Comparative risk assessment with focus on hydrogen and selected fuel cells: Application to Europe

Matteo Spada*, Peter Burgherr, Pierre Boutinard Rouelle
Laboratory for Energy System Analysis, Paul Scherrer Institut, Villigen PSI, Switzerland

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ABSTRACT
In this study, a first-of-its-kind comparative risk assessment is presented for accidents in the energy sector in EU28 with focus on hydrogen (H2) and selected fuel cells, namely proton exchange membrane (PEM), phosphoric acid (PAFC), alkaline (AFC) and molten carbonate (MCFC) fuel cells. The analysis is based on PSI's well-established framework for comparative risk assessment, using available historical experience from its ENergy-related Severe Accident Database (ENSAD). For H2, the technological risks are first identified and characterized to set up the so-called H2 ENSAD, a subset of ENSAD including historical observations related only to H2 accidents only. Afterwards risk indicators, namely fatality rate and maximum consequence, have been estimated for H2 and selected fuel cells, and then compared to fossil fuels, hydro-power and selected new renewable technologies. H2 and selected fuel cells showed fatality rates lower than natural gas, whereas maximum consequences were similar to other new renewables.

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Introduction
In our modern society, energy is one of the most important prerequisites for the production of goods and services, enabling sustainable industrial, social and economic development. However, the need to reduce green-house gas (GHG) emissions in order to limit global warming to at most 2 °C above pre-industrial levels, calls for a deep decarbonisation of the power sector [1]. Under a sustainable development perspective, technologies related to the energy carriers are thus requested to avoid environmental problems through harmful emissions or other impacts [2].

Hydrogen (H2) is an energy carrier with the potential for a more sustainable supply. Although presently used extensively as a chemical feedstock [2], H2 is considered to be on the rise as possible energy carrier in the future [3–5]. This is related to the fact that it is considered an environment-friendly fuel, since when used in a fuel cell or burned in an internal-combustion engine is mainly producing water vapour although nitrates have also been discovered [6]. Furthermore, it is a versatile energy carrier with potential for extensive use in electricity generation [1,7], for example in fuel cell systems, which are an important technology for converting H2 to power and heat [8]. However, although intimately linked, fuel cells
can also be used with other fuels than H₂, such as for example natural gas [1].

The agreement on an hydrogen based economy between the European Union (EU) and the United States (US) in 2003 [9,10] marked the start of international and national efforts to develop safe and reliable technologies for hydrogen production, storage, transport and consumption. This has been well established in EU, where a variety of projects have been carried out through the Fuel Cells and Hydrogen Joint Undertaking (FCH JU – http://www.fch.europa.eu). FCH JU is a public private partnership whose goals are to accelerate the development and deployment of fuel cells and hydrogen as energy carrier, and to launch them commercially by 2020, providing a relevant contribution to the transition to a low-carbon energy society.

One of the major requirements for commercial application of H₂ and its related technologies is that the safety and reliability of the required infrastructure is investigated, and that the associated risks are not significantly higher than that of existing fuel supplies, such as natural gas, etc. [11]. H₂ has already been used and safely handled for many years in several application areas (e.g. in aerospace technology, chemical processing, food and electronic industries). Furthermore, there have been an increasing number of regulations, standards and codes affecting design, installation, operation and maintenance of H₂ related infrastructures, which have been developed and implemented in the past decades to increase the safety and reliability of H₂ related infrastructures. For example, internationally, the International Organization for Standardization (ISO) introduced the Technical Committee TC 197 for hydrogen technologies in 1990 [12,13], while specifically in EU, directives like equipment for potentially explosive atmospheres (ATEX) or the pressure equipment (PED) have been developed in this context [14]. Nevertheless, hydrogen – as any other energy carrier – is not completely risk free, mainly due to its high flammability and the substantial amount of energy released if it burns or explodes. Furthermore, in comparison to current fossil energy carriers, it introduces different safety and regulatory issues that need to be understood and tackled. Generally, hydrogen-related accidents are not considered rare [9,15,16]. Therefore, H₂ is considered as a potentially unsafe fuel, if not handled with care [16]. As a consequence, it can possibly affect present and future hydrogen-related technologies, like fuel cells [17], power to gas [18], etc., in terms of accident risk in a full chain perspective.

In the past, several studies have focused on various risk and safety aspects of hydrogen and related technologies, such as, the risk and sustainability of hydrogen infrastructures [19], the analysis of hydrogen related accidents [9,15,16,20], the quantitative risk assessment for specific hydrogen related infrastructures [21–23], and hydrogen and fuel cells [24,25]. However, none of these specifically compared H₂ and hydrogen related technologies like fuel cells with other energy carriers (e.g. oil, coal, biomass, etc.).

