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Comparative Risk Assessment of Wind Turbine Accidents from a Societal Perspective

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Wind power plays a pivotal role in decarbonizing the world's electricity mix, and the current annual installed capacity growth is expected to continue, supported by ambitious targets, policies and cost reductions. However, wind power faces several social acceptance challenges that affect peoples' perception and can lead to opposition and protests. The main concerns are aesthetic impact, environmental effects on wildlife and biodiversity and health hazards. Risks and consequences due to accidents often lack an adequate analysis and discussion. Therefore, the aim of this study is a comparative risk assessment of onshore and offshore wind power accidents at a global level, under a societal perspective. First, a comprehensive data set is compiled that exclusively relies on open-source and publicly available information. The final data set comprises 2708 accidents for the period 2000-2022. Second, descriptive statistics and visualizations are used to identify temporal and geographic trends, and to relate accidents to different attributes (e.g., accident types). Third, selected indicators for fatality risk are calculated to compare different country groups and onshore vs. offshore activities. In summary, this study provides useful insights and a better understanding of accident risks with a focus on health impacts, thus complementing the industry's focus on occupational risk. Ultimately, it can help to smoothen controversies and achieve compromises in such complex decision-making processes.

Keywords: Wind Power, Risk Assessment, Energy-Related Severe Accident Database, Acceptance.

1. Introduction

In 2021, wind (6.6%) and solar (3.7%) power for the first time provided more than 10% of the world's electricity, which makes wind a major and strategic part to achieve the energy transition and switch to a green economy (REN21 2022). Despite the aftershocks of the COVID-19 pandemic and economic and geopolitical developments, due to the Russian invasion in Ukraine in 2022 (Steffen et al. 2020; Kuzemko et al. 2022; Żuk and Żuk 2022), new renewables are expected to grow at an unprecedented rate. Global wind capacity is foreseen to double in this period, underlining the importance of energy security and sovereignty in policy making (IEA 2022).

Although renewables in general receive broad public support, challenges in social acceptance for wind continue to exist regionally and locally. The opposition usually refers to aspects such as wildlife safety, biodiversity protection, noise, shadow flicker, visibility and landscape impacts, and loss in property values (Caporale et al. 2020; McKenna et al. 2022). On the other hand, risk assessment of wind turbine accidents and failures has received limited interest by stakeholders and the public. There are numerous risk assessment studies focusing on specific aspects, including for example occupational risk (Aneziris, Papazoglou, and Psinias 2014), component failures (Ferrari et al. 2018), offshore failure rates (Li et al. 2022), offshore navigation risk (Rawson and Brito 2022), and ship collisions with offshore wind farms (Presencia and Shafiee 2018). However, only a few studies analyze societal risk or employ a comparative perspective (Moura Carneiro, Barbosa Rocha, and Costa Rocha 2013; Spada and Burgherr 2023).

The overarching goal of this study is to present a comparative risk assessment for wind power, taking a societal perspective. To do so, a consistent and comprehensive data set of wind power accidents is initially compiled, which builds upon publicly available information. Next, an explorative analysis is carried out to describe time and geographic trends as well as patterns for selected attributes (e.g., types of accidents). Finally, selected indicators for fatality risk are calculated for different country groups and on-/offshore activities.

2. Approach and methods

Data on wind power accidents is collected by different organizations, including authorities (e.g., ARIA database[a]), industry organizations (e.g., (G+ Global Offshore Wind 2022), and independent private organizations that are often alliances of opponents (see Ertek and Kailas (2021) for an overview). The ARIA database is publicly available, but it has no comprehensive coverage as it only contains 16 events for France from 2004 to 2020. In contrast, industry sources such as the G+ Global Offshore Wind organization report several hundred events per year, but while earlier reports provided detailed incident lists (G9 Offshore Wind 2015), in recent years only incident totals are given (G+ Global Offshore Wind 2022). Therefore, this study uses an open-access data set by the Scotland against Spin (SaS) alliance (SaS 2023). In the following sections, it is explained in detail how this data was checked, harmonized and modified to fit the subsequent analysis.

