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Offshore wind H&S: A review and analysis

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ABSTRACT

The offshore wind industry is growing rapidly around the world. Many governments have set ambitious targets for growth to achieve their decarbonisation goals. As the industry grows it can become more challenging to build and operate wind farms safely. Wind farms are being constructed further from shore in tougher weather and sea conditions. In the UK, the Health and Safety Executive has raised concerns about safety performance. This paper aims to review the current state of health and safety in the offshore wind industry. It reviews the latest research, injury statistics and the state of legislation covering the sector. It also considers how the risk profile of the industry may change in coming years. The paper finds there is a need for more research specific to the safety challenges of offshore wind. Injury rate statistics show that performance is 3–4 times worse than comparable industries, and industry reports do not currently include large parts of the sector. Rapid growth and the implementation of new technologies will create additional challenges. Regulators should consider the implementation of industry specific safety legislation to manage the unique challenges of offshore wind.

1. Introduction

Offshore wind has seen significant growth in recent years. Installed capacity of offshore wind is now over 35 GW, and the projected growth rates up to 2025 are over 30 % annually [1]. As installed capacity increases, wind farms are becoming larger and are situated further from shore. The wind industry workforce can be expected to grow at a similar rate, training this new workforce and ensuring they are able to work safely will be a huge challenge. As of 2020, the offshore wind industry (OWI) in the UK employs over 26,000 people, 15,000 of which are in direct employment [2]. Direct jobs in the UK are expected to grow to over 40,000 by 2026. Jobs growth around the world can be expected to follow a similar trend. As the industry continues to grow it can be expected that health and safety (H&S) performance will come under increasing pressure.

The UK has one of the most developed offshore wind markets but has faced recent criticism. In July 2020, Trevor Johnson of the Health and Safety Executive wrote to industry to express concerns over H&S performance [3]. The letter commented that improvements in wind industry H&S performance have *"at best stalled if not reversed"*. It highlighted several incidents that have occurred in 2020 and called upon the industry to renew efforts to improve performance.

Sectors beyond the UK have also raised concerns, the European agency for health and safety at work commissioned a report on the safety challenges associated with new '*green jobs*' [4]. The report identified that the risks related to offshore wind were significantly greater than onshore wind. They identified challenges including remote worksites, accessibility issues and lower profit margins as all being risks to H&S performance. The report identified that pressures on the supply chain would also be significant, such as an increase in the use of small subcontractors and skills shortages due to rapid growth. The use of automation to reduce worker exposure was highlighted as an opportunity, however they also identified the risk potential for new issues arising over *'human-machine interface'* [4]. Finally, it was noted that there is a risk that there could be a *'conflict between green objectives and occupational health & safety'*. The United Nations sustainable development goals number 7 and 8 identify both the need for development of clean access to energy and also the promotion of *"safe and secure working environments"* to be important elements of global sustainable development [5]. It is important that offshore wind contributes to both goals. While there is an ethical responsibility of the industry to ensure its employees are not harmed, the economic benefits of a safety industry are also clear. The UK Health and Safety Executive estimates that workplace injuries cost employers £3.5 billion annually, furthermore a recent study on the economic benefits of investing in safety found a return in investment of around 1.3 for construction workers [6,7].

Understanding the safety challenges of developing offshore wind is important for industry to ensure that the sector can grow sustainably without negative impacts on the workforce. Regulators also need to

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Nomenclature

Abbreviations

H&S –	Health and Safety
UK –	United Kingdom of Great Britain and Northern Ireland
OWI –	Offshore Wind Industry
TRIR	total recordable injury rate
LTIR –	lost time injury rate
LTI	Lost time injury
RIDDOR	Reporting of Injuries, Diseases and Dangerous Occurrences Regulations
KPI	Key Performance Indicator
Hs	Significant wave height
GWO –	Global Wind Organization
SOV –	Service Operation Vessel
IOGP	International Association of Oil & Gas Producers
SPARTA	System performance, Availability and Reliability Trend Analysis
HASWA	Health and Safety at Work Act 1974
MHSWR	Management of Health and Safety at Work Regulations 1999
CDM	Construction (Design and Management) Regulations 2015

Notation

NT	No. of technician transfers/year
T	No. of turbines installed
R	Technician transfer rate/month

understand the unique challenges associated with offshore wind to make informed decisions regarding the need for implementation of regulation to manage the industry. This study set out to examine the safety performance of the offshore wind industry and the outlook for the future. This is not an easy question to answer, relying solely on traditional performance statistics is not a reliable method. Statistics only give a measure of the past performance of the industry and suffer from issues such as under-reporting. This study set out to look at multiple aspects of safety in the industry to make a holistic assessment of the state of the industry. It was decided to use statistics to complete a cross industry analysis and offshore oil and gas was selected as the industry with the most in common to offshore wind. The next step was to analyse the content of the existing safety literature in offshore wind to gauge the level of attention the area has received, where problems have been identified and potential gaps in the literature. The third phase of the study looked to understand how safety is governed by legislation, and the UK as a mature sector of the industry was selected for this analysis. Safety legislation is a primary level of control that sits at the top of the hierarchy of all other controls. Understanding the strengths and weaknesses of legislation in offshore wind can also provide information about how the industry is performing. Finally, the study looks to see how risk levels in the industry might change in the coming years. Again, the UK was used as an example for this, and crew transfer rates were selected as a useful proxy for worker to exposure to risk. This gives one indicator as to how risk levels might change in coming years. Looking at these four aspects of safety; statistics, existing research, legislation and risk exposure allow an overall picture of the performance to be built. Finally, it also allows for critique on the state of the industry and identify where challenges lie in ensuring the industry grows safely in the future.

The novel contribution of this work is to review and summarise the available H&S literature within offshore wind and other relevant industries. It also contributes an analysis of the safety statistics of the industry with comparison to a similar industry and a review of the key challenges for the future, including legislation and changing risk profiles. While there have been calls by various parties warning of the safety challenges the offshore wind industry faces, none of these have made a comprehensive assessment of the performance of the industry to date, reviewed the literature or offshore wind safety legislation.

The study considers the global offshore wind industry but for simplicity focuses on the UK for the legislative analysis and the growth estimates for technician transfer. The study is also limited by the publicly available injury rate data, this is discussed further in Section 4. As the UK industry is one of the global leaders in offshore wind, lessons from this jurisdiction can be applied to other countries with less developed offshore wind markets.

Section 2 sets out the literature review which includes relevant studies from similar industries where it helps to identify key challenges or lessons learned applicable to offshore wind. Section 3 analyses the H&S performance data, discusses challenges related to this data and considers industry performance. Section 4 makes a forecast of technician transfer rates growth and what this means for the risk profile of the industry. Section 5 reviews existing safety legislation and considers what other jurisdictions can learn from the UK. Finally, discussion, conclusions and recommendations for further work are presented in Sections 6 to 8.

2. Literature review

This section reviews the latest health and safety literature from the offshore wind and includes relevant sources from other industries. The review is split into subsections based on the type of source and subject area. The main topics covered are, industry and incident reporting, key performance indicators (KPIs), human impacts, decision making, HSE management and response, and finally legislation. A keyword literature review was completed using the Compendex and EEE search engines. A keyword literature search using strings ("safety" OR "H&S″ OR "health & safety") AND "wind farm" OR "wind turbine" OR "wind energy") returned over 2189 records in Compendex. However, an initial review of these results showed that the vast majority were related to the system safety of wind turbines and turbine components rather than the health and safety of personnel. To narrow the search the strings ("crew transfer" OR "personnel transfer") were added. This returned only 8 results, of which 4 were not relevant. Hand searches were then completed of the reference lists in the key articles which returned additional papers to incorporate into the review (snowball method) [8].