Therefore, a comparative risk assessment of accidents for a broad range of energy technologies with focus on H₂ and its related technologies is of major interest, using quantitative risk indicators to evaluate their safety performance and to rank the systems under consideration. In fact, accident risks and their various consequences can have important implications on the environmental (e.g. land and water contamination), economic (e.g. property damage, business interruption) and social (e.g. human health impacts) dimensions of sustainability. Furthermore, risk assessment and the calculation of transparent and consistent risk indicators is an essential contribution to support stakeholders in complex decision-making processes to plan, design and establish supply chains that are economic, efficient, reliable, safe, secure, and sustainable. Ultimately a comprehensive approach is required that combines and evaluates all considerations using a systemic perspective to find broadly accepted solutions that best meet the often-conflicting objectives and expectations of different stakeholders (e.g. industry, investors, authorities, etc.).

The current study presents a first-of-its-kind comparative risk assessment of energy-related accidents in the European Union with a focus on H₂ and fuel cell systems. This analysis considers only these stationary type fuel cells: proton exchange membrane (PEM) [26], phosphoric acid (PAFC) [27], alkaline (AFC) [28] and molten carbonate (MCFC) [29] fuel cells. The selection has been based on the level of technology maturity and the present use or potential future use of them as stationary systems [1,2,24,30–33]. Furthermore, only stationary systems have been considered to build a reasonable comparison with other centralized and decentralized energy systems, such as fossil, hydro and new renewable technologies.

The comparative risk assessment presented here is based on PSI’s well-established methodological framework. For fossil chains, and to a lesser extent for hydropower and wind, extensive historical experience is available in PSI’s Energy-related Severe Accident Database (ENSAD) starting from 1970. In contrast, for the other new renewables a combination of available data, modelling and expert judgment is needed. Generally, full energy chains are considered, since accidents do not just take place during the actual production phase [34].

In this study, the so-called H₂ ENSAD, a subset of ENSAD including historical observations related to H₂ accidents only, has first been set up based on historical observations and an extensive literature review (Section Data). Afterwards risk indicators, namely fatality rate and maximum consequence, were estimated using an historical approach, similar to [34], for H₂ and selected fuel cell systems (Section Comparative Risk Assessment). For the latter, indicators have been estimated based on the used fuel only, since it has been shown to be the most significant source of accident risk for these systems [24]. Finally, the risk indicators for H₂ and the fuel cell systems have been compared against fossil fuel alternatives, hydropower and selected new renewables technologies adapted from Ref. [34] for the EU28 country group (Section Results & Discussion).

Data

The ENergy-related Severe Accident Database (ENSAD)

The ENergy-related Severe Accident Database (ENSAD) was first established in the 1990s at the Paul Scherrer Institute (PSI) to close the gap related to the lack of specific databases collecting energy-related accidents, since till then this information was mainly included in general industrial databases only [35]. ENSAD comprehensively collects information about
accidents in all energy chains since 1970 that are attributable to fossil, nuclear, hydropower and, more recently, new renewables technologies [36]. Since its first release, ENSAD has been continuously updated with new information from different sources, such as specialized databases, technical reports, journal papers, books, etc. In contrast to databases that rely on a single or few information sources, the multitude of sources considered by ENSAD is thoroughly verified, harmonized, and merged to ensure consistent and high quality data [34,35,37].

In ENSAD, data about accidents and related consequences (e.g., human health effects, impacts on environment or economy) are collected and classified into energy chains and activities within those chains, since accidents do not only occur at the actual power generation step [34]. In general, an energy chain may comprise the following stages: exploration, extraction, processing and storage, transport, power and/or heat generation, waste treatment, and disposal. However, not all these stages are applicable to every energy chain.

Accident information in ENSAD is structured and recorded in different data-fields that can be assigned to four main blocks: general information (e.g., date, location, infrastructure type, energy chain, chain stage), accident information (e.g., cause, event chain, consequences), infrastructure information (e.g., infrastructure name, type, purpose, dimensions), and additional information specific for a particular energy chain. For accidents with information from multiple sources the consequences (e.g., fatalities, injured, economic loss, etc.) are linked to the other information through a 1:n relation to ensure that potential differences in consequences between sources can be tracked [38].

