Human factors in onshore and offshore wind: a scoping review.

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REVIEW ARTICLE

Human factors in onshore and offshore wind: a scoping review

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ABSTRACT

A safe, healthy and competent workforce in the wind power industry is essential for meeting climate goals and energy needs. Wind technicians conduct critical tasks on wind turbines often in remote, hazardous environments in onshore and offshore locations. However, industry incident data indicate safety concerns in relation to operations and maintenance work. Despite behavioural issues significantly contributing to these wind incidents, the limited human factors research in the wind sector typically focuses on design and physiology. A scoping review was carried out to examine the psychological and organisational factors that impact on wind technician safety, health, and performance. In total, 13 research articles examining human factors in wind were identified, as well as 8 items from the grey literature. A preliminary framework was developed encompassing individual, crew/team, organisational factors, and task and environmental factors. This framework can be used to direct future research and assist practitioners to design effective interventions.

Practitioner Summary: This scoping review provides practitioners with a preliminary framework of 13 human factors that impact wind technician safety, health and performance, emphasising psychological and organisational factors. This can be used to direct effective interventions that support worker safety, health and performance in the expanding wind industry and wider renewable energy sector.

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Human factors; psychological factors; wind technicians; onshore offshore wind; worker safety

1. Introduction

The global wind industry is experiencing an unprecedented period of expansion in response to net zero targets, emerging markets and international energy demands. In 2023, 54 countries across all continents built new wind power installations, making it the most successful year ever for wind, with forecasts of continued growth (GWEC 2024). This has significant economic implications with the wind energy market estimated to be worth \$89.60 billion globally in 2023 (Precedence 2024). Investment in offshore wind projects is estimated to be worth up to £92bn for the UK economy by 2040 (Renewable 2024). To meet the renewable energy targets of 50 GW, the UK aims to recruit over 72,000 people in offshore wind by 2030. Wind technicians, responsible for maintaining the operation of both onshore and offshore wind turbines, are a key growth group with global estimates suggesting half a million wind technicians will be needed by 2026 (GWEC. 2022). Ensuring a competent operations and maintenance (O&M) workforce is vital given that these costs typically represent 20-25% in the lifetime of a wind turbine (Wind Europe 2021). Onshore wind has historically had a greater market share of the wind energy industry, however, in recent years offshore wind has experienced a rapid growth (Desalegn et al. 2023). Such rapid progress presents challenges for maintaining safety standards and training at scale, with industry incident data revealing safety issues during operations and maintenance (G+ 2024).

Human factors and ergonomics approaches have been introduced in similar sectors as means of enhancing safety and accelerating training (e.g. Teperi et al. 2023). Yet, there is a limited understanding of human factors in the emergent wind industry, typically focusing on the ergonomic and physiological factors that influence wind technicians' performance. This scoping review examines the psychological and organisational factors that shape onshore and offshore wind technicians' safety and performance during O&M. The wind industry context (1.1), including health and safety (1.2), and human factors approaches (1.3) will be outlined in the

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next sections, followed by the study aim (2), methods (3) results sections (4) and discussion (5). It provides a foundation on which future research, industry safety guidelines, and training standards can be based, supporting an efficient and safe renewable energy sector.

1.1. Wind technicians

Wind technicians conduct varied and complex operational and maintenance activities (O&M) on wind turbines often in hazardous, remote environments. Tasks may need to be completed in limited time due to scheduling and pressure to complete within operational weather windows, sometimes working under extreme environmental conditions (e.g. hot/cold, high winds). Crews typically consist of two-four people, working with minimal supervision and often limited communication (e.g. with the beach or service vessel) for up to 12–14 hour shifts.

During scheduled preventative maintenance (e.g. on a biannual cycle), technicians will monitor and control the operations of the asset through inspections, technical checks or with a condition monitoring system. Alternatively, when the system has malfunctioned, technicians will be required to diagnose the cause of the failure and carry out corrective maintenance. This requires high-level risk awareness, problem-solving and decision-making skills. As breakdowns interrupt normal energy production, there will be an additional pressure to solve them as quickly as possible to get the turbine running again (Cunha, Silva, and Macedo 2024).