2.1. Industry and incident reporting

Industry reports are an important source of offshore wind H&S information. G+ publish an annual report which includes the latest incident statistics along with updates on safety initiatives and discussion on overall performance. G+ is an industry body promoting and coordinating health and safety initiatives in offshore wind [9]. It is made up of corporate members from Europe, North America and East Asia who share data and collaborate on safety initiatives.

Their main work areas are:

- "Incident data reporting,
- Good practice guidance,
- Safe by design workshops and learning from incidents,"

The members of the group include many of the largest wind farm developers and operators active in Europe, the USA and East Asia [10]. The report focusses on traditional lagging indicators such as the total recordable injury rate (TRIR) and the lost time injury rate (LTIR). Lagging indicators measure safety performance by recording accidents, this approach has many drawbacks which have been highlighted many times [11–13]. Each year the report also gives summaries of the numbers of accidents by work activity and work area. For example, in 2022 lifting and manual handling were the most common activities to result in accidents and the turbine was the most common location for an accident. Hours worked and injury rates are also published by country, however due to the low number of hours worked between each country, comparisons are unlikely to be statistically valid [12]. An analysis of the industry injury rates is explored in section 3.

Aside from G+ reports, sources of offshore wind incident data are not widely available. Asian et al. completed a study of media sources in an attempt to analyse the frequency and causes of incidents involving wind turbines [14]. They used a data mining approach due to a lack of available incident data from the wind industry. The study analysed 240 incidents between 1980 and 2013 which occurred both onshore and offshore. The nature of the data collection posed obvious limitations to the study as the authors could only find incidents that had been prominent enough to be reported in the media. The key finding of the paper was that incidents involving humans were mostly related to transportation activities during wind farm construction or operation. The study was completed before G+ began publishing industry wide incident statistics. Sovacool carried out a comparison of fatal injury rates across low carbon energy industry sectors [15]. It grouped together onshore and offshore wind and found that it had the worst fatal incident rate per TWh of all the energy industry sectors looked at. Large wind farm operators also publish injury rate data within their company reports, however these are also limited to either TRIR or LTIR and include little further information or analysis [16–18].

Within the UK, all employers have a duty to report H&S incidents, this is set by the legislation known as RIDDOR [19]. However, the data is reported on an industry sector basis and does not include a category specifically for offshore wind or renewable energy. Instead, the statistics are included in the category of electricity generation. As such, a specific analysis of this data to look at offshore wind performance is not possible. This contrasts with the UK offshore oil and gas industry which does have a specific category for reporting accidents under RIDDOR. Injury rates within the European Union are also reported in a similar way and cannot be separated out to collect data about the offshore wind industry [20].

The Norwegian oil and gas industry are an innovator in relation to reporting safety and risk data. The Norwegian risk level report (RNNP) is an annual report on the trends in risk level in the Norwegian oil and gas industry [21]. It publishes data every year on the health, safety and environmental performance of the industry. It aims to provide an overall picture of the industry risk level without solely looking at traditional lagging indicators like injury rates. The report includes leading indicators of risk levels in the industry. Leading indicators are measures that help to identify when risk levels have changed before accidents occur. In the case of the RNNP they use testing of the performance of barrier measures such as fire protection systems as a leading indicator [22]. It also includes a survey of dive workers to gain an understanding of their experience and their perception of the safety culture. The report publishes an overall '*Total risk indicator for major accidents*'. This is developed by combining leading and lagging indicators and assigning weights to create one overall statistic that measures the risk profile of the industry for that year.

In addition to accident reporting, industry organisations also publish documentation including safety guidelines, safety rules and safe design guides. Renewable UK published the Offshore Wind and Marine Energy Health and Safety Guidelines in 2014 [23]. The guidelines do not set specific standards for H&S in the industry, but they act as a guide to the existing H&S legislation and industry requirements and how they relate to the specific risks in the industry. They are written from a UK perspective and include an overview of legislation that applies to the UK offshore industry. The Energy Institute in collaboration with G+ publish the wind turbine safety rules, they provide standard safe work procedures for working on electrical and mechanical systems [24]. G+ have also published a number of reports on safe by design workshops that have been run in collaboration with industry, these include topics such as marine transfer, blade design and floating wind [25].

2.2. Key performance indicators

Industry reporting relies on statistics or key performance indicators (KPIs) to monitor and report the health and safety performance of the offshore wind industry. This section reviews the latest literature on KPIs. There has been some research regarding the best use of KPIs within the OWI, although not always with a strong focus on health and safety. Gonzalez et al. reviewed the use of KPIs in the wind industry, they found that their use was not widespread and that there was little literature available on the subject [26]. The paper focused on energy generation performance, reliability, maintenance, and finance but did not consider safety. A set of KPIs for use in wind farm O&M were proposed but did not consider H&S measures. Pfaffel has also studied the use of KPIs in offshore wind farms through an industrial survey [27]. The study found that while 20 out of 28 respondents used performance KPIs to monitor turbine operation, only 5 respondents used any H&S KPIs. The H&S KPIs found to be in use were:

- Total incident rate,
- Total lost time occupational illness frequency,
- Fatal incident rate,
- Recordable injury rate.

These results align with the findings of section 3.1 and indicate that the offshore wind industry is yet to adopt H&S KPIs beyond the traditionally used injury rates.

Torres et al. have proposed KPIs that incorporate quantification to demonstrate safety and security levels on an offshore wind farm [28]. The paper proposes the concept of a key risk indicator (KRI). A KRI is defined as *'a measure for possible exposure or loss'* [28]. These consider security threats such as cyber-attacks or piracy, as well as safety threats to personnel. One proposed KRI tracks the risk of personnel being stuck on a wind turbine, it would take into consideration metrics such as time of day, wave heights and light levels. The paper proposes that there should be safety and security goals as part of an operational wind farm set of KPIs, in addition to traditionally used metrics.

Seyr and Muskulus have looked at offshore wind KPIs and drawn knowledge from the oil and gas industry to propose safety KPIs for use in offshore wind [29]. The paper reviewed incident data from the OWI and identified a set of safety indicators that could be implemented to monitor safety performance. The majority of the indicators were all lagging indicators and were split into 4 categories [29]:

- Technical failure,
- Work environment and training,
- Transport and traffic,
- External factors.

Organisational safety indicators were also proposed directly from research related to the oil and gas industry [29]. The indicators from these papers include KPIs to measure the state of the O&M planning system, such as no. of work orders where material is fully received in the plant and time to response after a failure [30,31]. They also include measures of the cost and schedule performance of the project or facility, as these could give an indication if there is a risk of shortcuts being taken due to time and cost pressures [31]. The indicators proposed by Seyr go beyond any other research related to offshore wind but do not identify the need for leading and lagging indicators or the differences between process and personnel safety, as is widely acknowledged to be required in the wider safety literature.

Research has also been undertaken to assess the interdependencies of KPIs and '*safety and security goals*' [32]. This study by Kopke identified 9 safety and security goals for an offshore wind farm, which were modelled to assess how they relate to each other and effect the overall state of the wind farm. This research was further developed to include a Bayesian Network to improve the modelling of the wind farm [33,34].

These models all relate to the system or process safety of the windfarm and how they interact with personnel safety, rather than safety risks to personnel due to their work activities or behaviours.

The research on H&S KPIs for the offshore wind is still very limited, and there is an opportunity for the sector to learn for other industries and introduce innovations in this area. There is an extensive body of research on H&S KPIs, including leading and lagging indicators in the oil and gas and construction industries which has been reviewed in other works [35,36]. The debate on the use of H&S KPIS or safety indicators in process industries has been energetic since the early 2000s. Early issues with the reliance on traditional safety indicators such as TRIR were identified as a factor in the Texas City refinery explosion [13]. The debate rising from this continued in a special issue of Safety Science dedicated to process safety indicators [37]. A key issue raised was the need to understand the difference between process and personnel safety indicators, and that both are needed for an effective H&S management system [38]. Process safety hazards are those which concern operation of the plant and hazards that arise from a fault in the plant operation. For example, in the case of oil and gas, the unintended release of gas or chemicals [38]. In a wind turbine, this could be an electrical fire in the nacelle or a blade failure.