In the literature no common definition of severe accident exists, and also other terms such as major, catastrophic, etc. are used [34]. ENSAD focuses on severe accidents since most stakeholders including industry, authorities, NGOs as well as the general public and the media are more concerned about them. However, accidents with minor consequences (e.g., 1–4 fatalities) are also collected in ENSAD, and analyzed depending on the specific scope and objectives of a study [39]. Generally, a higher level of completeness is expected for severe accidents compared to small ones, since a more consistent reporting among countries can be assured. In ENSAD whenever one or more of the following seven consequence thresholds is met, an accident is considered to be severe:

- at least 5 fatalities or
- at least 10 injuries or
- at least 200 evacuees or
- an extensive ban on consumption of food
- a release of hydrocarbons exceeding 10,000 metric tonnes
- an enforced clean-up of land and water over an area of at least 25 km² or
- an economic loss of at least 5 million USD (2000)

The H₂ energy-chain for ENSAD

Following the general structure of ENSAD (Section The ENergy-related Severe Accident Database (ENSAD)), in this study a dedicated H₂ energy chain has been developed and implemented as a subpart of ENSAD. In the first step, following [40], the different chain stages belonging to the H₂ energy chain have been defined.

The first chain stage for H₂ is defined as the Production stage, since hydrogen must be industrially produced from various primary or secondary energy sources, depending on regional availability [41]. Primary energy sources useful for hydrogen production comprise renewable sources (e.g., biomass) as well as fossil fuels (e.g. natural gas and coal). Industrial production is presently mainly from steam reforming of natural gas, or less often from more energy-intensive methods, such as the electrolysis of water [42]. For the H₂ chain the second stage is defined as the Transport stage, which collects all types of accidents related to the transportation phase, for example due to a road accident of a hydrogen transportation truck, the phase of loading/unloading of hydrogen from a truck/rail wagon/ship/etc., due to a pipeline failure, etc. The third stage is defined as the Storage stage, which collects accidents related to the storage of hydrogen. Finally, the last stages defined for the H₂ energy chain in this study are the Direct Use, which refers to accidents related to the direct use of H₂ for electricity/heat production, and Other End Use, which refers to accidents related to other uses of H₂. In the latter case, not all accidents related to H₂ have been considered. In fact, only those that can be considered equivalent to the production of electricity or heat, namely hydrogenation and H₂ cooling, have been included, while others have been omitted, such as H₂ use in laboratory or desulfurization in refineries.

Overall, the H₂ energy chain for ENSAD is subdivided in 4 stages: Production, Transport, Storage and Use, which includes both Direct Use and Other End Use stages as defined before (Fig. 1).

Data collection

Accident data for the H₂ energy chain have been collected from different commercial and non-commercial information sources. In particular, accidents in Europe for the period 1995–2014 are considered in this study. The starting year of 1995, rather than 1970, has been chosen because H₂ is a relatively new technology when compared to large centralized generation options, and 1995 is also the year from which the production of H₂ in Europe is not comprehensively reported [43]. Furthermore, 2014 has been chosen as the end year, since there is often a delay until final, consolidated accident reports are available, particularly from sources that are only periodically updated.

Furthermore, only H₂ related accidents were considered for which hydrogen was the primary triggering event. In this way, accidents triggered by other materials, but subsequently involving H₂, are excluded. Finally, all accidents that resulted in at least one consequence (e.g., 1 fatality or 1 injury, etc.) were considered.

Table 1 provides an overview of the most important information sources that were used to build H₂ ENSAD. In addition to the listed industrial databases, other sources such as online resources (e.g., news portals, newspapers, magazines, etc.), technical reports, etc., were surveyed.

Once all sources were screened and the historical observations collected, the raw accident information was then
further processed to generate the final dataset for analysis. In particular:

- Accident records were verified, cross-checked and homogenized,
- Accidents not considered relevant for the H2 Energy chain were removed manually, and
- Accident subsets for different types of consequences were prepared.

The final dataset contains a total of 43 accidents attributable to the H2 energy chain for the period 1995–2014 in the EU28 country group. As shown in Table 2, most of the accidents caused at least 1 injury, while 10 of them resulted in evacuees and 8 in property damages or fatalities. Furthermore, only for 4 accidents a release of hydrogen was reported. Most of the accidents causing at least 1 fatality or 1 injury or 1 evacuee happened during the transport chain stage, while for release the number of accidents is shared among transport and storage. Finally, most of the accidents with property damages collected in this study happened in the production phase.