Work in onshore and offshore wind shares many similarities, with technicians completing the same type of tasks, however, the method of travel to the turbine and the environmental conditions can be different. Onshore wind turbines are typically accessed via road, requiring a drive of up to several hours to reach the wind farm, often in remote locations with varying road quality and access (Ladenburg et al. 2020). Technicians travelling to an offshore turbine, typically do so either from a port on Crew Transfer Vessel (CTV) for up to three-four hours or from a Service Operations Vessel (SOV) on which the crew live for rotations of two-three weeks. Transfer from the vessel to the turbine can occur up to three times per day depending on the work schedule.

Both onshore and offshore technicians will then need to ascend ladders inside the tower before reaching the nacelle which houses the generator, gearbox, drive train, and brake assembly (Milligan, O'Halloran, and Tipton 2019). Depending on the turbine size, the height of the average onshore turbine is 94 metres but currently can be up to 260 metres for offshore turbines. Whilst both onshore and offshore wind technicians can experience adverse environmental conditions (e.g. hot and cold temperatures) while working at height, offshore wind technicians may be exposed to additional hazards (e.g. sea state and taller turbines with subsequent turbine sway; Hanson 2013; Scheu et al., 2018). Crew are also first responders in an emergency response situation (e.g. casualty evacuation; Milligan, O'Halloran, and Tipton 2019). Onshore medical assistance will typically come via road, often using national medical services. Offshore medical assistance comes from nearby CTVs or SOV, or helicopter, depending on the severity of the situation. Subsequently access to, and response time from, emergency services will vary. Although some of the hazards are not unique to offshore wind installations, turbine maintenance activities may be more demanding when located in a remote maritime environment (Tveiten et al. 2011).

1.2. Safety in the wind industry

Wind workers in both sectors face a range of health and safety hazards including weather conditions, noise, vibration, long shift patterns, work pressure, isolation, poor communication, and contract uncertainty (Karanikas et al. 2021; Rowell, McMillan, and Carroll 2024). Technicians may also experience mast sway, particularly on very tall turbines, in which the turbine can sway in response to the weather conditions (Scheu et al., 2018). This can result in nausea or movement-induced illness, with associated reduction in performance or risk of errors (Hanson 2013; Hanson and Thatcher 2019). The tasks are physically demanding, requiring working at height and suspension in confined spaces, manual handling, and adoption of awkward body positions (Cunha, Silva, and Macedo 2024) with reports of musculoskeletal disorder symptoms (Fox 2019). Consequently, these factors may be impacting on technicians' health (e.g. sleep, Mette et al. 2018a), safety and productivity in the workplace.

Industry incident data reveal safety problems during operations and maintenance. In 2023, 1679 offshore incidents were recorded by the G+Global Health and Safety organisation with data submitted from their membership of 20+ wind companies from Europe, Asia and the US (G+ 2024). Whilst there was a 39% increase in the total number of hours worked, the recorded incident rate had an increase of 94% in relation to the 867 the previous year, including one fatality in 2023 (G+ 2024). Lifting operations, routine maintenance, manual handling, operating machinery, access/egress and transfer to/from CTVs were all identified as top work processes resulting in high consequence incidents (G+ 2022b, 2023). When examining operational sites only, electrical work was identified as having the highest recorded number of incidents (G+ 2023). The publicly available global G+incident data clearly emphasise the need to address safety and training in the wind industry, with the total recordable injury rate estimated to be three times higher and lost time injury rate four times higher in offshore wind, than in oil and gas (Rowell, McMillan, and Carroll 2024). Consequently, the wind energy sector may benefit from identifying and adapting approaches that have been successful for similar sectors to improve safety and address training, in particular human factors methods.

Human Factors (HF) approaches are particularly pertinent to the wind industry because of the combination of contextual characteristics such as the remote, hazardous environment, awkward working conditions and small multi-skilled teams with limited communication and supervision (Hanson and Thatcher 2019). HF in the wind industry is typically viewed from an ergonomic perspective (e.g. Fox 2019; NAS 2013) with research examining the physiological factors that impact on worker performance (e.g. job task analysis, Milligan, O'Halloran, and Tipton 2019, 2024). Yet, compared to other maritime industries, there is a limited understanding of the human factors for offshore wind operations impacting on worker safety and productivity (Rowell, McMillan, and Carroll 2024). Given the emergent nature of wind energy, to date the HF research has been disparate, focussing on occupational hazards (Karanikas et al. 2021) such as musculoskeletal (Fischer, Koltun, and Lee 2021), and worker seasickness (Earle et al. 2022). There are references to human and organisational factors beginning to appear in guidance using the UK Health & Safety Executive (HSE 1999) classification of HF into individual, task and organisational factors (e.g. G+ 2018a; Safety On 2021). Whilst data indicate that behavioural failures contributed to 60% of the working at height incidents on wind turbines (G+ 2018a), there does not appear to be a comprehensive understanding of the psychological and organisational factors affecting the key role of wind technicians. For example, a data mining study of 240 wind turbine incidents classified types of human causes for incidents but did not consider influencing factors (Asian et al. 2017).