Personnel hazards do not relate to the operation of the plant but impact people working there. For example this could be a worker falling from height while working on a wind turbine tower [38]. The confusion between personnel and process safety was found to be a factor in the 1998 explosion at a gas plant at Longford in Australia [39]. The plant had a very low lost time injury record, with zero LTIs in the previous year. The low injury rate gives an impression of a safe plant; however, this is only a measure of personnel safety, not process safety. Hopkins well known quote to explain this phenomenon was that, *"An airline, for instance, would not make the mistake of measuring air safety by looking at the number of routine injuries occurring to its staff"* [39]. Hopkins concluded that for a reporting system to be effective it must *'specify relevant warning signs'* [39]. Hopkins has also identified the importance of discerning between leading and lagging indicators, again stating that both are required for an effective system [38].

Issues have also been raised regarding statistical validity of measures such as TRIR, with warnings that they should only be used in certain situations such as cross industry comparisons where there are very large datasets to use for the calculations [12]. Small changes in TRIR or LTIR are often hailed as indicating performance improvements, but confidence intervals to show the statistical significance of these changes are never seen in industry publications or company reports.

Research from the construction industry is pushing for a move away from lagging indicators such as TRIR [40]. Leading indicators proposed for use in construction have included, frequency of pre task planning meetings, or number of site inductions completed [40]. These indicators are intended to predict the future performance of a H&S programme, as opposed to a lagging indicator such as LTI rate that records past performance only. Alruqi and Hallowell found that nine leading indicators currently in use in the construction industry have a significant correlation with injury rate [40]. However, the relationship between leading indicators and safety performance is very hard to quantify and there is yet to be any industry consensus on their best use either in oil and gas or the construction industry [40–42].

While the drawbacks of traditional injury indicators are well documented, and the need for innovation has been much discussed in other industries, the offshore wind industry has made little progress in this area and continues to be reliant on methods that have shown to be deficient in their ability to truly measure safety performance or industry risk levels. There is a requirement for specific research in this area for offshore wind that can address some of the challenges of the industry, such as remote and dispersed work locations, crew transfers and weather challenges. Consideration should also be given to the development of indicators for process safety as well as personnel safety, including the definitions of what these would mean for offshore wind.

2.3. Human impacts

This section discusses research into the stresses and health effects that offshore wind workers are faced with. A study into a job task analysis for a typical offshore wind worker highlights the challenging activities workers face [43]. These include, transferring from vessels to turbines, ladder climbing, moving through hatches, mechanical torquing and hauling a casualty in an emergency. Other research has shown that the most common physical strains to workers are caused by climbing, and that workers are also challenged by increased exposure to noise, vibrations, humidity, cold and heat [44].

Studies have also been completed specifically looking at health effects impacting workers in the wind industry in general [45,46]. Onshore there are some known health risks around turbine manufacturing, particularly around the use of epoxies for blade manufacturing. There are also challenges around noise exposure for onshore wind workers. However, for offshore wind more research is needed on challenges around ladder climbing and confined space working [46]. In particular for offshore workers the issues of accessibility and weather exposure are of concern [46]. These studies all highlight that the work of offshore wind workers is challenging with 12 h shifts and 14 day work rotations being normal [47]. Workers are normally hired for offshore work subject to the passing of pre-employment screening tests, as a result the workforce is generally of an above average fitness level and typically report themselves to be in good health [47,48].

Research has been completed to try to improve the safety and productivity of offshore wind technician transit [49]. The project has implemented a study looking at the effects of crew transfer vessel sailing on worker mental and physical wellbeing. The overall goal was to provide better advice to make the go/no go decisions prior to maintenance missions. A model was developed to understand and predict the impacts of motion sickness on workers.

Floating wind will potentially open up new hazards, but also allow for new maintenance strategies that may mitigate some risks [50]. There has been research on the effects of floating wind turbine motion on workers carrying out tasks inside the nacelle and the potential impacts of motion on their health and performance. This has suggested that the motions of floating wind turbines which are likely to be in the low frequency range (less than 0.5Hs) may cause motion sickness and create difficulties for technicians to complete maintenance activities [51]. Other research has indicated that the accelerations experienced due to nacelle motion will not have a significant impact on technicians ability to work [52].

Relative to other industries the amount of research into human impacts and health effects on industry workers is limited. As the industry continues to grow and evolve, further research on this area is important. The existing research on health impacts highlights some of the unique challenges offshore wind faces, such as the reliance on ladder climbing for access, exposure to noise, vibration, heat and cold and seasickness. The development of leading indicators for measuring risk levels in the industry should look to incorporate these issues into future research.

2.4. Forecasting and decision making

Weather forecasting and decision making for better crew transfer safety has been looked at by Gilbert et al. [53]. The study recognises that pressure to increase access to offshore turbines while cutting maintenance costs will increase the risk of crew transfers taking place in marginal conditions. A key aspect in safe and successful transfers is reviewing the weather forecast for the day and deciding whether a maintenance task should go ahead. The study developed a model based on probabilistic weather forecasts to predict the likelihood of successful crew transfers. It then developed a visualisation to represent that data in as simple a method as possible so operations managers can make informed decisions. Guanche et al. developed a model to predict the behaviour of floating wind turbines and transfer vessels in order to safely predict when transfers can be made [54]. Offshore wind is unique in the challenges it faces to managing its operations and maintenance activities. Wind turbines are remote and distributed, creating challenges for condition monitoring and activity planning. When maintenance work is required, activities are also limited by the weather conditions and capabilities to access the turbines. The combination of these restrictions creates huge challenges in planning work which can increase pressure on H&S performance. Research in maintenance operations and weather forecasting can help improve the planning of operations allowing risk to be better managed. As the floating wind sector develops these challenges could become even more important as sites are likely have worse weather conditions, which will increase the complexity of maintenance scheduling [50,55].

2.5. HSE management and emergency response

Ahsan et al. have looked at HSE management systems in the Danish offshore wind industry and proposed that more standardised systems are needed [56]. Their study interviewed offshore wind farm technicians and managers, they found that although most systems were developed under OHSAS 18001, there was a lot of variability in systems between companies. The study recommended that more emergency response standardisation across the industry would make it easier for technicians or subcontractors that work across multiple projects and overall improve standards. Research has also looked into emergency preparedness at Danish wind farms [57]. The study interviewed 18 parties from across the Danish offshore wind industry. They found that operators have varying emergency response systems, and the response system is fragmented across the industry. It was also noted that operators do not share resources such as helicopters, in some instances workers were reported to have non-life threatening but painful injuries and due to non-availability of helicopters must endure uncomfortable sea journeys back to shore for medical attention.

The Global Wind Organisation (GWO) have developed training standards for the offshore wind industry [58]. Their goal is to make H&S training standardised across the industry to raise standards and to make it easier for companies to ensure their employees have been adequately trained. If workers have been trained to GWO standards then they would be able to move between projects or employers without needing to be re-trained each time. The GWO has developed standards that cover training in areas including basic safety, advanced rescue and first aid. Over 200,000 people have completed training to GWO standards [59].

Due to the remote location of wind farms emergency response is an extremely important element of keeping offshore wind workers safe. The development of further research in this area is required to share ideas and improve standards as the industry grows. Section 3 discusses the rates of emergency response incidents reported in the industry.