**Overview of H2 accidents in Europe**

In this section, an overview of the collected data for accidents attributable to the H2 energy chain in Europe is given for the period 1995–2014. In Fig. 2a the annual number of accidents in EU countries involving H2 and causing at least one consequence (e.g., 1 fatality or 1 injury, etc.) is shown. The collected accidents result in an average of ~2.2 accidents per year. Furthermore, the annual data can be roughly subdivided into a phase from 1995 to 2004 with an average of ~1.7 and a phase from 2005 to 2014 with an average of ~2.6. However, although H2 production in the EU28 during the period 1995–2014 has constantly increased, the normalized number of accidents per H2 production roughly shows two different patterns: a general decreasing trend up to 2004, followed by no trend, i.e., generally stable normalized number of accidents, in the period 2004–2014 (Fig. 2b).

Most of the collected accidents happened due to Man-Made (52%) and Technological (41%), distantly followed by Natural (5%) causes (Fig. 3a). Man-made accidents are due to anthropogenic causes, such as human errors, lack of maintenance, etc., Technological accidents refer to structural failures, such as mechanical failures, pump failures, etc., while the Natural category covers accidents triggered by natural hazards, such as heavy rain, floods, earthquakes, etc. Finally, one of the collected accidents could not be assigned to any of the three cause categories due to lack of information. Fig. 3b depicts the percentage shares of accidents by chain stages. Almost half of the collected accidents occurred in the Transport stage, followed by the Production, Storage and Use stages. This is in accordance with other energy chains, such as for example natural gas, where it has been shown that the transport stage is most prone to accidents [39]. Furthermore, this accumulation of transport accidents can be expected, since an accident during this phase can cause explosions and fire due to the high flammability of hydrogen.

**Comparative risk assessment**

**Overview on comparative risk assessment**

In general, there is no agreed definition of the term risk [44]; however, in engineering and natural sciences, risk (R) is commonly expressed as the product of the frequency of an event (f) and the severity of the resulting consequences (S) [45].

\[
R = f \times S
\]

The number of accidents per year gives the frequency, while severity measures the extent of the consequences of each accident. Measures for the severity of consequences of accidents are for example the number of fatalities, the amount of financial losses (e.g. insured loss, business interruption, total loss) or the amount of the released substance in tonnes, kg, etc.

In this study, the accident risk of energy chains is assessed by using the standard historical-based approach to estimate aggregated risk indicators (e.g., fatality rates). Aggregated and normalized risk indicators allow a straightforward comparison between energy chains and country groups [34]. However, it is important to consider a variety of risk factors (e.g. average vs. extreme risk) and types of consequences (e.g. fatalities,
<table>
<thead>
<tr>
<th>Source</th>
<th>Provider</th>
<th>Observation period</th>
<th>Number of observations</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis, Research and Information on Accidents (ARIA) [51]</td>
<td>The French Ministry of Ecology and Sustainable Development</td>
<td>1992-Now</td>
<td>40,000</td>
<td>This database contains a list of incidents that have produced or have the potential to produce an impact on the public such as damage to human health or public safety. There is a dominance of accidents that occurred in France, but some important foreign accidents are also registered.</td>
</tr>
<tr>
<td>The Failure and Accidents Technical Information System (FACTS) [52]</td>
<td>Unified Industrial &amp; Harbour Fire Department</td>
<td>Last 90 years</td>
<td>25,200</td>
<td>This database includes both accidents causing severe damage or danger and near misses, which involved hazardous materials or dangerous goods that have happened all over the world. Detailed information is available for the most serious accidents; most of it electronically. This data based was discontinued, but partially continued by OSH Update. It contains accidents involving hazardous substances from 95 countries around the world, especially the USA, the UK, Canada, Germany, France and India, which resulted in or had the potential to produce an offsite impact.</td>
</tr>
<tr>
<td>Major Hazard Incident Data Service (MHIDAS)</td>
<td>Major Hazards Assessment Unit of the United Kingdom Health and Safety Executive.</td>
<td>NA</td>
<td>~10,000</td>
<td>This data based was discontinued, but partially continued by OSH Update. It contains information on occupational health and safety issues. In this study two out of the 26 databases, namely HSELINE and MHAID (Major Hazards Accidents and Incidents), are used.</td>
</tr>
<tr>
<td>OSH Update + Fire [16]</td>
<td>Collection of 26 databases</td>
<td>Depending on the database</td>
<td>NA</td>
<td>This database provides a collection of 26 databases, namely HSELINE and MHAID (Major Hazards Accidents and Incidents), are used.</td>
</tr>
<tr>
<td>Major Accidents Reporting System (eMARS) [53]</td>
<td>the Major Accident and Hazards Bureau (MAHB) of the European Commission's Joint Research Centre</td>
<td>NA</td>
<td>NA</td>
<td>First established by the EU’s Seveso Directive 82/501/EEC in 1982 and has remained in place with subsequent revisions to the Seveso Directive in effect today. The purpose of the eMARS is to facilitate the exchange of lessons learned from accidents and near misses involving dangerous substances from EU, OECD and UNECE countries, to improve chemical accident prevention and mitigation of potential consequences.</td>
</tr>
<tr>
<td>Hydrogen Incidents and Accidents Database (HIAD) [5]</td>
<td>European Commission Joint Research Centre (JRC)</td>
<td>1978-Now</td>
<td>NA</td>
<td>It is an international open communication platform collecting systematic data on hydrogen-related undesired events (incidents or accidents).</td>
</tr>
<tr>
<td>Hazard Intelligence (HINT)</td>
<td>Ility Engineering</td>
<td>2000–2014</td>
<td></td>
<td>It was an international journal of hazardous incidents that have occurred in the chemical and related industries. The incidents reported in HINT were gathered by a network of local correspondents and by a meta-search engine developed for Ility Engineering. The journal ceased to exist in 2014.</td>
</tr>
</tbody>
</table>
injuries, etc.) because no single aspect or indicator can provide the full picture [34]. In this context, fatality rate and maximum consequences (fatalities) have been chosen, since it has been shown to be a good combination in order to assess the risk of accidents in the energy sector. The fatality rate provides a measure of expected fatalities per unit of energy produced, whereas the maximum consequences expressed as the maximum number of fatalities observed in a single accident of