2. Study aim

The aim of the scoping review was to examine the HF research that has been conducted in the offshore and onshore wind context to date with particular reference to psychological and organisational factors influencing wind technicians' safety, health and task performance and to organise it into a framework that can be used to direct future research within this emerging industry.

3. Method

3.1. Search method

A scoping review was selected as a suitable approach as it allows for the examination of key factors relating to a concept or topic, mapping the available evidence and giving an indication of the volume of studies as well as an overview (Munn et al., 2018). The review was conducted with reference to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis extension for scoping reviews checklist (PRISMA-Sc-R; Tricco et al. 2018).

Five scientific databases were selected for use in the review process based on recent journal articles examining human factor related topics in the wind industry (e.g. Karanakis et al. 2021; Milligan, O'Halloran, and Tipton 2019), ensuring an adequate representation of the potential research. This consisted of Scopus, Web of Science, Science Direct, PubMed, and Spinger. Google Scholar was used to identify any additional relevant papers during the snowballing process, but it was not used in the initial search.

Keeping in mind the wide range of potential search terms to cover psychological and organisational factors, initial searches found that more specific search terms did not identify further articles. Consequently, a generic set of Boolean search strings were developed and refined: (e.g. "offshore wind" OR "onshore wind" OR "wind operator" OR "wind technician") AND ("human factors" OR "safety" OR "health" OR "hazard" OR "risk" OR "decision making" OR "awareness" OR "teamwork" OR "organisational culture" OR "fatigue" OR "stressors"). The initial search was completed by January 2024. Hand searches/snowballing were completed of the reference lists of the already identified articles by July 2024, resulting in further papers (Figure 1).

3.2. Article eligibility criteria

Given the limited research anticipated, minimum selection criteria were applied (Cochrane quality control Higgins and Green 2008; Pare and Kitsiou 2017 for methods). The inclusion criteria were that the article: focuses on wind technicians; relates to operations and maintenance activities; was published in English; and describes a study discussing the psychological and/or organisational factors that impact on wind technician

