

The presentation and discussion of results is divided into four distinct sections, namely (1) the historical experience available in ENSAD, (2) analysis of major fossil energy chains, (3) comparative evaluation of accident risks for fossil, hydropower, nuclear and new renewable technologies and (4) estimation of external costs of severe accidents.

3.1. Current status and content of ENSAD

In total, ENSAD currently comprises 32705 accident records. Of these 83.2% are classified as man-made, 16.3% as natural disasters, and 0.5% as conflicts. Among man-made accidents, 20245 are attributable to the energy sector, and of these 93.8% occurred in the years 1970–2008.

According to ENSAD’s severe accident definition, 3367 accidents resulted in at least 5 fatalities in the years 1970–2008, 968 in at least 10 injured persons, and 515 met both criteria. Tables 1 and 2 provide an overview of severe accidents per energy chain and country grouping for fatalities and injured, respectively.

While ENSAD provides a comprehensive coverage of severe accidents in fossil energy chains, the historical experience for severe accidents in hydropower, particularly for OECD and EU 27, is less pronounced. Therefore, additional information on hypothetical dam failure scenarios is included in Section 3.3. For nuclear energy a more detailed coverage is provided in Section 3.3 including a summary of simplified level-3 PSA results as well as of the three core melt events that took place at nuclear power plants so far. Finally, ENSAD currently does not contain many severe accidents for new renewable technologies.

Table 1

<table>
<thead>
<tr>
<th>Energy Chain</th>
<th>OECD</th>
<th>EU 27</th>
<th>non-OECD</th>
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<tr>
<td></td>
<td>Acc</td>
<td>Fat</td>
<td>Acc</td>
</tr>
<tr>
<td>Coal</td>
<td>87</td>
<td>2259</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>162</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1214</td>
</tr>
<tr>
<td>Oil</td>
<td>187</td>
<td>3495</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>58</td>
<td>1856</td>
<td>358</td>
</tr>
<tr>
<td>Natural gas</td>
<td>109</td>
<td>1258</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>58</td>
<td>1856</td>
<td>14</td>
</tr>
<tr>
<td>LPG</td>
<td>11</td>
<td>116</td>
<td>1</td>
</tr>
<tr>
<td>Hydro</td>
<td>1</td>
<td>1</td>
<td>156</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>Nuclear</td>
<td>–</td>
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<td>–</td>
</tr>
<tr>
<td>Biofuel</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Biogas</td>
<td>–</td>
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<tr>
<td>Geothermal</td>
<td>–</td>
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</table>


b Teton dam failure (USA, 1976).

c Belci dam failure (Romania, 1991).

d First line non-OECD w/o China, second line China.

* Banggiao/Shimanant dam failures (China, 1975) together caused 26,000 fatalities.

* Only immediate fatalities of the Chernobyl accident are shown here. See text for a more detailed discussion of the nuclear chain.
3.2. Major fossil energy chains

In this section the focus is on coal, oil and natural gas energy chains, for which ENSAD comprises extensive historical accident data for the period 1970–2008. In Fig. 2 accidents (left) and fatalities (right) are assigned to different energy chain stages. In the coal chain accidents during mining activities are by far dominating, which is also reflected when looking at fatalities. Overall, gas accidents are the main cause of mining accidents, although for example in China also water hazard leading to mine flooding with a share of 15% is a concern (Burgherr and Hirschberg, 2007). In the oil and gas chains the majority of accidents are attributable to the transport & storage stage. The second and third most common causes are extraction & exploration and refinery processing in the case of oil, and heating & power plant and extraction & exploration for natural gas. Transport accidents in the oil chain predominantly relate to ships and pipelines in long distance transport, whereas in regional and local distribution it is road tankers. For natural gas, pipelines are the major means of transport, except in the case of liquefied natural gas (LNG) that is transported by specially designed ships. A more detailed discussion of accident causes can be found in Burgherr and Hirschberg (2009).

Fig. 3 shows cumulative curves of individual country shares to total accidents (a) and fatalities (b) in fossil energy chains. The coal chain exhibits a clearly different pattern than oil and natural gas, which is due to mining accidents in China that contribute 90%, while all other countries together account for the remaining 10%. Therefore, the Chinese coal chain needs to be analyzed separately (Burgherr and Hirschberg, 2007; Hirschberg et al., 2003). Ukraine, Russia and India are ranked second to fourth, followed by Poland, USA and Turkey as first OECD countries. In contrast, the cumulated accident curves for oil and natural gas show much less extreme distributions than coal. Curves for fatalities show similar patterns, except that for the oil chain the curve shows a steeper increase with already the top three countries making up 50% of all fatalities, whereas for natural gas it is the top five. However, the two curves are then approaching each other, and above the 75th percentile this trend is actually reversed.

