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Comparative Accident Risk Assessment of Energy System Technologies for the Energy Transition in OECD Countries

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This study presents a comparative accident risk assessment for different energy technologies, e.g., fossil fuels (incl. CCUS), Hydropower, H2, Nuclear, and new renewables, in the Organization for Economic Co-operation and Development (OECD) countries. The quantitative analysis is based on the historical observations collected in the Paul Scherrer Institute (PSI)'s ENergy-related Severe Accident Database (ENSAD) and updated using different sources, for the period 1970-2020, whereas for Nuclear a simplified level-3 Probabilistic Safety Assessment (PSA) is applied. Furthermore, for each energy technology, risk indicators, e.g., fatality rate and maximum consequences, are estimated to allow for comparison. Generally, fatality rates for Nuclear, Hydrogen, Hydropower and new renewables perform better than the fossil energy chains. In contrast, maximum consequences can be far highest for Nuclear, intermediate for fossil and Hydropower, and lowest for new renewables, which are less prone to severe accidents. Overall, no technology performs best or worst in all respects, thus trade-offs and priorities are needed to balance the conflicting objectives such as energy security, sustainability, and risk aversion to support rationale decision making.

Keywords: Risk Assessment, Energy-Related Severe Accident Database (ENSAD), Fossil Fuels, Renewable Energy Systems, OECD.

1. Introduction

In our modern society, energy is one of the most important prerequisites to produce goods and services, enabling sustainable industrial, social, and economic development. However, the need to reduce greenhouse gas (GHG) emissions to limit the global rise in temperatures to 1.5°C above pre-industrial levels, calls for a deep decarbonization of the power sector (IPCC 2018). Under a sustainable development perspective, different technologies, such as, for example, Solar Photovoltaic (PV), Wind, Hydrogen (H2) as energy carrier, Deep Geothermal Energy (DGE), Biomass, Carbon-capture, Utilisation and Sequestration (CCUS), and so on, are thus requested to avoid environmental problems through harmful emissions and other impacts.

In the broader context of the energy transition and the goal to decarbonize electricity and heat production, it is of major interest to have a comparative perspective of risk related to accidents for a broad range of energy technologies. This is useful in evaluating safety performances of technologies, but it is also essential to support stakeholders in complex decision-making processes to plan, design and establish supply chains that are economic, efficient, reliable, safe, secure, resilient, and sustainable (e.g., Volkart et al. 2016).

Accidents in the energy sector can occur because of the exposure of people and their socio-economic activities to technological failures, human errors, natural events, and intentional attacks (e.g., Burgherr and Hirschberg 2014). In the past, comparative accident risk in the energy sector has been assessed based on the estimation of risk indicators, i.e., fatality rate and maximum consequences, calculated using historical data for fossil energy chains (e.g., Burgherr and Hirschberg 2014), Hydropower (e.g., Kalinina et al. 2016), and only to some extent to new renewables (e.g., Sovacool et al. 2016). Furthermore, the last comparative accident risk assessments known by the authors do not consider a comprehensive set of energy technologies, but rather focusing on a restrict set of them (e.g., Burgherr and Hirschberg (2014); Sovacool et al. (2015); Boccard (2018))

Based on these premises, in this study a comparative accident risk assessment based on historical observations for different energy technologies, e.g., fossil fuels (incl. CCUS), Hydropower, H2, and new renewables, is presented for the Organization for Economic Co-operation and Development (OECD) countries. In particular, the current analysis is based on the historical observations collected in PSI's ENergy-related Severe Accident Database (ENSAD) and updated using different sources, for the period 1970-2020 (Kim et al. 2019). In contrast, for Nuclear, previous estimations based on a simplified level-3 Probabilistic Safety Assessment (PSA) are considered (e.g., Burgherr and Hirschberg 2014). Furthermore, for each energy technology, risk indicators, e.g., fatality rate and maximum consequences, are estimated to allow for comparison.

The remainder of this paper is structured as follows. First, an overview is presented of ENSAD and the collected historical observations for each considered energy technology (section 2). Afterwards, the method implemented in this study to estimate the risk indicators is described (section 3). In section 4, the comparative accident risk assessment for the considered energy technologies is shown and discussed. Finally, in section 5, the conclusions of the study are drawn.

2. Data

2.1 Overview on 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 included in general industrial databases only (e.g., Hirschberg et al. 1998). ENSAD comprehensively collects information about accidents in all energy chains since 1970 that are attributable to fossil, hydropower and, more recently, new renewables technologies (e.g., Kim et al. 2019).