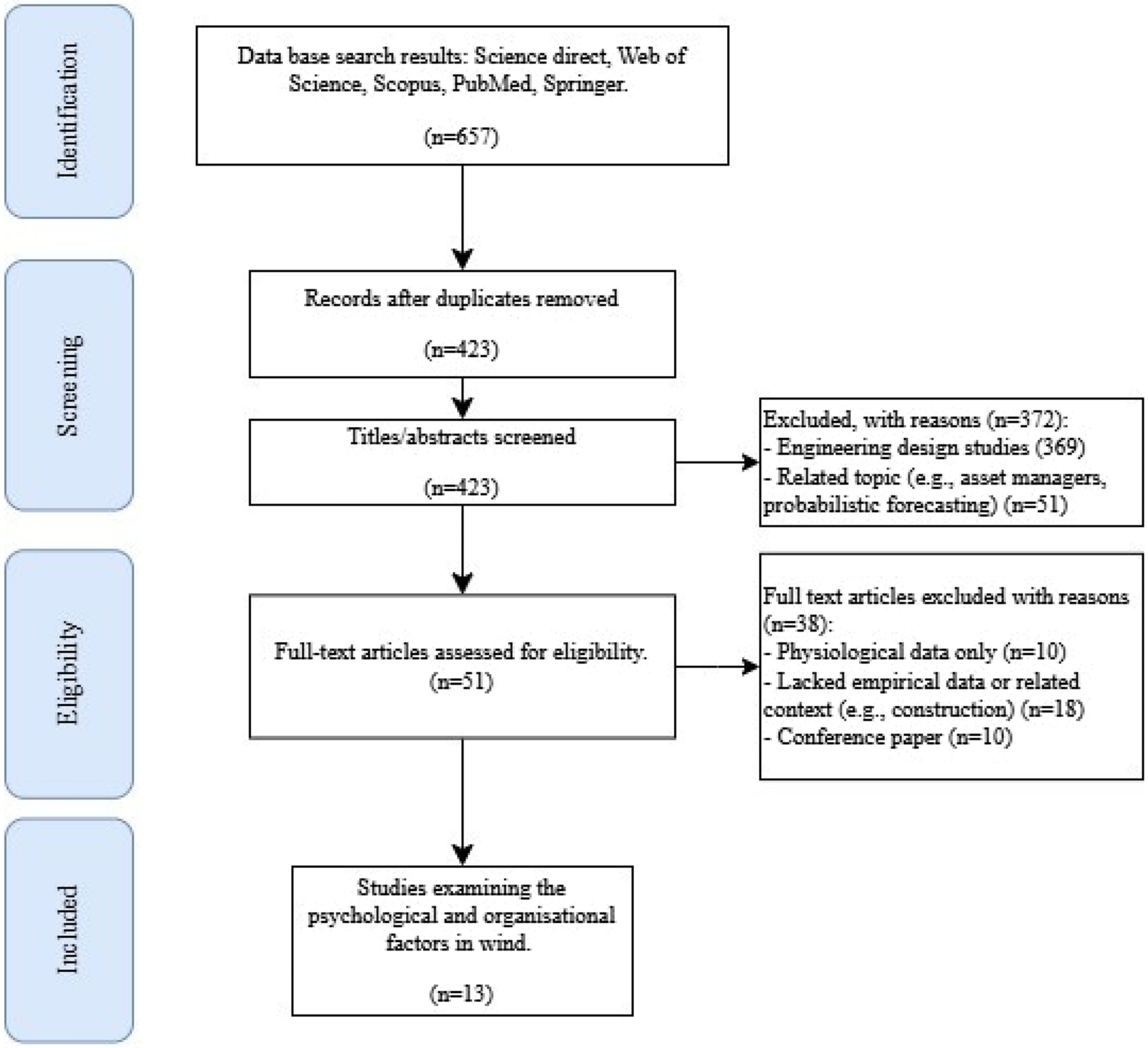

Figure 1. Summary of the paper selection process for this scoping review.

safety and/or performance. A broad approach to the psychological and organisational factors was adopted, with any factors at the individual, task, and organisational level accepted, in line with the HSE (1999) categorisation of HF that was in use in the wind industry. Given the nature of the wind industry, this was widened to include environmental factors (e.g. HSE 2024). No date restrictions were applied. Early in the search process it became apparent that not all papers clearly discriminated between onshore and offshore wind and given the limited body of research and the number of overlapping tasks, the search criteria were widened to include onshore wind (Boolean search terms above). Whether a study examined onshore or offshore technicians, or both, will be explicitly included in the results, where possible.

The exclusion criteria were that the article: was a conference paper; related to construction operations for wind turbines and their installation (e.g. Somi, Seresht, and Fayek 2021); or it relied on previous research findings or conjecture (e.g. a literature review). Research examining the potential human factors which may impact on O&M planners/managers was not included (e.g. Dawid, McMillan, and Revie 2016; Taylor and Jeon 2018). Similarly, HF research relating to shipping operations for offshore wind transport (e.g. G+ 2018b) was excluded.

3.3. Study screening and selection

Initially, 657 records were identified from the search with 234 excluded due to duplication. The remaining records were screened based on the eligibility criteria with the majority relating to engineering aspects of wind turbines (e.g. blade design). Given the broad topic areas and limited HF research in wind, any studies that discussed a potentially relevant factor were retained for full review (i.e. where the human factor was not explicit but potentially relevant). This reduced set of 51 studies was then reviewed for suitability by both authors with 38 excluded for not focusing on O&M (e.g. construction), conference papers, or lack of empirical data, including only reporting physiological data. A total of 13 studies were reviewed, including a Doctoral thesis and a Masters thesis, as outlined in Table 1.

Recognising that other sources (e.g. industry guidelines, sector incident reports, and industry news articles) may provide valuable insight into the psychological and organisational factors in wind, supplementary searches were conducted using popular search engines (e.g. Google Scholar) for grey literature (e.g. industry reports not indexed in the scientific databases). As these are not subject to the inclusion and exclusion criteria outlined above, the 8 items are shown separately in Table 2.