2.6. Risk assessment

Puisa et al. have studied the potential for new risks associated with the use of multiple systems on service operation vessels (SOVs) in the offshore industry [60]. They highlighted that a complex system could have emergent properties that may pose unexpected risks. An example was an SOV with multiple systems that all have associated risk assessments and method statements for their operation. Traditional risk assessments will not pick up interactions between the different systems, a systemic hazard analysis is proposed to assess the interaction of multiple systems in an environment such as an SOV.

Mou et all performed an assessment of the key safety risks on Chinese offshore wind farms [61]. Their study used questionnaires sent to industry members to then prepare a fault tree analysis of an offshore wind farm. The study focussed on system rather than personnel safety and proposes the key risks based on responses received from 50 personnel in the Chinese offshore wind industry.

The risks associated with offshore wind will change as the industry grows and new technologies and automation are integrated into operations. Puisa has highlighted that as the complexity of offshore operations increases unexpected interactions between parts of the offshore system have the potential to create new risks. As the industry grows there is the potential for more new systems and technology to be implemented. For example, floating wind turbines open up new activities such as tow to shore maintenance and floating to floating heavy lifts. New systems incorporating automation, such as autonomous vessels and drones may also be deployed. The introduction of these new technologies can increase the complexity of offshore operations and result in the emergence of new safety challenges. This is again, an area with little research in the offshore wind sector.

2.7. H&S legislation

Research on offshore wind legislation has called for the implementation of safety case regulations as used in the oil and gas industry [62]. H&S challenges in offshore wind have been highlighted, including skills shortages, emergency preparedness, and increasing risks related to working further offshore. The adoption of stricter regulation has been proposed as a method of managing these issues and preventing incidents [62,63]. A detailed analysis of H&S legislation can be found in Section 4.

2.8. Discussion

This literature review section looked at existing OWI safety literature and relevant literature from other industries. This analysis has highlighted several areas where there are challenges in the OWI to be addressed and further research is required:

- Innovation is required in the reporting of accident data,
- The UK and EU sectors lack an official reporting method for offshore wind accident data,
- Leading indicators need further development for the offshore wind sector,
- Offshore wind work is physically demanding with unique challenges and requires further research,
- The unique planning constraints on the O&M of offshore wind could place pressure on operational safety, further innovation is needed in this area,
- The rapid growth of the sector and implementation of new technologies could lead to emergent risks that are unexpected.

3. Health and safety statistics analysis

This section will look at the available H&S accident data from the offshore wind industry to gain insights on the industries performance. To make a performance comparison, data was collected from the offshore oil and gas industry. Offshore oil and gas was selected as it is an industry that deals with similar challenges such as extreme weather conditions, transfer of materials and personnel to offshore structures and remote work locations. Much of the daily activities of offshore workers are also similar, such as electrical and mechanical maintenance work, managing lifting operations, climbing ladders, and accessing confined spaces. Data used in the comparison are collected from G+ and the international association of oil and gas producers (IOGP). The study is limited by the available accident data from the offshore wind industry, of which G+ is the only available source.

3.1. H&S accident data analysis

Injury rate statistics available for offshore wind include the TRIR and LTIR, the drawbacks of these are outlined in Section 2, however this is the data available and is still an industry standard. While injury rates can be unreliable when working with small numbers, cross industry comparisons with large datasets are valid [12]. 95 % confidence intervals were calculated for both data sets using the Wilson Confidence Interval method [12,64].Fig. 1 shows a comparison of the TRIR for the offshore oil and gas and offshore wind industries. Fig. 2 shows the same comparison but using the LTIR.

In Figs. 1 and 2 the size of confidence interval for the oil and gas industry data is an order of magnitude smaller than that of the offshore wind industry. This is due to the much larger number of hours worked in the oil and gas data, this increases the confidence in the validity of the statistics. For example, in 2020 the recorded hours worked from IOGP were over 650 million, whereas just 25 million hours were recorded by G+. Both industries have shown a decline in incident rates since 2015, however the offshore wind industry incident rates are significantly higher. Over the past 5 years the wind industry TRIR has been over 3 times higher and the LTIR 4 times higher than the offshore oil and gas industry. Due to the greater volatility in the offshore wind statistics and the lower personnel hours it is harder to draw a conclusion that the decline in numbers represents a significant improvement in performance. Factors that govern injury rates are extremely complex and have been much debated in the research, some factors that are commonly agreed to be important are safety culture, worker competence and training standards, stakeholder engagement, supply chain capabilities, design and planning and hazard identification and control.

G+ also publish the incident rates for the industry broken down between the operations and the construction phases of projects. Fig. 3 shows the comparison of the two datasets. The data is only available for 4 years but shows a clear difference between the two project phases. The TRIR for operational sites is on average 3 to 4 times that of construction sites. The reasons for this discrepancy are not clear. It might be expected that construction would have a worse injury rate, wind farm construction will include more high-risk activities such as heavy lift operations and working conditions will be changing every day, however this may mean wind farm construction sites receive more attention from senior management and safety inspectors. Differences in injury reporting may also be a factor, research has shown that temporary workers are less likely to report injuries due to job security concerns [66]. The nature of construction work will mean that more workers are on temporary contracts compared to O&M contracts which are likely to be longer term, so this could mean there is more under-reporting on construction projects.

The G+ statistics have recorded no fatalities since they started reporting in 2014. However, an internet search can find reports of serious incidents that do not appear in the G+ statistics, highlighting

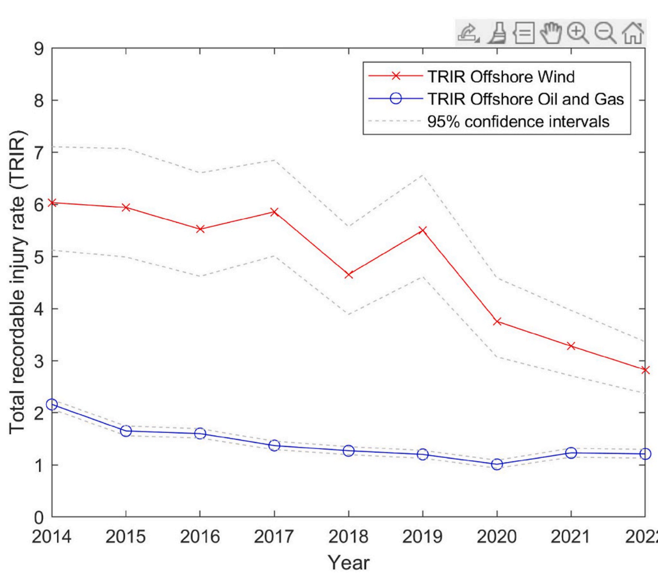

Fig. 1. Comparison of TRIR for offshore wind and offshore oil and gas industries [10,65].

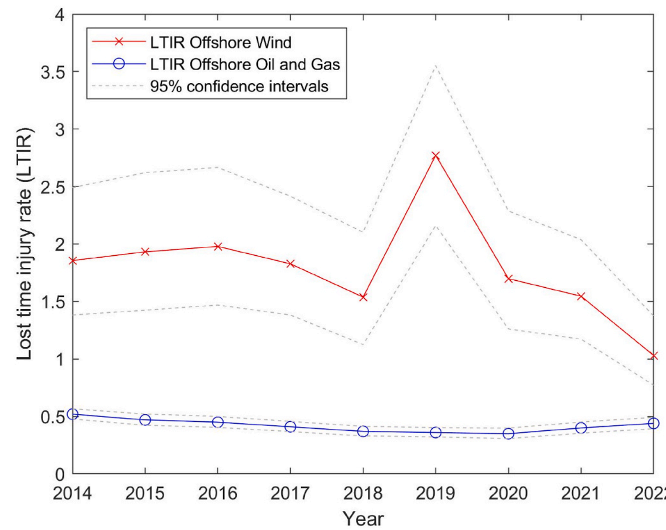

Fig. 2. - Comparison of the LTIR for offshore wind and oil and gas industries [10,65].