<table>
<thead>
<tr>
<th>H₂ for EU28</th>
<th>Accidents/fatalities</th>
<th>Accidents/injuries</th>
<th>Accidents/evacuees</th>
<th>Accident/release (kg)</th>
<th>Accidents/property damages (Euro 2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>1/1</td>
<td>12/55</td>
<td>1/2</td>
<td>0/0</td>
<td>5/4417520</td>
</tr>
<tr>
<td>Transport</td>
<td>4/22</td>
<td>13/119</td>
<td>7/4195</td>
<td>2/328</td>
<td>2/4048980</td>
</tr>
<tr>
<td>Storage</td>
<td>1/2</td>
<td>9/46</td>
<td>1/100</td>
<td>2/2527</td>
<td>0/0</td>
</tr>
<tr>
<td>Use</td>
<td>2/2</td>
<td>5/14</td>
<td>1/60</td>
<td>0/0</td>
<td>2/1761292</td>
</tr>
<tr>
<td>Total</td>
<td>8/27</td>
<td>39/234</td>
<td>10/4357</td>
<td>4/2855</td>
<td>9/10227792</td>
</tr>
</tbody>
</table>

Fig. 2 – a) Number of accidents per year collected for H₂ in the European Union (EU28) in the period 1995–2014. b) Cumulative normalized number of accidents per H₂ production in EU28 and H₂ production in EU28 for the period 1995–2014.
a certain energy chain can be seen as a measure of risk aversion. The latter plays an important role in risk management for different stakeholders. According to Thomas it is “a measure of the feeling guiding the person who faces a decision with uncertain outcomes” [46]. Finally, fatalities have been considered as severity indicator, since they generally comprise the most reliable consequence indicator with regard to completeness and accuracy of the data [47].

In this study, to be comparable with previous studies, the fatality rate risk indicator is normalized to the unit of Gigawatt-electric-year (GWeyr) [34]. This is commonly chosen as normalization factor because large individual plants have capacities in the neighbourhood of 1 GW of electrical output (GWe). This makes the GWeyr a natural unit to use when presenting normalized indicators generated within technology assessment. Additionally, based on [34], in this study confidence intervals (5% and 95%) are constructed for the fatality rate using a Chi-square distribution in order to take into account possible random fluctuations, for example, due to the lack of data.

**Risk indicators for the H2 energy chains**

For the calculation of the H2 energy chain fatality rate and maximum consequence indicators for comparative purposes, only severe accidents were considered. This is related to the fact that these risk indicators for the other energy chains, i.e., fossilis, hydro and selected new renewables, considered in this study, have been specifically assessed for severe accidents according to the ENSAD definition [34]. Table 3 shows a summary of the severe accident information for the H2 chain that is extracted from the data collected in this study.

For the H2 energy chain in the EU28 country group, the total number of fatalities used for the estimation of the fatality rate resulted to be 20 for a total of 2 accidents over the period of interest. This means an average of 10 fatalities per accident. Furthermore, the maximum number of fatalities recorded for a single event is 14. Finally, to estimate the fatality rate, the total production in GWeyr is needed (Section Overview on comparative risk assessment). In this study, confidence intervals (5% and 95%) are constructed for the fatality rate using a Chi-square distribution in order to take into account possible random fluctuations, for example, due to the lack of data.