2.1. *Checking of data set*

First, individual data records were verified, and checked for completeness and consistency. The original data set comprised 3206 entries for the period 1980-2022. Next, 309 accident records were removed because they provided a general overview of wind power risks and did not report on individual events. Lastly, 86 duplicates were not considered because for the same event more than one data record was generated to report different types of consequences (e.g., fatalities and injuries). This resulted in a reduced data set of 2811 events (data records).

In a second step, the 9 data records in the years 1980-1989 were not accounted for. These early years are not fully representative because only fatal accidents were reported, and eight out of nine refer to the USA, which suggests a reporting bias. The temporal distribution of accidents is given for the period 1990-2022 (a total of 2802 accidents). The data set was further restricted to the years 2000-2022 for the characterization of the data set and calculation of basic statistics to ensure that the analysis is representative for today's situation, and to provide a sufficient and fair coverage of offshore accidents as well. In the end, the final data set consisted of 2708 individual events.

2.2. *Consolidation of data records*

Subsequently, the final data set was harmonized, which included several modifications. Location information for site/area and country were standardized and new fields added for "Year" and "On/Offshore" as well as "OECD" and "EU27" membership of countries, to allow for a consistent sorting and filtering. Details of the events are only given as flow text in the field "Details". Moreover, additional data fields were created to make this information easy to use and visualize. These included human health consequences, namely the numbers of fatalities and injuries and the status of the affected persons, i.e., workers (occupational) or general public (public). For environmental consequences, impacts were categorized to affected animals, spills/leaks, etc. Lastly, fields for accident types (e.g., blade failure, fire, human health, etc.) and life cycle phase (e.g., construction, operation, maintenance, etc.) were generated and filled up.

2.3. *Characterization of data set*

The annual numbers of accidents as well as the accidents that resulted in fatalities were plotted for the years 1990-2022 to provide an overview of the temporal distribution of accidents. The subsequent evaluations focused on the period 2000-2022 because for the earlier years no offshore fatalities and injuries were reported (see section 3.1 for further explanations). This included the

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[a] https://www.aria.developpement-durable.gouv.fr/the-barpi/the-aria-database/?lang=en

corresponding plots for accidents by country, type of accident, type of environmental impact, and life cycle phase.

2.4. *Risk indicators*

Risk indicators were calculated for three country groups, namely OECD (Organisation for Economic Co-operation and Development), non-OECD and EU27 (excluding UK) countries. These aggregated indicators determine the extent of expected risk, whereas maximum consequences serve as a proxy for risk aversion (Burgherr and Hirschberg 2014). The results presented here focus on fatalities, but corresponding indicators for injuries can be calculated as well.

Fatality rates were normalized per unit of electricity generation (i.e., Gigawatt-electric-year, $GW_e yr$) to ensure direct comparisons between country groups as well as corresponding onshore and offshore accidents. For this purpose, the year 2022 had to be excluded because electricity generation data was only published until 2021 at the time of writing this article (IRENA 2023). Fatality rates were computed for all fatal accidents (≥1 fatality), but also the so-called severe fatality rates were calculated, which only include accidents with at least five fatalities (Burgherr et al. 2019). If for a specific country group and on-/offshore combination no severe accidents were reported, the aforementioned study assumed a severe accident rate equal to 1% of the total fatality rate. This could be seen as a quite optimistic assumption, which is why a more conservative approach was applied in the present study, i.e. the ratio between accidents with fatalities and all accidents was used as a correction factor instead.

The maximum consequences indicator refers to the deadliest single accident of a given country group during the observation period for onshore and offshore events, respectively.

3. Results

In the following sections results are presented with regard to (1) temporal and geographic distribution of accidents, (2) patterns by accident type and life cycle phase, (3) environmental impacts, and (4) risk indicators.

3.1. *Temporal and geographic distribution*

Fig. 1 shows the number of onshore and offshore accidents per year. The observed increase exhibits a similar pattern with the growth in global wind energy generation capacity until about 2010 (Sadorsky 2021). However, afterwards accident numbers stabilize, and the most recent years may even point towards a reduction in accidents. Offshore accidents are quite stable and at a lower level, but the expected, 10-fold global capacity growth until 2035 (BNEF 2022) will reveal if current safety levels are sufficient.