The articles were subjected to Braun and Clarke (2022) thematic analysis, producing a preliminary list of the HF that impact on worker safety and performance in offshore wind. Themes were grouped based on the HSE's (1999, 2024) categorisation of HF as this has already been applied in wind industry guidelines (e.g. G+ 2018a) and is reflected in the wider HF literature (e.g. in healthcare, Carayon et al. 2015). This categorises HF at the individual, the task and organisational levels. During analysis, an additional theme at the crew/group level was identified and the task theme was expanded to include environmental factors.

During the review and analysis process, it became apparent that many of the psychological and organisational factors discussed in the studies were closely linked to task and environmental factors. Whilst the study focus was on the former, a task and environmental factor theme summarising the relevant literature was included to provide a comprehensive review of the factors shaping wind technicians' performance during O&M. Additionally, given the limited HF research studies in wind energy, relevant studies that did not meet the eligibility criteria but that contained relevant reference to the psychological and organisational, as well as task and environmental factors have been provided in the results narrative (but not Table 1) to provide a richer understanding of the HF shaping wind technicians' safety and performance during O&M.

4. Results

In total, 13 research studies examining HF in onshore and offshore wind were identified, as well as eight items from the grey literature. Given the relatively nascent nature of wind energy, it is unsurprising that most of the HF research has been conducted over the past five years with many of the papers including as part of their methods, literature reviews to scope out particular issues (e.g. hazards or risks). Mainly qualitative methods such as interviews and focus groups have been employed, along with surveys to capture technicians' perceptions and experiences of working in the offshore and onshore wind sector. It is notable that a range of terms have been used in relation to a wind technician (e.g. worker, operator) and for accuracy have been retained in the results. However, it is possible that these may have different connotations in depending on the context.

Four categories, consisting of 13 factors were identified with 15 sub-factors, as shown in Figure 2. These factors are likely to interact with each other. It is notable that HF are starting to be recognised within the industry guidance materials, nonetheless, the results suggest that human factors, and their impact on safety and performance, are not well understood in the wind industry.

4.1. Individual factors

Three categories of individual factors were identified consisting of cognitive, social and personal resource skills that allow wind technicians to cope with a range of performance shaping factors as summarised in the later sections, including nine sub-factors.

4.1.1. Cognitive factors

Four cognitive sub-factors were identified in the scoping review, consisting of situation awareness, decision making, cognitive flexibility and competence as shown in Figure 2.

Situation awareness and decision making are essential for most jobs and have been recognised by industry as key skills for both offshore (G+ 2018b) and onshore wind (Safety On 2021). *Situation Awareness (SA)* was identified as an essential cognitive skill for offshore wind workers (Albrechtsen 2012), particularly when working at height (G+ 2018a). This included effectively detecting, monitoring, and interpreting signals of potential risk, including wave height and wind strength, building up a mental model of the turbine and external environment (e.g. weather, sea state; and identifying indicators to isolate the fault (Albrechtsen 2012; Hansen 2017). Furthermore, wind technicians' SA skills were flagged as key features in a resilient management system for reducing human error, such as preparedness, vigilance, anticipation and scenario planning (Mentes and Turan 2019).

Decision making skills in relation to troubleshooting, being able to assess potential solutions for the situation, and subsequent maintenance decisions are

Table 1. Summary of the 13 research studies identified shown in chronological order.