**Overview on the selected fuel cells for comparative assessment**

Fuel cells are flexible, modular systems that convert chemical energy directly into electricity without combustion by electrochemically combining oxygen from air with hydrogen. Although some systems are designed to produce electricity only, the most common stationary application is combined heat and power (CHP), which increases the overall efficiency of the system [32]. Furthermore, in the case of stationary systems, hydrogen is not the only fuel that can power fuel cells. In fact, natural gas is the most widely used for CHP type fuel cells, along with Liquefied Petroleum Gas (LPG) and biogas.

Fuel cells are often classified based on their operating temperature, i.e., low- (60–250 °C) and high-temperature (600–1000 °C), and the electrolyte utilized. Common types of low-temperature fuel cells include proton exchange membrane (PEM), phosphoric acid (PAFC) and alkaline (AFC) fuel cells, while molten carbonate (MCFC) fuel cells are commonly used for the high temperature range [2].

In this study, four types of stationary fuel cells are considered for comparative risk assessment purposes, which are summarized in Table 4.

**Risk indicators estimation for PEM, PAFC, AFC and MCFC fuel cells**

As for H2, the fatality rate and maximum consequence indicators for the fuel cells are calculated for severe accidents only.

For fuel cells fuelled by hydrogen (PEM, PAFC and AFC), the data for their respective risk calculations are extracted from the H2 chain analysis developed in this study. Furthermore, only accidents related to production, transport by pipelines, storage and use of hydrogen are considered. This follows the holistic concept behind the comparative risk assessment developed at PSI in which a full-chain approach is taken into account for each energy technology [34]. Similarly, for the natural gas fuelled MCFC only accidents in the period 1995–2014 in EU28 related to the production, transport by pipelines, storage and use of natural gas are considered from ENSAD [38]. Table 5 shows a summary of the severe accident information used in this study for the calculation of the risk indicators of the selected fuel cells.

For H2 fuelled fuel cells only one severe accident with 6 fatalities is used for the estimation of risk indicators in EU28 in the period 1995–2014. For natural gas in the EU28 country group (1995–2014), a total number of 11 accidents with cumulated 115 fatalities are used, and the maximum number of fatalities recorded in the worst single event is 21.

As for H2, fuel cell risk indicators are normalized to GWeyr (section Overview on comparative risk assessment). In this context, since no accidents related to any fuel cell system are found, all consequences collected from accidents in other industries can be allocated to the respective fuel cells. Therefore, to overcome this issue, the fatality rate risk indicator is weighted by the share of material used by the system.
during its lifetime with respect to the total production over the period of interest (1990–2014). Based on this premise, the normalization factor is given by the following equation:

\[
NF = \frac{\text{total fuel use over system life (kg)}}{\text{total production 1995–2014 (kg)}} \times \frac{1}{P_{\text{GWe}}}
\]  

(3)

where NF is the normalization factor for the fuel of interest, and \( P_{\text{GWe}} \) is the net production over the entire lifetime of the system. Based on Eq. (2), the total fuel use over system life can be estimated for each fuel cell as follow:

\[
\text{total fuel use over system life (kg)} = \frac{\text{Capacity (kWe) \times 365 \times 24 \times \text{Lifetime}}}{ce \times P_{\text{Energy}} \times 8.76e9}
\]  

(4)

where 8.76e9 is used to convert kWh in GWeyr. By combining Eqs. (3) and (4), the normalization factor is finally given by:

\[
NF = \frac{1}{ce \times P_{\text{Energy}} \times \text{total production 1995–2014 (kg)}}
\]  

(5)

where the parameters used in this equation are summarized in Table 6 for each fuel cell.

Similar to Eq. (2), the inverse of the normalization factor (1/NF) gives the production in GWeyr for each of the selected fuel cells. The corresponding values for PEM, PAFC, AFC and MCFC are 467, 337, 561 and 3816 GWeyr, respectively.

Results & discussion

In this section, results of the comparative risk assessment for the EU28 country group are presented for the two risk indicators fatality rate and maximum consequence. These two risk indicators are estimated for the H2 energy chain and the four fuel cell systems, while for fossil, hydropower and selected new renewables technologies they are adapted from Ref. [34]. Indicator values for hydropower are based on the OECD instead of the EU28 country group. The reason for this is that for the chosen period the former is generally considered more representative and thus also a valid proxy for EU28.