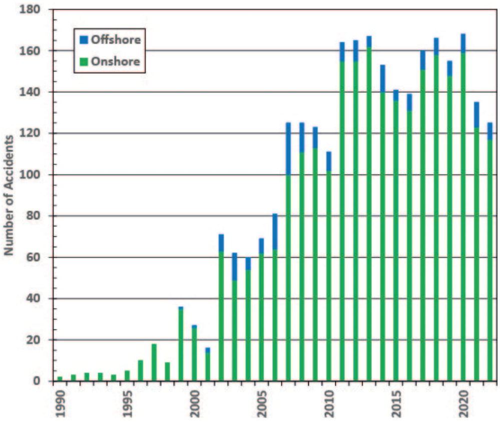

Fig. 1. Annual numbers of worldwide, onshore and offshore accidents in the period 1990-2022.

Despite the substantial increase in reported accidents since 2000, there is no corresponding rise in annual fatalities, i.e. values vary from about five to ten (Fig. 2). The peaks in certain years are attributable to specific events. In 2011, two occupational accidents in China resulted in three and five fatalities, and a collision between a car and a truck transporting an oversized wind component in the USA killed three citizens. In 2012, a similar traffic accident between a bus and truck in Brazil killed 17 citizens, whereas two occupational accidents in Germany and China led to three and five deaths, respectively. In 2020, 15 people from an indigenous village in Mexico were killed during a wind power protest. Two similar events in Oaxaca State caused the injury of 20 and 22 persons in 2011 and 2013, respectively. Such aggressive acts are unprecedented and have not been observed anywhere else yet (Zárate-Toledo, Patiño, and Fraga 2019).

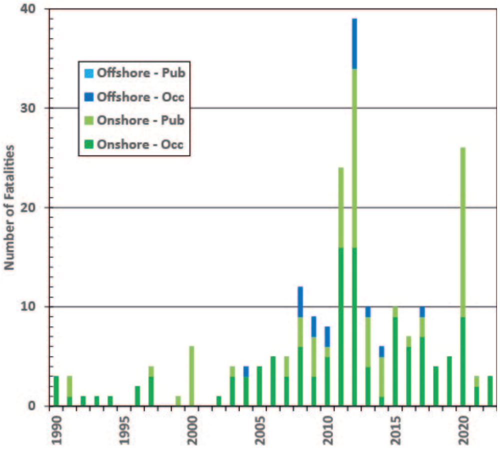

Fig. 2. Annual numbers of occupational (occ) and public (pub) fatalities in worldwide onshore and offshore accidents in the period 1990-2022.

Fig. 3 displays the cumulative contributions of individual countries to total accidents and fatalities for the years 2020-2022. The top 10 countries in terms of accidents account for 89.4% of all events, and all belong to EU27 and/or OECD. Concerning fatalities, the top 10 countries make up for 90.7% of total deaths and include two non-OECD countries (Brazil and China).

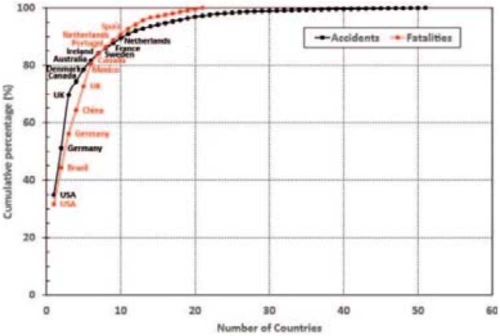

Fig. 3. Cumulative curves of accident and fatality shares by country for the period 2000-2022.