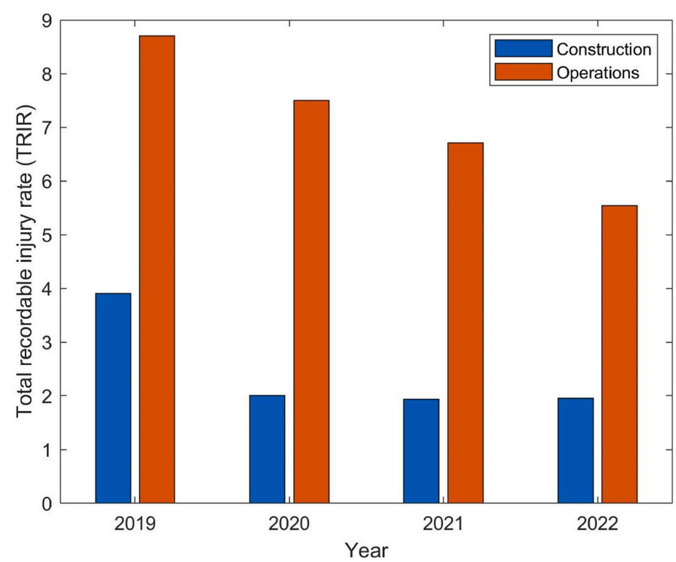

Fig. 3. Comparison of offshore wind construction and operations injury rates [7].

that not all offshore wind projects will be included in those figures [67]. G+ are the only organisation publishing accident statistics specifically for offshore wind, however it is missing large parts of the industry. Fig. 4 shows the hours worked by country for all G+ members that reported accident statistics [10]. Fig. 5 shows the GW of installed capacity of offshore wind farms globally [59].

The differences in the charts highlight that there are large sections of the offshore wind industry which are not included in the G+ data. While China has the largest installed capacity, they do not have any reporting in the G+ data set. This is a key limitation to this study and the availability of more accident data covering the entirety of the offshore wind industry would allow for further research to be completed.

Emergency response incidents are also reported by G+, these indicate when an accident has required response of an emergency team and possible medical evacuation of personnel. These are therefore a good indicator of accidents with higher potential for negative outcomes.

Fig. 6 shows the number of emergency response events every year reported by G+. There has been an average of 30 emergency response events every year since 2014. G+ also report that on average 40 % of

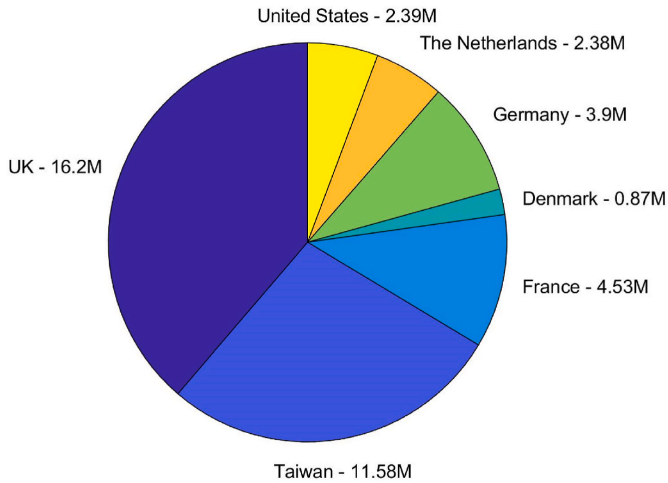

Fig. 4. Hours worked in G+ member countries.

these have been classed as high potential incidents.

3.2. H&S statistics discussion

The results shown in section 3.1 indicate that the OWI industry injury rates are significantly higher than the offshore oil and gas industry. This suggests that there is scope for large improvements in H&S performance at offshore wind farms. The offshore wind TRIR shows a slight decreasing trend over the past five years, however any improvement in the LTIR is less obvious. The OWI has had no fatal incidents reported since G+ began collecting data, however, the relatively high total recordable injury rate and number of emergency response events could indicate that there is a risk of serious incidents.

Research has shown a link between the number of minor safety incidents and how they might relate to more incidents or fatalities [68]. The accident triangle, also known as Heinrich's triangle, is well known among H&S professionals. It is based upon research from Heinrich in the 1930s which established a relationship between the number of minor incidents and major incidents. More recent studies have updated the triangle with new statistics, one such study from the US estimated a relationship of 500 lost workday cases to one fatality [68]. Research from the oil and gas industry has investigated whether the Heinrich, or Bird's triangle still holds in the 21st century [69]. A study using a large H&S database from the oil and gas contractor Schlumberger found that as TRIRs have reduced over time, the fatality rates have not reduced at the same rate [69]. This appears to show that the Heinrich triangle may no longer hold true. The authors concluded that a reduction of minor incidents will not always lead to a reduction in serious incidents and that we need to consider the category of incidents [69]. Despite debate about the validity of the Heinrich triangle, many minor incidents indicates that there may be unaddressed risks and that these could lead to more serious accidents occurring.

Figs. 4 and 5 show that there is a large section of the industry, primarily in China where accident numbers are not included in the G+ data. This indicates there are potentially many more accidents taking place that are not included in accident data. Media reports that can be found online also indicate some serious accidents have taken place, possible including fatalities. Furthermore, under-reporting of occupational accidents is known to be an issue across all types on industries. A recent study in Australia found that only 19 % of occupational injuries were correctly recorded [70]. The study concluded that case management was being used to reduce injury rates, so for example, recordable injuries were downgraded to first aid injuries. These issues will contribute to error in this type of study; however, this is likely to mean that injury rates are worse than reported and reinforces the need for

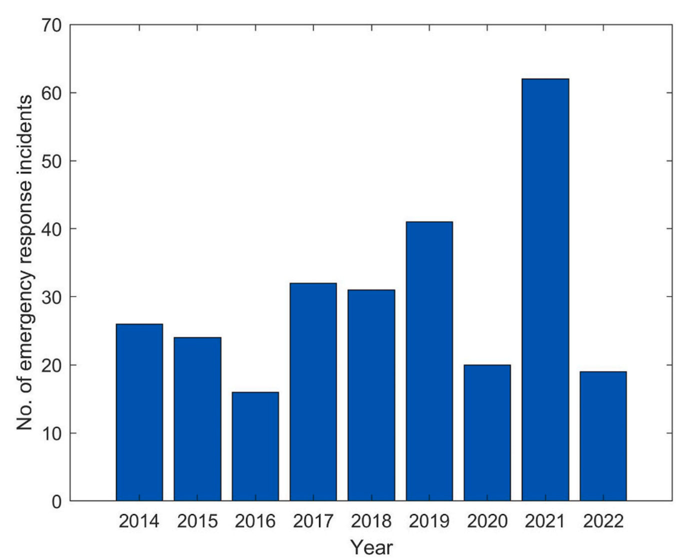

Fig. 6. no. of emergency response events each year among G+ members.