Fatality rate comparison

Fig. 4 shows expected fatality rates, including the confidence interval 5–95%, for the H2 energy chain and the selected fuel cell systems (PEM, PAFC, AFC and MCFC) for EU28. The figure also provides a comparison with fossil, hydro (OECD) and new renewables technologies.

The fossil energy chains, i.e. coal, oil and natural gas, have the highest fatality rates, which is in accordance with previous studies by the authors [34]. The extensive historical accident data that is available for these technologies is also reflected in the rather narrow confidence intervals. Additionally, this is also an indication that these fully mature
technologies relatively little improvement in terms of accident risk can be expected on a short to medium time horizon.

The H2 energy chain performs better than natural gas and MCFC, followed by PAFC, PEM and AFC fuel cells, which comparable to CHP Biogas. The difference among fuel cells is strongly related to the dependence of the fatality rate to the type of fuel used on the selected fuel cells, i.e. natural gas for MCFC and H2 for the others, and to the electrical efficiency (Table 6). Although fuel cell research can be tracked back to the 1950s (e.g. Tom Grubb’s work for General Electric on PEM fuel cells), fuel cell systems are still considered to be at a rather early stage of commercialisation and large-scale deployment. Therefore, the much wider confidence intervals represent both the scarce accident records and the still low production in GWeyr. The smaller confidence interval for MCFC is attributable to the significantly higher electricity production (in GWeyr) than for the other fuel cell systems (see section Risk indicators estimation for PEM, PAFC, AFC and MCFC fuel cells). Furthermore, the larger confidence intervals of H2 fuelled fuel cells could be interpreted as a significant potential for future improvements that likely leads to further reductions in fatality rates as indicated by the 5% percentile of the confidence intervals, whereas a development trajectory towards higher fatality rates (95% percentile) appears rather unlikely as it would imply no technological learning. Finally, the smaller confidence interval for the H2 energy chain compared to the one for the H2 fuelled fuel cells is related to the fact that H2 is considered more mature because, particularly for the production, transport and storage stages, it can benefit from the long-standing industrial experience from other sectors.

Among the remaining technologies, photovoltaic (PV) performs best, and it also has the lowest fatality rate of all considered alternatives, almost three orders of magnitude lower than coal. The next best performers were Hydro (OECD), Wind Onshore (Germany) and Deep Geothermal Energy (DGE) with quite similar fatality rates, and then Wind Offshore (UK). Hydro is clearly the most mature technology together with fossil technologies and wind onshore benefits from a strong growth in installed units and capacity over the past two decades. For PV, the current analysis needs to be extended to include a confidence interval estimate. Wind Offshore is still less mature than Wind Onshore and thus future learning could potentially reduce both the fatality rate and associated

Table 6 – Parameter considered for the calculation of the normalization factor for each fuel cell considered in this study.

<table>
<thead>
<tr>
<th>Fuel cell</th>
<th>Capacity (MWe)</th>
<th>Lifetime (year)</th>
<th>Electrical efficiency in % (ce)</th>
<th>Energy density in GWeyr/kg ((\rho_{\text{energy}}))</th>
<th>Total production of the fuel 1995–2014 (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEM(^a)</td>
<td>1</td>
<td>20</td>
<td>50</td>
<td>3.8E-9</td>
<td>2.46E+11</td>
</tr>
<tr>
<td>PAFC(^b)</td>
<td>1</td>
<td>20</td>
<td>36</td>
<td>3.8E-9</td>
<td>2.46E+11</td>
</tr>
<tr>
<td>AFC(^c)</td>
<td>1</td>
<td>20</td>
<td>60</td>
<td>3.8E-9</td>
<td>2.46E+11</td>
</tr>
<tr>
<td>MCFC(^d)</td>
<td>1</td>
<td>12.5</td>
<td>60</td>
<td>1.8E-9</td>
<td>1.99E+12</td>
</tr>
</tbody>
</table>

\(^a\) Fuel cell using hydrogen.
\(^b\) Fuel cell using natural gas.
\(^c\) [54].
\(^d\) [55].
confidence interval, although one should keep in mind that the harsh environmental conditions pose a similar challenge as for offshore oil and gas installations. Finally, DGE is a clearly emerging technology and most ongoing activities concern pilot and R&D projects, thus the current estimates should be considered with some caution.