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 (e.g., Burgherr and Hirschberg 2014).

Recently, a new version of ENSAD, the ENSAD v2.0, has been released (e.g., Kim et al. 2019). In contrast to the old MS Access ENSAD, ENSAD v2.0 is a spatial database with comprehensive GIS functionality, running on a Platform as a Service (PaaS) cloud environment, which comprises accidents for different energy chains in the period 1970-2016 (www.ensad.ch).

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 (e.g., Burgherr and Hirschberg 2014).

In the literature no common definition of severe accident exists. ENSAD focuses on severe accidents since industries, stakeholders, decision-makers, etc., are more concerned about them, although accidents with minor consequences (e.g., < 5 fatalities) have been collected and analyzed when needed (e.g., Spada et al. 2018). In ENSAD whenever one or more of seven consequence types (e.g., ≥ 5 fatalities, ≥ 10 injuries, etc.) is met, an accident is considered to be severe (e.g., Burgherr and Hirschberg 2014).

In this study, fatalities are considered as severity risk indicator. In fact, they generally comprise the most reliable indicator regarding completeness and accuracy of the data (e.g., Burgherr and Hirschberg 2014).

2.2 ENSAD Update

This study focuses on the comparative accident risk assessment for different energy technologies in OECD countries. ENSAD v2.0 contains 7852 unique severe accidents (≥ 5 fatalities) in OECD countries for fossil energy chains in the period 1970-2016. Furthermore, for Hydropower and H2, in ENSAD v2.0, accidents with ≥ 1 fatality in OECD countries for the period 1970-2016 and 1990-2015, respectively, were collected to get a sound dataset to be used for comparative purposes, resulting in a total of 405 unique historical observations.

In this study, ENSAD has been updated for the period 2017-2020 for fossil and Hydropower, related accidents and 2016-2020 for H2. On the other hand, for Biomass, Biogas CHP, and Wind, accidents with ≥ 1 fatalities, due to the immaturity of these technologies, for the period 2000-2020, 1995-2020, and 1996-2020, respectively, are collected, since for these chains, historical observations were not continuously recorded in ENSAD. Furthermore, accidents related to Nuclear, Solar PV and CCUS are not collected, since risk indicators are adapted from Burgherr and Hirschberg (2014), Spada et al. (2022) and Meng et al. (2022), respectively. Finally, accidents with ≥ 1 fatality for DGE are collected for the period 2019-2020 to assess the risk indicators following the methodology proposed in Spada, et al. (2021), which consider potential OECD power plant scenarios and risk indicators derived for blowouts and different hazardous substances used during the drilling, stimulation and operational phases of a plant.

Based on these premises, the following databases were scrutinised for historical observations:

- The Analysis, Research, and Information on Accidents (ARIA) database is operated by the French Ministry of Ecology and Sustainable Development (https://www.aria.developpement-durable.gouv.fr/the-barpi/the-aria-database/?lang=en).
- HSELINE of the UK Health and Safety Executive (HSE) Information Services that collects references to documents relevant to health and safety at work since 1977 (http://oshupdate.com/).
- The Major Hazards Accidents and Incidents Database (MHAID) contains information on worldwide accidents or incidents involving hazardous materials (http://oshupdate.com/).
- The National Response Center (NRC), which contains information on notifications of oil discharges and hazardous substances releases in the USA (https://nrc.uscg.mil/).
- The Dartmouth Flood Repository, which is the global active archive of large flood events since (https://floodobservatory.colorado.edu/Archives/index.html).
- The Hydrogen Incident and Accident Database (HIAD) developed by the European Commission Joint Research Centre (JRC) collects H2 related accidents worldwide (https://hysafe.info/hiad-2-0-free-access-to-the-renewed-hydrogen-incident-and-accident-database/).
- The Scotland against Spin database, which comprises a list of accidents related to wind power since 1980 (https://scotlandagainstspin.org/turbine-accident-statistics/).
- Other sources, such as newspapers, national and local publications, etc.

All the accidents collected from these sources were homogenized prior to analysis, to avoid possible double counts. The final dataset is presented in Table 1.

Table 1. Summary of accidents that occurred in fossil, H2, Hydropower, Biogas CHP, Biomass and Wind energy chains for OECD countries.