Author(s)	Context	Method	Psychological and Organisational Summary Points
Mette et al. (2017)	Offshore Wind (Germany)	Interviews (n = 42)	• Experiences of job demands and working conditions. • Physically demanding work, Absence from home, long shifts, social support, psychically demanding work, and camaraderie were discussed with variation in perceived job demands.
Mette et al. (2018a)	Offshore Wind (Germany)	Interviews (n = 21)	• Identified stress, fatigue, difficulties detaching from work, and sleeping problems. • Teamworking and social support valuable for coping. • Sense of control and adopting a self-determined approach to scheduling work identified for dealing with job demands.
Mette et al. (2018b)	Offshore Wind (Germany)	Online Survey (n = 250)	• Examined relationships between job demands, personal and job resources and stress. • Psychological detachment from work and social support partially mediated the impact of stress.
Ahsan et al. (2019).	Offshore Wind (Denmark)	Interviews (n = 26) and online survey (n = 136).	• Examines HSE management systems via stakeholders. • Workers perceive unharmonized HSE management systems, lack of common standards and gaps in incident reporting as potential risks with additional training reported as valuable (e.g. safety leadership, team coordination and communication). • Company specific HSE procedures are creating additional complexity, given sub-tenders of key suppliers, sub-contractors and sub-suppliers.
Fox (2019). (Masters Project)	Onshore & Offshore Wind (USA)	Literature review, video observations and online survey (n = 30)	• Ergonomic study of wind technicians during ladder climbing activities identified a range of environmental and task factors (e.g. workload, shift length/pattern and heat stress). • Highlights the need to institute a positive reporting culture in which workers feel able to report incidents, injuries and MSD symptoms.
Mentes and Turan (2019).	Offshore Wind (unspecified)	Literature review, plus expert input via workshops.	• Applies resilience engineering principles to maintenance activities for turbine management. • Discusses technician situation awareness and risk awareness, team situation awareness and teamwork, task complexity and time pressure, as well as organisational factors such as reporting and safety culture.
Milligan, O'Halloran, and Tipton (2019).	Offshore Wind (UK)	Document review, observations focus group (n = 9)	• Job task analysis highlights factors including physically demanding tasks, condition of PPE, shift pattern, fatigue, seasickness and environmental conditions.
McMaster (2020) (Doctoral project)	Onshore & Offshore Wind (likely UK given author location)	Systematic review, interviews (n = 10) and diaries (n = 19).	• Examines impact of fatigue on health, safety and productivity. • Fatigue cumulative for those on SOVs with teamworking and emotional intelligence regarded as important for coping with working/ living conditions. • A macho culture regarding reporting fatigue or ill health emphasised the need to foster a just culture as well as highlighting the potential risk of burnout for wind workers.
Pedersen and Ahsan (2020).	Offshore Wind (Denmark)	Literature review and interviews (n = 18).	• Examines emergency preparedness for offshore wind as judged by industry stakeholders • Variation between operators in terms of safety training, protocols, emergency response plans, and work instructions. • Offshore workers must assess an emergency situation and make the decision to determine if help is needed.
Earle et al. (2022).	Offshore Wind (UK)	Interviews (n = 14), vessel (n = 14) data, & survey app (n = 164 days of data).	• Examined technicians' experience of seasickness and wellbeing during transit on crew transfer vessels. • Developed a model to predict technician wellbeing that can be used to inform go/no-go decisions for sailing. • Discusses the effects of seasickness on technician cognition, fatigue, readiness to work, work performance, and safety via interview and app data.
Hussain, Khan, and Mover (2022)	Onshore wind (Pakistan)	Literature review, site visits (n = 7), online survey (n = 69 from 24 wind farms).	• Development and pilot testing of a Quality, Environment, Health and Safety culture scale but no evidence of psychometric analyses.
Cunha, Silva, and Macedo (2024)	Onshore wind (Portugal)	Activity diaries (n = 6), interviews (n = 5) and focus groups (n = 17).	• Examined the physical and psychosocial risks experienced by workers. • Risks reported include weather conditions, working at height and in confined spaces, awkward postures, ladder climbing, work pressure, emotional demands, poor communication and contract uncertainty.
Rowell, McMillan, and Carroll (2024)	Offshore Wind	Global G + incident data.	• Focus on health and safety in the offshore wind sector including analysis of G + incident reports. • Identified factors that may impact on worker safety (e.g. ladder climbing, confined space working, worker physical and mental wellbeing, and motion sickness.), • Emphasises the need to improve current HSE reporting for wind with a stronger focus on leading indicators (including safety culture) with better incident recording tools.

essential for corrective maintenance (Hansen 2017). Augmented reality technologies have been offered as a means of supporting troubleshooting during maintenance (e.g. Liu, Tsai, et al. 2023). *Cognitive flexibility* or readiness, relating to the ability of workers and teams to adjust and adapt to known and unknown

Table 2. Summary of the eight resources referencing HF in the offshore and onshore wind industry identified in the grey literature (e.g. industry guidelines, reports and news articles) in chronological order.