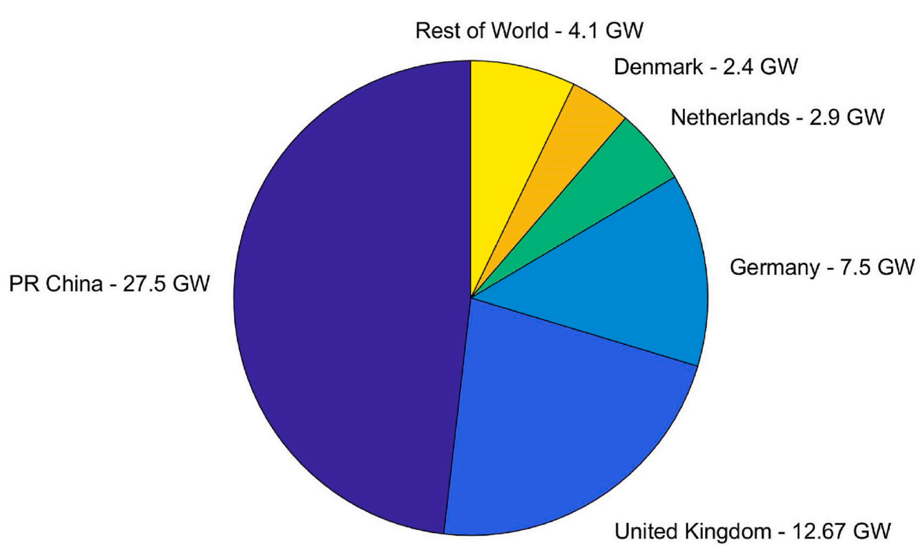

Fig. 5. Global GW of installed capacity of offshore wind by country.

improvement.

Overall, the comparison of incident statistics shows what there is opportunity to improve H&S performance in offshore wind. The offshore wind industry is still in the early stages of development so it is not surprising that it might not have the same performance level of a mature industry such as oil and gas, however as the industry continues to grow it is important that safety improvements are also made. While performance can be improved, the industry should also look at innovative methods of risk measurement and reporting as have been developed in other industries. The reliance of the OWI on TRIR and LTIR to measure performance, particularly where they are reported without the use of confidence intervals is a weakness.

4. Risk profile and industry growth

4.1. Background

Offshore wind continues to grow worldwide, while growth is usually discussed in terms of additional MW of capacity installed, it can be useful to consider other measures when considering risk exposure. To this end, an analysis of the number of technician transfers to turbines expected to occur annually up until 2030 within UK waters has been calculated. Technician transfers to a turbine can be considered a good measure of risk exposure, as it quantifies the number of visits to turbines by personnel who will be exposed to risk in the journey itself, as well as the transfer to the turbine and the subsequent work that they are carrying out on the turbine. UK data is used for the calculation in this section; however the same trends will apply to other offshore wind sectors.

4.2. Methodology

To calculate the future number of technician transfers, it is necessary to find the expected number of turbines installed each year and the average number of visits per turbine.

i) Turbine numbers

Figures from Renewable UK show that in early 2022 there were 2297 offshore wind turbines installed and commissioned with a cumulative generation capacity of around 10.4 GW [71]. There are over 500 turbines currently being installed and a further 687 turbines planned in consented projects. If these projects are completed by 2026, the UK will have a total of 3507 installed. This represents a 53 % increase in the number of installed offshore turbines. The UK government has set a target of 40 GW of installed capacity by 2030, to achieve this the total number of turbines will need to increase to over 4,600, roughly double the numbers installed in 2022 [72]. For future projects up to 2030 a turbine size of 15 MW was assumed in the calculations.

ii) Technician visits

The increased turbine numbers will, in turn, increase the amount of maintenance work to be done and the number of technician visits to a site. SPARTA is a collaborative project run by the renewable energy catapult in the UK. It collects operational performance data from owners and operators in UK offshore wind industry. According to the SPARTA project the average technician visits to a turbine in their reporting period covering 2019 to 2020 was 6.5 [73].

A technician visit is defined as one technician visiting a turbine, including their step on and step off after their work. Other research from an operational offshore wind farm in the UK reported that turbines were visited by a vessel just under 19 times per year [74]. If an average vessel visit involved 4 technicians, then the numbers from the two sources would agree.

Based on the numbers outlined here, a forecast of future wind turbine technician transfers has been completed. The forecast is based on the following calculation steps:

$$N_T = 12\ T\ R$$

where:

N_T = No. of technician transfers/year.

T = No. of turbines installed.

R = Technician transfer rate/month.

The technician transfer rate is based on figures from the SPARTA project. The technician transfer rate has shown a trend of decreasing since the SPARTA figures were first published in 2015. It could be expected that there will be some continuation of this trend in decreasing technician visits due to improved O&M management. The forecast technician transfer numbers have therefore, been calculated as a range based upon the transfer rate staying as the current rate and following a similar trend of reduction up to 2030.

4.3. Transfer forecast results

The expected number of technician transfers have therefore been calculated based on the assumptions stated. Fig. 7 shows the projected growth in technician visits based on the reported average visits by SPARTA.

Transfers are projected to grow from around 180,000 per year in 2022 to between 300,000 and 350,000 per year in 2030. The upper estimate assumes that the technician transfer rate stays constant from 2020 until 2030. The lower range estimate assumes that the rate decreases following a similar pattern as seen between 2014 and 2020. Technician transfers gives a quantifiable indicator for the exposure that workers have towards the H&S risks associated with operating and maintaining an offshore wind farm. The more transfers there are indicates more journeys to the wind farm, more transfers to a turbine and more work carried out on turbines, these are all times when workers are exposed to risk. Any changes in the way wind turbines are operated and maintained that can reduce this number has strong potential to reduce the number of safety incidents occurring across the entire industry. With wind farms moving further offshore, technicians will also be travelling further and working in different ways. The latest round of leasing for wind farm sites in Scotland (Scotwind) includes 10 potential floating wind farm sites, the average distance to shore of these sites is greater than 100 km, whereas existing fixed bottom sites tend to be around 50 km from shore [50]. This shows another factor that is likely to increase the risk exposure to offshore wind workers in the coming years as the industry grows globally.

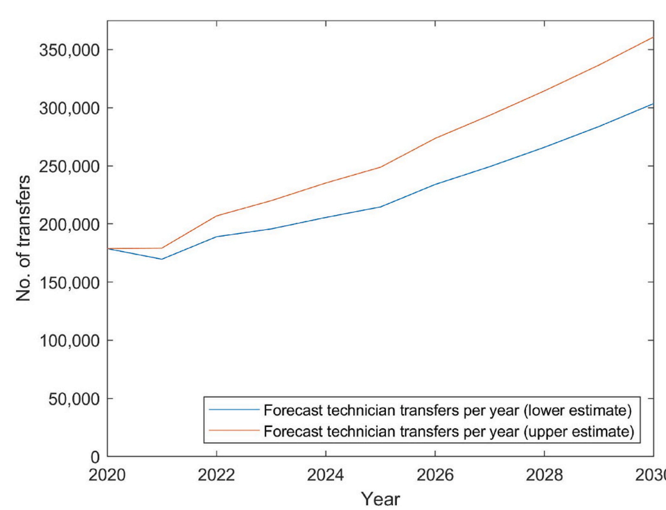

Fig. 7. - Technician transfer numbers UK forecast growth to 2030.

5. Health and safety legislation

One of the key aspects of success in managing health and safety relates to the governing legislation that sets minimum requirements to which industry must comply. It has been noted that in the early days of offshore wind development the H&S risks were often underestimated [75]. One challenge to effectively manage offshore wind H&S is developing an adequate legislative regime that is suitable for the full range of activities involved in operating and maintaining an offshore wind farm [75]. There has also been commentary that one of the reasons for the relatively poor safety record of the offshore wind industry is due to the lack of a comprehensive safety legislation regime [62]. Comparisons have been made to the offshore oil and gas industry in the 1970s, which went through rapid growth and suffered from poor H&S performance as a result [62]. This led to the introduction of new legislation to manage the industry [63]. This section looks at how the UK applies legislation to the management of safety in offshore wind. As one of the largest existing offshore wind markets lessons learned in the UK have the potential to be applied to other countries. For this study, a review was completed of the relevant legislation that applies to offshore wind energy operations and maintenance in the UK. Comparison was then made to the legislation applicable to the UK offshore oil and gas industry. It should be noted that while this work refers to UK legislation, there can be differences in applicable legislation across the constituent countries of the UK. For example, Northern Ireland has its own version of the Health and Safety at Work Act. For simplicity, the study refers to UK legislation, but care should be taken to check applicability across the different jurisdictions within the UK. This study also has not considered shipping legislation that is often applicable to vessels involved on offshore wind energy work.