Energy Chain	Accidents / Fatalities	Time Period	Severity Threshold [fatalities]
Coal	113/2691	1970-2020	5
Oil	214/3977	1970-2020	5
Natural Gas	127/1537	1970-2020	5
H2	27/56	1990-2020	1
Hydropower	16/116	1970-2020	1
Biogas CHP	10/22	1995-2020	1
Biomass	18/22	2000-2020	1
Wind	57/61	1996-2020	1

3.1 Overview of Risk Indicators

For comparative risk assessment two methods are commonly used: frequency-consequence (F-N) curves and indicators (e.g., Jonkman, et al. 2003). The former is a common way to express collective and societal risk in a quantitative assessment, while the latter provides a direct comparison between energy chains in a concise way, by considering a variety of factors, because no single aspect can provide the full picture (e.g., Kalinina et al. 2016).

In this study, indicators are used for comparative purposes. Fatality rate and maximum consequences (fatalities) have been chosen since it has been shown to provide sufficient information to compare different energy chains (e.g., Spada, et al. 2021). The maximum consequence is assessed as the maximum number of fatalities observed in a single accident for a certain energy chain. The fatality rate is defined as the ratio between the aggregated fatalities over a period under interest and the amount of electricity produced by the energy chain in the same period.

3.2 Normalisation

To derive a comparable measure for the fatality rate above, the unit of electricity produced used in this study is the Gigawatt-electric-year (GWeyr). The latter is chosen since large individual plants have capacities about 1 GW of electrical output (GWe). Therefore, the GWeyr is a natural unit to use when presenting normalized indicators generated within technology assessment (e.g., Burgherr and Hirschberg 2014). In this study the production data are collected from the International Energy Agency (IEA) world energy statistic and balances (https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances) and converted from kilotons of oil equivalent (ktoe) in terms of GWeyr. Furthermore, for fossil, Hydropower, Biogas CHP, Biomass, Hydrogen, Wind energy chains the GWeyr are estimated by considering an efficiency factor:

- Fossil energy chains: 0.35 (e.g., Burgherr and Hirschberg 2014);
- Hydropower: 0.8 (e.g., IEA-ETSAP and IRENA 2015);
- Biogas CHP: 0.45 (e.g., Abanades et al. 2022);
- Hydrogen: 0.5 (e.g., Maisonnier et al. 2007);
- Wind Energy: 0.5 (e.g., U.S. DOE 2015).

The resulting normalization factors are shown in Table 2.

Table 2. Summary of the production in terms of GWeyr in fossil, Hydrogen, Hydropower, Biogas CHP, Biomass and Wind energy chains for OECD countries.

Energy Chain	Production [GWeyr]	Time Period
Coal	65621	1970-2020
Oil	65826	1970-2020
Natural Gas	57638	1970-2020
H2	2886	1990-2020
Hydropower	7351	1970-2020
Biogas CHP	430	1995-2020
Biomass	4907	2000-2020
Wind	845	1996-2020

3.3 Accident risk assessment of new renewables in a comparative context

As discussed in Section 2.2, the historical observation for H2, Hydropower, Biogas CHP, Biomass, Wind and DGE are collected for all accidents with at least one fatality for a statistical matter, i.e., lack of severe accidents. Therefore, to get a comparable value for these energy chains with the fossil energy chains an approximation needs to be made. In this context, the number of accidents with fatalities ≥ 5 over the entire dataset collected in Section 2.2 are compared to the total number of collected accidents. For each aforementioned energy chain, the following contribution of severe accidents to the total of each dataset are found:

- H2: 10%;
- Hydropower: 45%;
- Biogas CHP: 30%;
- Biomass: 5%;
- Wind: 5%;
- DGE: 10%.

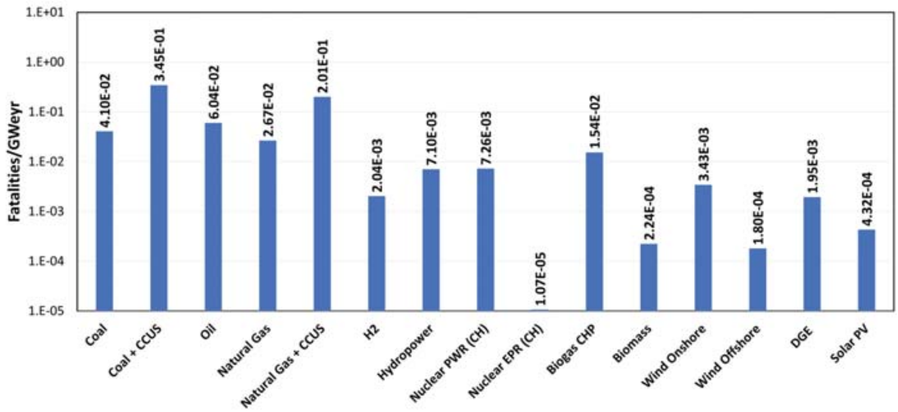

Fig. 1 Fatality rates for fossil fuels, H2, Hydropower, Biogas CHP, Biomass, Wind On- and Offshore, DGE Nuclear (adapted from Burgherr and Hirschberg (2014)), and Solar PV (adapted from Spada et al. (2022)) estimated in this study for the OECD country group.