The evaluation of country specific patterns in fossil energy chains was based on the three risk indicators accidents per GWeyr, fatalities per GWeyr and maximum consequences of a single accident, using data of the period 1970–2008. The results of principal component analysis (PCA) showing the position of countries on the first two principal component (PC) axes are given in Figs. 4–6.

Fig. 4 shows the positions of individual countries for the coal chain on the PC1 × PC2 factorial map. The first two PC axes accounted for 58% and 34.5%, of the total variation. Both accident (AR) and fatality rates (FR) were negatively related to PC1, with higher AR values on the positive and higher FR values on the negative PC2 half-axis, respectively. PC2 was best explained by maximum consequences, i.e. higher values were attributable to the negative half-axis. Overall, positions of OECD countries form a rather clear cluster, except for Turkey where one very deadly accident in 1992 resulted in 272 fatalities, which is almost three times greater than the second largest. EU 27 countries (see inset) also distinctly cluster with only Romania having a substantially higher FR. Non-OECD countries exhibit a more heterogeneous patterns, with some of them close to the bulk of OECD and EU 27 countries. However, with exception of South Africa and Russia for these countries only few accident data are available, which means that their positioning may rather reflect an underreporting problem than their actual performance. Finally, BRIC countries are clearly divided in two groups, i.e. China and India vs. Brazil and Russia because the former experienced significantly higher maximum consequences, and particularly in the case of China a high FR was observed.

Fig. 5 displays the positions of countries for the oil chain, with PC1 and PC2 explaining 59.5% and 34% of total variation. Accident patterns in fossil energy chains...
and fatality rates are positively related to PC1 with FR on the positive and AR on the negative PC2 half-axis, whereas maximum consequences are related positively to PC2. Similarly to coal, OECD and EU 27 countries show a tighter clustering than non-OECD countries. The non-OECD countries overlapping with the OECD cluster are again those for which only few accident data are available. For the oil chain, BRIC countries group close together with the exception of Brazil. This can again be attributed to a single large accident, i.e. a pipeline explosion and fire in 1984 that destroyed a shanty town southeast of Sao Paulo killing 508 people.

Fig. 6 shows the positions of countries for the natural gas chain on the PC1 × PC2 factorial plane, accounting for 64.4% and 34.4%, respectively. The fatality rate and maximum consequences are positively related to PC1 and PC2, respectively, whereas in the case of the accident rate there is a contribution to both axes although stronger to PC1. The OECD and EU 27 country groups are again rather compact, with one exception each, namely South Korea (single accident with 109 fatalities in 1995) and Greece (high AR and FR). The isolated position of China is primarily due to a very large accident in which a well explosion caused 243 fatalities, whereas in the case of Philippines the reason is again limited data. Non-OECD countries show again more variation for natural gas, however, there is a stronger overlap with OECD and EU 27 than in the case of oil and coal chains, which for most countries is again due to limited accident data.

In a last step, average, normalized accident and fatality rates between OECD and non-OECD countries were compared (Fig. 7). Both rates were clearly lower in OECD for the coal and oil chains, whereas for natural gas only fatality rates differed. For all three chains confidence intervals were much smaller for OECD than
non-OECD countries, indicating that OECD is more homogenous, thus supporting the results of PCA.

3.3. Comparative evaluation

Fig. 8 shows (a) fatality rates and (b) maximum consequences for fossil, nuclear, large hydropower and new renewable technologies in OECD, EU 27 and non-OECD countries. Among fossil chains, natural gas performs best with respect to both metrics. The fatality rate for coal in China is distinctly higher than for the other non-OECD countries (compare also Burgherr and Hirschberg, 2007; Hirschberg et al., 2003). However, a comparison between data for 1994–1999 and 2000–2008 is indicative that China is improving and slowly approaching the non-OECD level.

Among large centralized technologies, modern nuclear and OECD hydropower plants show the lowest fatality rates, but at the same time the consequences of extreme accidents can be very large. Experience with hydropower in OECD countries points to...
very low fatality rates, comparable to the representative PSA-based results obtained for nuclear power plants, whereas in non-OECD countries, dam failures can claim large numbers of victims.