The discussion of legislation often involves arguments over the burden of cost and administration and that there is already too much H&S legislation, recent reviews have found this not to be the case. In 2011, Professor Löfstedt was asked by the UK government to review all UK health and safety legislation to determine if it was fit for purpose and if there was scope to reduce and simplify legislation [76]. The report found that there wasn't a case to significantly reduce legislation and that it had a net benefit in terms of reducing incidents and costs for industry. However, there were areas where legislation could be simplified and consolidated.

The Health and Safety at Work Act (HASWA) 1974 sits at the top of the H&S legislation hierarchy and is applicable to the UK offshore wind industry and the offshore oil and gas industry [77,78]. The HASWA consolidated much of the existing H&S legislation and introduced a risk-based philosophy that allowed duty holders to assess risks and implement suitable measures to mitigate them to a level that is *'as low as reasonably practicable'*.

The HASWA was extended in 2013 by the Health and Safety at Work Acts 1974 (Application outside Great Britain) Order 2013. This ensured that the act would apply to works outside UK territorial seas and to floating offshore wind turbines [79].

The HASWA also created the Health and Safety Executive and gave it powers to both issue regulations and to enforce the application of regulations and investigate incidents. While it is not possible to directly assess the impact of legislation such as the HASWA, there has been an improvement in H&S performance across industries in the UK since its introduction in 1974. UK construction industry annual deaths were at 276 in 1964 and fell to 100 by 1984, there were many improvements in working practices over this time, but improvements to the legislative regime likely also account for some of this improvement [80].

The HASWA gives power to the Health and Safety Executive to implement further health, safety, or environmental regulations. There are many of these across all industries that regulate all kinds of activities, from the use of personnel protective equipment, to lifting equipment and the control of hazardous substances. Regulations made under the HASWA only specifically apply offshore if there is a clause within them that confirms their application [81].

Below the HASWA the next most significant pieces of legislation that apply to the OWI are the Management of Health and Safety at Work Regulations 1999 (MHSWR) and the Construction (Design and Management) Regulations 2015 (CDM Regulations). The MHSWR introduced a statutory requirement for duty holders to complete risk assessments for their work activities [82,83]. This requirement applies to the OWI industry and oil and gas industries. It also includes other requirements such as a duty for employers to provide adequate training and providing information about risks to employees.

The CDM regulations are one of the most important requirements that apply to offshore wind, they do not apply to offshore oil and gas [83]. The MHSWR regulations place duties on certain key stakeholders' in projects. The key duty holders are the Client, the Principal Designer and the Principal Contractor. The CDM regulations define construction work as including activities such as commissioning and maintenance, so wind farm maintenance activities are included within their scope. There are however edge cases where short duration and routine maintenance jobs won't fall under the CDM regulations. The regulations set out responsibilities and processes that must be followed by all parties. These include a requirement for designers to consider risks throughout all stages of the lifecycle of a facility. Designs must consider how a plant will be maintained, and suitable mitigation measures should be built in. For example, handrails at exposed edges where personnel would need access for maintenance. The regulations first came into force in 1994 and so would not have originally expected their extensive use for offshore wind energy works. There are not any aspects that specifically address offshore risks. These include aspects such as development of a construction phase plan and engineering risk assessments. Since the first issue of the regulations in 1994 they have been updated in 2007 and 2015. Updates have attempted to streamline the legislation and take on board criticism from users. It has been questioned if their introduction has led to any improvements, and the safety statistics from the UK construction industry do not show any obvious signs that they have [80].

The CDM regulations do not apply to offshore oil and gas, their closest equivalent would be the Offshore Installations (Safety Case) Regulations 2005. Wifa has claimed that the H&S performance of the OWI lags the oil and gas industry and that a lack of suitable legislation is a cause for this [62]. They proposed that legislation like the safety case regulations should be implemented in offshore wind. Wifa also completed a comprehensive review of the safety case regulations and found that while there have been criticisms the regulations are 'robust and would benefit other offshore industries' [63].

In terms of legislation, the clear difference between oil and gas and offshore wind are the application of CDM regulations and the safety case regulations. With the safety case regulations applying to oil and gas, but not the OWI and CDM applying to OWI but not oil and gas. It is worth comparing the two pieces of legislation to help inform how suitable the CDM regulations are in governing H&S in the OWI. Table 1 shows a summary of the key differences between the two pieces of legislation.

The first point of comparison is considering the background for the implementation of both pieces of legislation. The safety case regulations

Table 1
Comparison of items included in legislation.

Feature	Legislation	
	CDM 2015	SCR 2005
Construction phase plan	✓	
Health and Safety file	✓	
Safety and environmental management system		✓
Major accidents prevention policy		✓
Formal review and acceptance		✓
Focus on emergency response		✓
3rd party verification		✓

arose as a direct reaction to the Piper Alpha disaster. They were implemented following the recommendation of the report by Lord Cullen into the disaster [84]. The motivation for developing the CDM regulations were to address the poor performance the construction industry had seen in the 1980s [85]. A key reason for the poor performance was believed to be a lack of coordination between Clients, Designers and Contractors. The strategy of the CDM regulations was to reduce incidents by improving the design and planning processes of construction work [80]. The CDM regulations and Safety Case Regulations, therefore, have a focus that reflects their origins. The CDM regulations are focussed on assigning duties to the various parties to construction projects. These are, the Client, Designers and Contractors. They also emphasise designing out risks and improving planning and management of the construction phase of a project. The Safety Case Regulations have a strong focus on major accident prevention.

The key deliverables of the CDM regulations are, the '*Construction Phase Plan*' and the '*Health and Safety File*'. The construction phase plan is drawn up by the principal contractor in charge of the works. It must cover all aspects of the construction work and will set out how work is carried out while managing risk to health and safety. It is completed prior to setting up site and constantly updated throughout the project. There are no formal requirements for its review and approval by any other parties. The Health and Safety file is a record that contains all the documents that would be required to safely maintain, repair, renovate or demolish a project.

So, the Construction Phase Plan is a key document how the H&S of a project is managed, whereas the H&S File is a deliverable that remains with a project after completion and enables future users to have all the necessary information about the project available to them.

The key deliverables of the safety case regulations include the documentation of the safety and environmental management system.

This needs to include aspects such as the:

- Organisational structure,
- Identification and evaluation of major hazards,
- Emergency planning and response,
- Management of change,
- Performance monitoring,
- Audit and review arrangement.

The safety case also requires a major accidents prevention policy to be implemented by the duty holder. There are other notable differences between the two sets of legislation. The safety case Regulations require the review and acceptance of the safety case by the competent authority. There is no specific review and approval of the construction phase plan under the CDM regulations. The safety case regulations require the development of a safety and environmental management system. The regulations also require that the implementation of the safety and environmental system and the functioning of safety critical systems are verified by a 3rd party. The operation of which will be checked by an '*independent*' and '*competent*' verifier. There are also specific penalties for a duty holder if the procedures on the safety case are not followed, these can include fines and up to 12 months imprisonment in Scotland, or 3 months in England and Wales. The safety case regulations also require confidential and anonymous reporting systems that allow workers to raise safety concerns. There is also a requirement for a monitoring system to track and report the H&S performance of the facility. Finally, the safety case regulations have a stronger focus on emergency response. The safety case regulations state that the '*duty holder must perform internal emergency response duties*' and includes 14 clauses specifying requirements. Part 4 of the CDM regulations includes milder language such as *'where necessary … suitable and sufficient arrangements for dealing with any foreseeable emergency must be made'*.