Therefore, the fatality rates estimated considering the entire dataset, i.e., accidents with ≥ 1 fatality, for H2, Hydropower, Biogas CHP, Biomass, Wind, and DGE, are corrected by scaling them to the percentage of their severe accidents.

4. Results

In this section, the comparative accident risk assessment results for the OECD country group are presented in terms of two risk indicators, namely fatality rate and maximum consequence. These two risk indicators are estimated for the fossil fuels, H2, Hydropower, Biogas CHP, Biomass, and Wind On- and Offshore. Wind is separated according to the IRENA statistics (https://www.irena.org/Data), where ~ 95% of the OECD production is allocated to Onshore and the leftover to Offshore. Furthermore, risk indicators for DGE are updated from Spada et al. (2021). Finally, Nuclear risk indicators are adapted from Burgherr and Hirschberg (2014), Solar PV indicators from Spada et al. (2022) and the CCUS indicators from Meng et al. (2022).

4.1 *Fatality Rate*

In Fig. 1 the fatality rate, which is the total number of fatalities per GWeyr is shown for fossil (incl. CCUS for Coal and Natural Gas), H2, Hydropower, Biogas CHP, Biomass, Wind On- and Offshore, DGE, Nuclear, and Solar PV energy chains for the OECD country group.

Overall, the accident risk is higher for Coal (incl. CCUS) followed by Natural gas (incl. CCUS). This is somehow expected, since with CCUS the chain of both Coal and Natural gas enlarges due to the inclusion of extra steps, such as CO2 transportation (e.g., through road, pipelines, etc.), CO2 utilisation and CO2 sequestration, which could increase the number of potential accidents and, therefore, the accident risk. However, the reduction of CO2 emissions for these two energy chains significantly drops due to the sequestration of this greenhouse gas e.g., Meng et al. (2022).

By considering the energy chains without CCUS systems, the accident risk result higher for the fossil energy chains, Oil, Coal, and Natural Gas, respectively, closely followed by Biogas CHP, which has similar accident risk level to Natural gas.

Among the other renewable systems, all technologies performs better (up to two orders of magnitude) than the fossil and Biogas CHP energy chains. In particular, Biomass performs best, followed by Solar PV, Wind Onshore, DGE, Wind Offshore and Hydropower.

Interesting to note is H2, which performs better than Hydropower and Nuclear PWR, i.e., at the similar level of Wind and DGE, in contrast to the results for EU28 country groups were it performed similar to Natural Gas (Spada et al.,

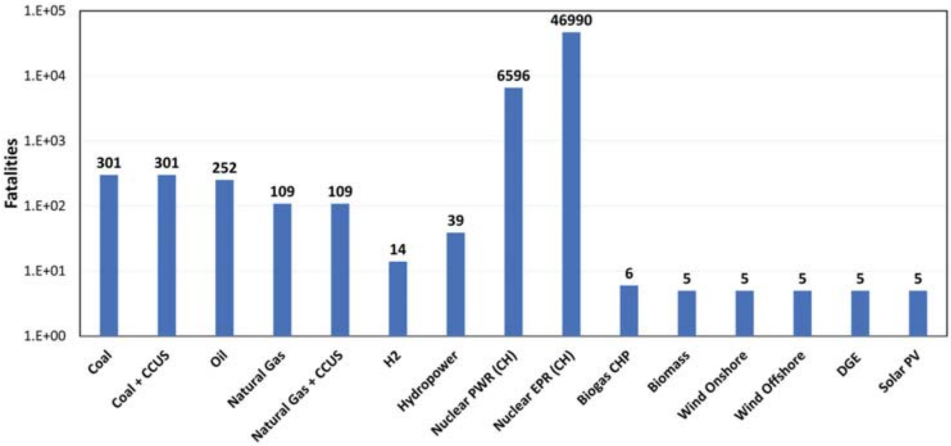

Fig. 2 Maximum consequences (fatalities) for fossil fuels, H2, Hydropower, Biogas CHP, Biomass, Wind On- and Offshore, DGE, Nuclear (adapted from Burgherr and Hirschberg (2014)), and Solar PV (adapted from Spada et al. (2022)) estimated in this study for the OECD country group.