3.2. *Accident types and life-cycle phases*

In the period 2000-2022, the most common types of accidents included blade failure (471 events), Fire (429), structural failure (255) & mechanical failure[b] (150). Accidents during transport consisted of 253 road accidents and 47 ship accidents, which is in good agreement with other studies (Firetrace International 2020; Jou 2022; Moura Carneiro, Barbosa Rocha, and Costa Rocha 2013; Asian et al. 2017). In contrast, there were only 33 ice throw events recorded, although this type of accident can potentially lead to personal injuries and damage to structures and objects in the vicinity of a turbine (e.g., public roads, housing, power lines and shipping routes).

Fig. 4 shows the relationship between the life cycle phase of wind turbines and the numbers of accidents and fatalities for the years 2000-2022. Accidents during the operation phase dominate the category onshore accidents, followed distantly by transport, construction and maintenance phases. For offshore accidents, operation, maintenance and construction phases amount to almost 90%. Concerning fatalities, the major life cycle phases had rather similar contributions for onshore accidents, while offshore construction and maintenance had the highest shares. The remaining accidents were also classified, namely as events related to manufacturing of components, planning (e.g., bribery, planning errors, violation of regulations or consent), decommissioning at end of life or due to legal and regulatory offence, and external aspects (e.g., opposition and protest, legal and regulatory violations relating to operations).

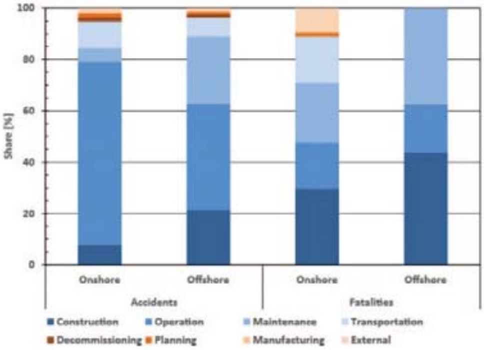

Fig. 4. Worldwide accidents (left) and accidents with fatalities only (right) in different life cycle phases during the years 2000-2022.

3.3. *Environmental impacts*

The compiled database of wind power accidents contains 257 events that report environmental

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[b] Nonconsequential structural damage

impacts, 88% of which since 2008. There are another 111 entries that are not attributable to a specific event, but imply environmental impacts in general. This increase over time is probably not only due to wind power growth, but also changes in legislation, reporting requirements and increased attention by the public, media and NGOs.

Damages to wildlife is the dominant contributor with 53.7%, of which 90% concern birds and bats. However, the current level of information given in the accident descriptions does not allow for a detailed analysis on actual numbers of animal deaths and species affected over time and by location, etc. Nevertheless, the evidence from the previously mentioned generic database entries indicates that the problem deserves careful consideration and evaluation within a sustainability perspective, and site-specific assessments are needed (Msigwa, Ighalo, and Yap 2022).

Spills and leaks of lubricants (i.e. oils and greases) had the second largest share with 23.3%, potentially affecting farmlands, forests, freshwater bodies including groundwater, sea, etc. Examples of potential spill components include the gearbox, generator, hydraulic systems and transformer of the wind turbines. Other environmental impact categories are much less of a concern, varying between 4% and less than 1%.

3.4. *Risk indicators*

Fatality rates were calculated for onshore and offshore wind power in OECD, non-OECD and EU27 (i.e. w/o UK) countries in the years 2000-2021, for all accidents with fatalities and severe (≥5 fatalities) accidents (Fig. 5).

For all accidents, offshore fatality rates were consistently higher than the corresponding onshore country group values. In contrast to expectations, based on risk assessments for other technologies, non-OECD performance is similar to OECD and EU 27 (Burgherr and Hirschberg 2014). Possible explanations could be that large-scale capacity growth in non-OECD countries started later, and that reporting in some countries may be less complete, especially for public information sources that were used in this study.

Severe accidents, on the other hand, exhibit a different pattern. OECD and EU27 countries have lower fatality rates compared to non-OECD, and the difference is more pronounced for onshore by about one order of magnitude, whereas offshore values are of the same order. This could be an indication of differences in legal and regulatory frameworks as well as the organizational and management safety cultures between the country groups.