There are some aspects of the safety case regulations that stand out as being superior to what is required under the CDM regulations. These include the safety case itself which requires the operator to develop a comprehensive document that covers the full scope of a project from engineering to decommissioning. In contrast, CDM regulations require the construction phase plan. The construction phase plan is also a comprehensive document that aids in planning a project, however it was not developed specifically for operating and maintaining an offshore wind farm. It was intended for the management of a construction project, although it does apply to maintenance activities. It is unlikely that maintaining a wind farm offshore was ever thought of when the legislation was written. Other advantages of the safety case regulations are, it's focus on emergency response with the specific nature of offshore work in mind, and the requirements for regulator acceptance and 3rd party verification of its systems. Finally, requirements for reporting and worker involvement. The clear difference is that the safety case regulations were specifically written for Offshore Oil and Gas work, but CDM regulations were not written with the offshore wind industry in mind.

There are many other important pieces of legislation that apply to both industries. These are often more prescriptive and set standards for specific activities or hazards. These include legislation for lifting operations, the operation of mechanical plant and standards for personal protective equipment. This section has highlighted that they key difference between the legislative regimes of offshore wind and oil and gas are the applicability of the CDM Regulations and the safety case regulations. The UK has opted not to develop specific legislation for the offshore wind industry, but the application of existing legislation may lead to gaps in the legislation that fail to address risks unique to the industry. The offshore oil and gas industry has successfully implemented specific legislation which has a strong focus on elements important to that industry such as emergency response and verification of safety critical systems.

Other leading offshore wind markets are taking different strategies in terms of the development of legislation. Norway has put the regulation of offshore wind under the authority of the Petroleum Safety Authority and are currently developing offshore wind specific legislation [21]. The USA went through a reorganisation of the regulatory authorities for offshore energy following the Macondo disaster, and offshore wind is now overseen by the BSEE and it is expected that existing regulations will be updated to address the challenges of offshore wind [86]. As offshore wind continues to grow across the world the development of specific safety legislation for the sector is an important factor in ensuring the industry is managed safely.

6. Discussion

This work set out to complete a review of the state of H&S in the offshore wind industry. In doing so it has looked at the latest research in the industry, the performance based on accident statistics, the changing risk profile and how the industry manages safety through legislation.

The literature review found that while there is some industry specific research there is far less than more established sectors such as oil & gas or civil construction industries. The literature highlights that offshore wind development should be considered as a high-risk activity which has unique challenges. These include the impacts on workers related to the stresses of offshore wind work, challenges of planning maintenance around weather restrictions, and emergency response management. Relative to other industries there has been little innovation on implementing innovative methods of measuring risk levels and safety performance. The industry can learn from oil & gas the importance of moving beyond lagging indicators of safety performance and developing indicators specific to the challenges of the industry. The literature review also identified that the deployment of new technologies and more complex systems into the offshore wind industry has the potential to create emergent risks that have not been anticipated.

The review of safety statistics shows the global offshore wind industry has a worse performance as compared to an industry with similar challenges, such as the oil & gas industry. In addition, large parts of the industry are not covered by reporting bodies such as the G+. There are some signs of recent performance improvements however, it remains to be seen if this is a significant trend. It should be noted that caution must be applied when looking at performance indicators such as TRIR. Offshore wind is a far younger industry with less work hours in an operational year, so a single injury has a greater impact on the injury rate as the denominator is much smaller. It is also very encouraging that G+ has not reported any fatal incidents since they began publishing results. Again, this needs to be considered with caution as a high minor incident rate, could indicate the potential for more serious incidents in the future. A simple google search highlights three serious incidents in the offshore industry reported in the media between May 2020 and October 2021, one of which resulted in multiple injuries and one with four persons lost at sea [87] [88] [67]. None of these are found in industry reports. Furthermore, it is important to ensure that injuries are reported and not hidden, research into injury reporting rates show that under reporting appears to be common in many industries, so a danger of over focus on injury rates is that pressure builds to under report. This is a further reason to look at the development of more innovative measures of safety performance.

This study has also considered the changing risk profile of the industry and has shown that there will likely be an increased exposure of offshore technicians as the industry grows. In addition, the development of more remote sites and roll out of new technologies, has the potential to increase the risk of more serious incidents. When considered in the context of the high existing injury rates and the numbers of emergency evacuations this highlights the need for further focus on the safety management of the industry.

Finally, the study has considered how safety legislation is used to manage the industry with an in depth look at the UK safety legislation considering its place as one of the largest offshore wind markets. It was seen that the UK has so far chosen not to adopt specific legislation for the offshore wind market. This contrasts with the oil and gas sector which developed specific legislation based upon hard lessons learnt following serious accidents. This study has highlighted some of the unique challenges of managing safety in the OWI. The comparison of the CDM regulations and the safety case regulations also highlights that the CDM regulations are weaker in several key areas and weren't written with offshore operations in mind. As the wind industry continues to grow the development of specific legislation tailored to the needs of the industry should be considered. Other developing sectors such as the USA and Norway are both looking at developing specific legislation to address challenges in offshore wind. Other jurisdictions around the world should consider the development of specific legislation that can address the risks faced in offshore wind. Once legislation from Norway or other countries is released this could be of great benefit to other countries in developing their own frameworks.

The study is limited to the available accident data that is reported in the public realm, primarily that published by G+. If more data became available this would allow the scope of the study to be broadened. Analysis of technician transfer numbers and safety legislation was based on the UK industry, as a leader in the offshore wind market, there is more information available in the UK compared to other countries. Additional analysis including more countries would be beneficial for further studies.

7. Conclusions

The offshore wind industry presents significant H&S challenges, which require further attention from academic research The literature review identified that research on the safety challenges of offshore wind is still very limited and further work is needed in the human worker impacts, safety performance measurement and emergency response. Methods of safety performance reporting are limited to lagging indicators and the industry should look at developing more innovative reporting methods of risk and safety performance such as those used in the oil and gas sector. This should include innovative methods such as industry specific leading indicators of risk and industry sector injury reporting at a national level.

This paper highlights that offshore wind is a high-risk industry and current injury rates are 3–4 times those of the oil & gas industry, indicating there is huge potential for improvement. It also found that existing globally reported injury rates are missing key sectors such as China and do not include some serious incidents due to not being part of the scope of reporting groups.

Rapid growth and the changing nature of the industry mean the risk profile of the industry is growing. Worker exposure to hazards is likely to grow due to more offshore work taking place in the coming years. In conjunction with the development of more remote sites and the implementation of new technology this could mean the potential for more serious accidents to occur. A focus from research, industry and regulators on safety is important to ensure these challenges are met before serious accidents take place.

Finally, legislation is a key aspect of the management of safety performance, regulators should consider the development of industry specific legislation as has been done in the oil and gas sector to ensure the offshore wind sector can be safely managed.

8. Further work

Further work in this area includes the development of key performance indicators to measure H&S performance and to assess risk levels. This would include more innovative methods to present existing data as well as industry specific leading indicators. Research on the impacts on offshore workers and how these can be reduced as the industry grows is also important, this should include consideration of the impacts of the implementation of new turbine platform designs and technologies such as automation.

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CRediT authorship contribution statement

David Rowell: PhD Candidate, Conceptualization, Formal analysis, Data curation, Writing – original draft, Visualization, Investigation. **David McMillan:** Reader, Supervision, Writing – review & editing. **James Carroll:** Reader, Supervision, Writing – review & editing, All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: David Rowell reports financial support was provided by Engineering and Physical Sciences Research Council.

Data availability

Data is taken from freely available reports which have been referenced.

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