2018). Moreover, Nuclear EPR performs best among all energy chains considering the expected risk, i.e., the fatality rate. These results are in line with the previously published accident risks for various energy technologies in OECD countries (e.g., Boccard 2018). Finally, these results are affected by uncertainty due to the limited historical observations, in particular for new renewables technologies. Therefore, results are expected to be more robust for Coal, Oil, Natural Gas and Hydropower, with respect to CCUS, H2, Biogas CHP, Biomass, Wind, DGE and Solar PV. Furthermore, the results for Nuclear, since they are based on a PSA level-3 modelling are affected by different uncertainties related to the knowledge about the system (epistemic) and the model (aleatory).

4.2 *Maximum Consequences (fatalities)*

In Fig. 2 the maximum consequences, in terms of fatalities, is shown for fossil (incl. CCUS for Coal and Natural Gas), H2, Hydropower, Biogas CHP, Biomass, Wind On- and Offshore, DGE, Nuclear, and Solar PV energy chains for the OECD country group.

With respect to fatality rate, the largest maximum consequences are found for Nuclear EPR and PWR, which are based on a simplified 3-level PSA and includes latent fatalities. These results shows that although the lowest expected accident risk for nuclear, the consequences for a low probability/high consequence event could be catastrophic due to the release of specific radionuclides in specific high populated areas. However, these values strongly depend on different parameters and model assumptions considered for the analysis, as shown, for example, for the Fukushima Daiichi accident in 2011 (e.g., World Health Organization 2013; Tsuboi et al. 2022). Furthermore, this result shows how important is to consider different indicators to be able to draw sound conclusions from a comparative accident risk assessment.

For the OECD country group, Nuclear is followed by Coal and Coal (incl. CCUS), due to the Soma Coal Mine Accident in 2014, where an explosion provoked 301 fatalities during the shift turn (e.g., Spada and Burgherr 2016), followed by Oil and Natural Gas / Natural Gas (incl. CCUS).

Among the remaining technologies, Biomass, Solar PV, Wind and DGE performed best, followed by Biogas CHP, H2 and Hydropower, showing a relatively low accident risk in case of an extreme event, i.e., low probability event.

These results are in line with the previously published accident risks for various energy technologies in OECD countries, except for Coal, since the Soma Coal Mine accident is not considered, and for Nuclear, which is based on a fatality rate for latent fatalities that are not comparable with the presented estimation (e.g., Boccard 2018). Finally, these results are uncertain in the sense that an extreme event, causing more fatalities than the worst historical observation, should not be completely excluded for all energy technologies, except for Nuclear. In the latter, being based on a probabilistic model, which includes some cut-offs, the uncertainty for latent fatalities is large, since they depend on different factors, including, for example, the response of the population to the radiations, the density of the population around the plant, etc.

5. Conclusions

This study presents a comparative accident risk assessment for different energy technologies. The framework for comparative risk assessment applied here is based on the PSI's ENSAD (ENergy-related Severe Accident Database), which systematically collects accidents in the energy sector, except for nuclear where estimations are based on a simplified level-3 Probabilistic Safety Assessment (PSA). Two accident risks indicators are quantified and compared, namely fatality rate and maximum consequences, for fossil energy chains (Coal, Oil and Natural Gas), Hydrogen, Hydropower, Nuclear, Biogas CHP, Biomass, Wind, Deep Geothermal Energy, and Solar PV in the OECD country group.

Fossil energy chains generally exhibit highest fatality rates, while H2, Nuclear and new renewable technologies perform 1 to 4 orders of magnitude better. For Nuclear there is a big difference between Generation II (PWR) and Generation III (EPR) plants. In contrast, Nuclear performed worst for maximum consequences (fatalities), demonstrating how important it is to consider different indicators in a comparative assessment to get the full picture. Fossil energy chains rank in the middle, and H2, Hydropower and new renewables have lowest maximum consequence values. Finally, it is important to note that probabilistic estimates for Hydropower can be in a similar range as for Nuclear PWR, contrasting historical experience (e.g., Burgherr and Hirschberg 2014).

Depending on the chosen accident risk indicator, the ranking of technologies can change, and if additional aspects such as energy security and sustainability are included, the picture becomes even more complex, calling for methods like Multi-Criteria Decision Analysis (MCDA) to support rationale decision making.

Future research should focus, for example, on the inclusion of non-OECD country accidents for an extended comparative accident risk assessment for different energy technologies and a quantitative uncertainty analysis for the assessment of risk indicators.

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