To date, three core-melt events have occurred in nuclear power plants, namely at Three Mile Island 2 (TMI-2, USA, 1979), Chernobyl (Ukraine, 1986), and Fukushima Daiichi (Japan, 2010). At TMI, the collective effective dose to the public was about 40 person-Sv, on the basis of which one extra cancer fatality was estimated. However, 144,000 people were evacuated from the area around the plant. For more information see Hirschberg et al. (1998). The Chernobyl accident resulted in 31 immediate fatalities. PSA-based maximum consequences including expected 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 comprehensive study by numerous United Nations organizations up to 4000 persons could die due to radiation exposure in the most contaminated areas (Chernobyl Forum, 2005). This estimate is substantially lower than the upper limit of the PSI interval, which, however, was not restricted to the most contaminated areas.

Published health effects of the Fukushima Daiichi nuclear accident show large variations, which is partially attributable to different assumptions and methods used. For example, Ten Hoeve and Jacobson (2012b) estimated an additional 130 (range 15–1100)
worldwide cancer related latent fatalities, von Hippel (2011) about 1000, and Beyea et al. (2013) about 600. See also the discussion in Richter, Ten Hoeve and Jacobson, 2012a). In contrast, Vitázková and Cazzoli (2011) reported a much higher value of 10,000, and some rather extreme sensitivity cases up to 300,000 latent fatalities. Finally, the World Health Organization (WHO, 2013) recently published an authoritative report concerning health risks inside and outside Japan.

According to current knowledge, new Generation III reactors are expected to have significantly lower fatality rates than

**Fig. 8.** Comparison of (a) fatality rates (with 5% and 95% confidence intervals) and (b) maximum consequences of a broad selection of energy technologies. Fossil and hydropower is based on the ENSAD database (period 1970–2008); for nuclear a simplified level-3 PSA is applied; and for other renewable sources a hybrid approach using available data, modeling and expert judgment is used. Abbreviations: PWR=pressurized-water reactor; EPR=European Pressurized Reactor; CH=Switzerland; RBMK=reaktor bolshoy moshchnosty kanalny, a boiling watercooled graphite moderated pressure tube type reactor; PV=photovoltaic; CHP=combined heat and power; and EGS=Enhanced Geothermal Systems.
currently operating power plants because of various safety augmenting systems, but maximum consequences could increase due to the much larger radioactive inventory of a 1600 MW EPR, as indicated by the results of a simplified level-3 PSA (Burgherr et al., 2011, 2008; Roth et al., 2009).

As mentioned above historical experience for Hydropower in OECD and EU 27 countries suggest rather limited consequences of 14 and 116 fatalities, respectively. Additional analyses based on empirical and theoretical approaches suggest that a hypothetical dam failure could have much more dramatic consequences in the order of up to 11'000 fatalities assuming zero pre-warning time (Burgherr and Hirschberg, 2005, and references therein). However, this result is strongly dependent on the model chosen and the actual pre-warning time, among various other factors. For example, a sufficient pre-warning time of two hours would reduce fatalities to 2–27. Additionally, potential consequences have to be viewed under consideration of the frequency of occurrence of such an event, which for Swiss dams is in the range $10^{-5}$ to $10^{-4}$ events per dam year (Hirschberg et al., 1998).

All other renewable technologies exhibit distinctly lower fatality rates than fossil chains, and are fully comparable to hydro and nuclear power in highly developed countries. Concerning maximum consequences, those renewable sources clearly outperform all other technologies because their decentralized nature strongly limits their catastrophic potential. However, it should be noted that current analyses of risks associated with new renewables have limited scope and do not include probabilistic modeling of hypothetical accidents. This may have bearing, particularly on results for solar PV. Furthermore, future large-scale storage of intermittent electricity produced by PV, solar-thermal or wind using hydrogen may add another risk component (Dubois et al., 2013) that is not considered in current analyses.

3.4. External cost of centralized technologies

Table 3 shows external costs of fossil energy chains and hydropower in OECD, EU 27 and non-OECD countries for the period 1970–2008, using ENSAD data. The external cost value for nuclear represents a calculation for a Swiss power plant (Hirschberg et al., 1998), whereas estimates for new renewables are restricted to those technologies, for which sufficient data was available.

Among fossil energy chains, OECD and EU 27 countries generally exhibit significantly lower external costs than non-OECD, except for natural gas, where the difference is distinctly less pronounced. For the coal chain, values for China are about one order of magnitude higher than for other non-OECD countries and even two orders of magnitude compared to OECD and EU 27. The value for hydropower in non-OECD is strongly driven by the extremely deadly accident of the Banqiao/Shimantan dam failures (China, 1975) that resulted in 26'000 fatalities. If this accident is excluded then the external cost estimate for non-OECD decreases by about one order of magnitude.