**Maximum consequences**

In Fig. 5 the maximum consequences, in terms of fatalities, are shown for the same set of technologies as in Fig. 4. Fossil energy chains have the largest maximum consequences; however, the value for Oil is about a factor 2.5 higher than for Coal, and there is a similar difference from Coal to Natural Gas. The MCFC fuel cell is performing slightly better than Natural gas, followed by the H₂ energy chain and Hydro (OECD), which have slightly higher maximum consequences than CHP Biogas and Wind Offshore (UK). The overall lowest maximum consequences are found for PV and Wind Onshore (Germany), followed by the selected fuel cell systems fuelled by H₂, suggesting they are generally less prone towards extreme events.

The highest maximum consequence values for fossil energy chains stem from the fact that these accidents happened at installations with many workers or public locations with many people. In the case of Hydro (OECD), the worst historical accident point towards rather limited consequences; however, additional analyses based on empirical and theoretical approaches suggest that a hypothetical dam failure could have much more dramatic consequences [34]. Finally, it should be noted that current analyses associated with new renewables have limited scope, since they do not consider probabilistic modelling of potential low-probability high-consequence, hypothetical accidents. The same reservation also applies to the H₂ energy chain and fuel cell systems. Despite these potential uncertainties in maximum consequence estimates, accidents with large numbers of fatalities are less likely for new renewable, hydrogen and fuel cell technologies due to their decentralized nature.

**Conclusions**

In this study, a comparative risk assessment of energy-related accidents with focus on the H₂ energy chain and selected fuel cell systems, namely proton exchange membrane (PEM), phosphoric acid (PAFC), alkaline (AFC) and molten carbonate (MCFC) fuel cells, is presented. In a first step, the technological risks of H₂ were identified and characterized to set up a so-called H₂ energy chain. Then, historical accidents relevant for the H₂ chain were collected and added as a separate subpart to PSI’s ENSAD. Lastly, PSI’s established framework for comparative risk assessment was used to comprehensively evaluate accident risks in EU28 for the H₂ energy chain and fuel cell systems, and to compare them with fossil, hydro and new renewable technologies. In this way, a consistent set of risk indicators can be provided, which is necessary to support decision-making processes of authorities, industry and other stakeholders with transparent and unbiased facts.

The H₂ chain developed for PSI’s ENSAD roughly shows two different patterns of the normalized number of accidents per H₂ production in EU. In the period 1995–2003 the normalized number of accidents decreases, followed by a stable period from 2004 to 2014. This indicates that the increasing number of regulations, standards and codes that have been developed and implemented in EU in the past decades increased the safety and reliability of H₂ related infrastructures. However, this also suggests that improvements in safety measurements...
are still needed to avoid potential consequences. In particular, in the transportation sector in which most of the accidents happened in the past. Furthermore, man-made related issues have been shown to be one of most important triggers of accidents in the past, showing the need of safety improvements by focusing on management of operator errors.

In this study, two accident risk indicators were quantified, namely fatality rate and maximum consequences. Overall, the fatality rates for the H₂ energy chain and the fuel cell systems were lower than for natural gas, but higher than for hydro and for most of the selected new renewable technologies, excluding CHP Biogas, which is comparable with H₂ fuelled fuel cells. The relatively large confidence intervals for fuel cell systems are an indication of the potential for future reductions in fatality rates due to technological learning and large-scale deployment. In contrast, maximum consequences for the H₂ chain and fuel cell systems were similarly low as for hydro and the other new renewable technologies, implying that they are substantially less prone to high-consequence events than fossil energy chains. Furthermore, these results suggest that improvements of safety procedures and standards should rather focus on the level of ‘every day’ or operational risk aspects in the handling of H₂ and fuel cell systems, whereas for fossil and hydro chains accidents with potentially large consequences are the major concern.

Future research should focus on different topics. These could be to further improve the quality of accident data, increase the number of relevant historical observations, and analysing other country groups (e.g., OECD and non-OECD countries) to get a better and more robust understanding of the various risk aspects. An analysis focusing on the Storage and End-Use stages of the H₂ supply chain will also be beneficial to increasing the understanding of overall risk in the fuel cell sector. Furthermore, a more comprehensive analysis of the potential risks associated with different types of fuel cells is needed. This would acknowledge that different fuel cell technologies have widely ranging operating parameters and conditions, potentially affecting the risk levels associated with them. Whereas MCFC require high temperatures and pressures with the commensurate material fatigue and compromised longevity, for example AFC are low temperature and pressure with moderate material requirements. As holistic energy storage systems are currently the focus of the power industry, an analysis focusing on gas-to-power, power-to-gas, integration with renewable energy systems and combinations thereof would be of great interest for different stakeholders. Finally, a systematic and exhaustive treatment of uncertainties should be considered in the assessment of risk indicators, since uncertainty is a combination, among others, of epistemic and aleatory factors [50].

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