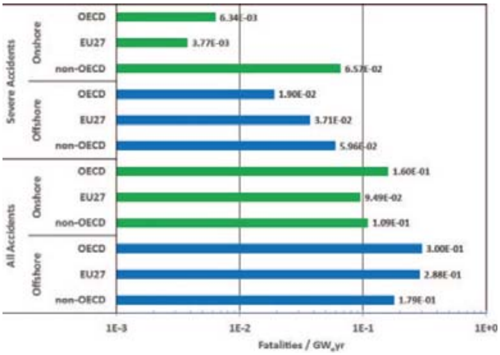

Fig. 5. Onshore and offshore fatality rates for all accidents (≥1 fatality) and severe accidents (≥5 fatalities) in OECD, EU27 and non-OECD countries in the period 2000-2021.

Maximum consequences, expressed as single wind power accidents with most fatalities, are rather low, which is similar to other new renewable technologies such as solar PV, enhanced geothermal systems (EGS) and Biogas (Burgherr and Hirschberg 2014). An overview is given in Table 1.

Table 1. Maximum consequences in onshore and offshore accidents for the three country groups in the period 2000-2021. Occ = Occupational, Pub = Public fatalities.

Country Group	Onshore [Fatalities]	Offshore [Fatalities]
OECD	5 (2013, USA, Occ) 15 (2020, MEX, Pub)	3 (2012, GER, Occ)
EU27	2 (2013, NLD, Occ)	3 (2012, GER, Occ)
Non-OECD	5 (2011 & 2012, CHN, Occ) 17 (2012, BRA, Pub)	1 (2017, CHN, Occ)

The severe accident threshold for onshore wind was only reached in OECD and non-OECD country groups. The deadliest events resulting in public fatalities caused 15 and 17 fatalities, respectively (see section 3.1 for details), whereas the worst occupational accidents led to 5 fatalities in both country groups. On the contrary, maximum consequences of onshore accidents in EU27 and offshore accidents in all three country groups were below the severe accident threshold, varying between 1 and 3.

4. Conclusions

This analysis demonstrated that publicly available information can provide a rich data source for wind power accidents. However, the results question the consistency and comprehensiveness of the reporting in non-OECD countries, and especially non-fatal accidents could be unpublished. Nevertheless, the coverage of accidents that resulted in death or injury should be sufficiently complete, which is confirmed by few reports providing disclosed, cumulative data from industry associations.

Despite the usefulness of publicly available data, substantial verification, cross-checking and harmonization efforts are needed to ensure that data quality meets scientific standards as employed for example by PSI's Energy-related Severe Accident Database (ENSAD) (Kim et al. 2018).

The compiled data set provides an exemplary cross-section view of the types of accidents, based on all wind turbine life cycle phases, as well as the impacts of the accidents on human health and the environment of accidents.

Specifically, the data demonstrate an upward trend in raw numbers of accidents since the 2000's, which is induced by the strong increase in installed capacity that is further accelerated by new ambitious targets and/or policy improvements in numerous countries (e.g. USA, UK, EU, Brazil, India, China, Australia). However, the global, 5-year averages of accident numbers have stabilized since 2010, and since no pronounced trends for human health consequences (i.e. fatalities, injuries) were observed, current regulations and HSE practices seem effective.

Indicators like fatality rates show that emerging and developing countries (i.e. non-OECD) exhibit higher risks of severe accidents, and that in general the more adverse offshore environment is particularly risk-prone. Finally, the decentralized nature of wind power, compared to other large, centralized power plants, highlights their limited potential for the occurrence of catastrophic accidents in terms of fatalities.

In conclusion, wind power, like all other new renewables, can play a key role towards a more sustainable, safe and secure energy future. This study lays the foundation for a fruitful, data-driven dialogue to smoothen public acceptance and reduce societal risks, in order to actively accommodate renewable energy production in the long-term climate and net-zero plans.

In a next phase, the current analysis will be expanded. In particular, additional aspects of the database will be explored such as causes of accidents, affected turbine components, different types of environmental impacts, and additional risk indicators, including coverage of injuries. Lastly, accident data will be combined with wind farm databases, etc. to calculate more location-specific impacts.

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