The external costs shown in Table 3 are for immediate fatalities of severe (≥5 fatalities) accidents, however, in the case of nuclear they are dominated by latent fatalities. PSA-based external costs for an accident at a Swiss nuclear power plant have been assessed at 1.02E-3 EUR-cents/kWh (1.2E-3 USD-cents/kWh)1, with 5th and 95th percentiles at 8.88E-5 and 3.24E-3 EUR-cents/kWh, respectively (Hirschberg et al., 1998). It should be noted that these results include radiation-induced health effects that are totally dominated by latent cancer fatalities. Additionally, Hirschberg et al. (1998) used for the value of statistical life (VSL) 4 million USD (3.41 million EUR) compared to the value of 1 million EUR established in the EU project NewExt (Burgherr et al., 2004). Other studies claim significantly higher external costs for nuclear, for example Laes et al. (2011) report 1.04E-2 EUR-cents and Rabl and Rabl (2013) even 3.80E-1 EUR-cents/kWh, both of which are significantly higher values than the Swiss estimate. However, due to differences in methodologies and assumptions, these values are difficult to compare.

Table 3 also provides results for selected new renewables for which external costs could be calculated based on available fatality data in ENSAD. For wind onshore and geothermal estimated values were in the same range as for hydro in OECD countries, whereas biogas was in the same order of magnitude as for natural gas in OECD and EU 27 countries. However, one should also keep in mind that external costs for new renewables are based on currently available experience that is less comprehensive than for large centralized technologies. In contrast to the present study, Rabl and Rabl (2013) report a significantly higher external cost due to accidents for wind augmented by NGCC (natural gas combined cycle) of 4.0E-1 EUR-cents/kWh, and the 4.87E-2 EUR-cents/kWh for wind by Rentizelas and Georgakellos (in press) are also clearly higher. Again it is difficult to establish concrete reasons for these differences, but it seems that these two studies included health impacts from air pollution into their estimates. For example, Larsson et al. (2014) provide a broad overview of external costs quantified in different studies. Although their comparison did not explicitly address external costs from severe fatal accidents, it suggests that external costs from impacts on human health, climate change, and other environmental issues dominate.

Following the Fukushima nuclear power accident the discussion on accident costs has recently been addressed from different viewpoints, including additional aspects such as social and institutional factors, risk targets and threat beliefs (Al Shehhi et al., 2013; Aoki and Rothwell, 2013; Hartmann et al., 2013; Kampanart et al.,

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1 Exchange rate 1 USD = 0.85355 EUR.
4. Conclusions

PSI’s comparative risk assessment approach provides a comprehensive framework for the objective and quantitative evaluation of severe accidents in the energy sector, with the database ENSAD as the core element.

This study demonstrates how accident risks (e.g. in terms of fatalities) can be effectively evaluated for different regional aggregates within the same energy chain and across technologies. Differences among country groups and technologies were explored using various risk indicators representative of technical performance (e.g. accident and fatality rate) and socio-economic impacts (e.g. maximum consequences and external costs).

Among the major centralized technologies, expected accident risks are by far lowest for hydro and nuclear, whereas performance of fossil energy chains is significantly worse. On the other hand the maximum consequences of low-frequency hypothetical severe accidents, representing a measure of risk aversion, are by far highest for nuclear and hydro (provided population density downstream from the dam is high), in the middle range for fossil chains and very small for new renewables, which are currently less sensitive to the issue of severe accidents, although their large-scale utilisation may add new risk aspects such as storage risks to buffer and regulate intermittent production, and geopolitical aspects when large renewable capacities are installed in less stable regions (e.g. North Africa).

External costs of severe accidents are rather insignificant when compared to the effects of global warming and air pollution (Burgherr and Hirschberg, 2008a). Nevertheless consequences of accidents in terms of human health (e.g. fatalities) as well as on the environment and society should not be neglected, since they can have large-scale and long-term impacts (e.g. Deepwater Horizon, Fukushima).

Our analysis of accident risks supports the notion that in addition to decentralized new renewable technologies also centralised, low carbon technologies such as nuclear and CCS could play an essential role towards a more sustainable energy future and the mitigation of climate change effects. However, the major challenge remains to address people’s safety concerns with regard to low-probability high-consequence accidents that are often driven by aspects of risk aversion and public acceptance, i.e. catastrophic leakage of CO₂ storage or a nuclear accident with a large release of radioactivity (NEA, 2012; Torvanger and Meadowcroft, 2011).

In summary, a comprehensive risk assessment across a broad range of energy technologies should consider a set of risk indicators that cover different risk aspects and perspectives. Consequentially no technology performs best or worst in all respects, i.e. trade-offs, compromises and priority setting are necessary to define a consensus energy technology portfolio, which ultimately is a societal decision to which science can provide objective and transparent inputs to foster informed and rational decision making and policy formulation (Bruine de Bruin and Bostrom, 2013).

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