Author(s)/Source	Context	Content Type	Human Factor Summary Points
National Academy of Sciences (2013).	Offshore Wind (USA)	Worker Health & Safety Special Report (310)	• Human factors are recognised as important in offshore wind worker health and safety context, predominantly from an ergonomic perspective including task/ environment factors • Many companies had existing safety programs but a lack of consistent guidelines.
Renewable (2015)	Onshore Wind (UK)	Health & Safety Guidelines	• Guidelines highlight the need for health and safety leadership, including visible and active commitment from leadership to develop a positive safety culture. • Includes generic guidance on human factors, flagging the need for learning from incidents and sharing of best practice.
Tveiten et al. (2011).	Offshore Wind (Norway)	SINTEF HSE report.	• Identifies the HSE safety risk and hazards associated with offshore wind, outlining psychological (mental overload, stress) and physiological effects, time pressure, lack of expertise, communication and procedures as potential risks.
Mette et al. (2019 Health Offshore, Hamburg)	Offshore Wind (Germany)	Online manual	• Manual for health promotion for the offshore wind industry includes reference to environmental conditions, noise, confined space conditions, social relationships, and sleep.
G+ Global Offshore Wind Health & Safety Organisation (2018a)	Offshore Wind (Global)	Working at height good practice guidelines	• The behavioural safety section of the working at heights guidelines includes reference to the HSE's three groups of contributory human factors: the job/task, individual, and organisation. • Recognises that errors are often rooted in organisational factors, highlighting the importance of establishing a strong safety culture with reference to safety culture maturity model. • Individual factors are also flagged in relation to competence in their role and potential rescues, awareness to identify, communicate and mitigate potential hazards.
Rosenburg and Stavrakakis (2021).	Offshore Wind (USA & UK)	Online Webinar recording	• Speakers highlighted safety concerns, particularly regarding how safety is prioritised, speaking up about safety concerns, workloads, long rotas, turbine design, and the impact of fatigue. • Variation in training standards, particularly with sub-contracting, may impact on safety.
Safety On (2021).	Onshore Wind (Global)	Human factors in renewables guidelines	• eBook provides an introduction to HF, including job, individual and organisational factors. • As part of the setting to work guidance, situation awareness, teamwork, risk perception, competence, and communication are identified as necessary. • Highlights that inadequate resources, poor communication, fatigue, organisational culture, complex procedures and poor design can influence human performance.
G+ Global Offshore Wind Health & Safety Organisation (2022a).	Offshore Wind (Global)	G+ Improving compliance workshop: basic lifting operations.	• Outputs from a workshop designed to improve basic lifting include reference to procedures, competence, inappropriate attitudes towards safety, lack of worker awareness and safety culture. • Lack of worker awareness was highlighted as a potential rule-based mistake with suggestions on how to support induvial and team awareness.

situations are essential for avoiding incidents or mitigating the consequences (Albrechtsen 2012). Given limited communication with colleagues (e.g. on the beach or service boat), technicians need the ability to adapt their decision making, coping with unplanned maintenance tasks or rapidly evolving situations (Hansen 2017).

Competence was emphasised by industry guidelines, stressing the importance of having a competent wind technician workforce, not only in terms of their day-to-day role but for potential emergency rescues, as well as having a strong risk awareness (G+ 2018a; Safety On 2021). If unable to identify a solution, technicians would call a colleague for advice (crew factors). However, lack of expertise has been identified as potential hazard for both operations and maintenance phases of offshore wind (Tveiten et al., 2011) (organisational factors).

4.1.2. Social factors

Two social sub-factors were identified in the scoping review, consisting of frontline management and emotional intelligence as shown in Figure 2.

Front-line management qualities relating to individual leadership skills for team supervisors or senior authorised persons were identified. Typically, front-line managers are technicians who have been promoted. Consequently, these skills may be valuable for technicians with these management competencies included as selection criteria for technicians, highlighting the value of individual workers' social skills (e.g. Bose and Chatterjee 2016). With limited formal supervision, technicians may need to develop their own individual management skills. This includes setting/maintaining the crew safety attitudes, sharing tasks, and being aware of other team members' performance (e.g. coping with fatigue, seasickness). Front-line managers will also likely require a level of leadership skills for emergency response (Pedersen and Ahsan 2020), as non-injured crew members will be responsible for helping the injured parties in an emergency scenario. *Emotional intelligence* was also identified as a key skill for wind technicians, particularly when supporting colleagues with stressors, seasickness and fatigue (McMaster 2020).

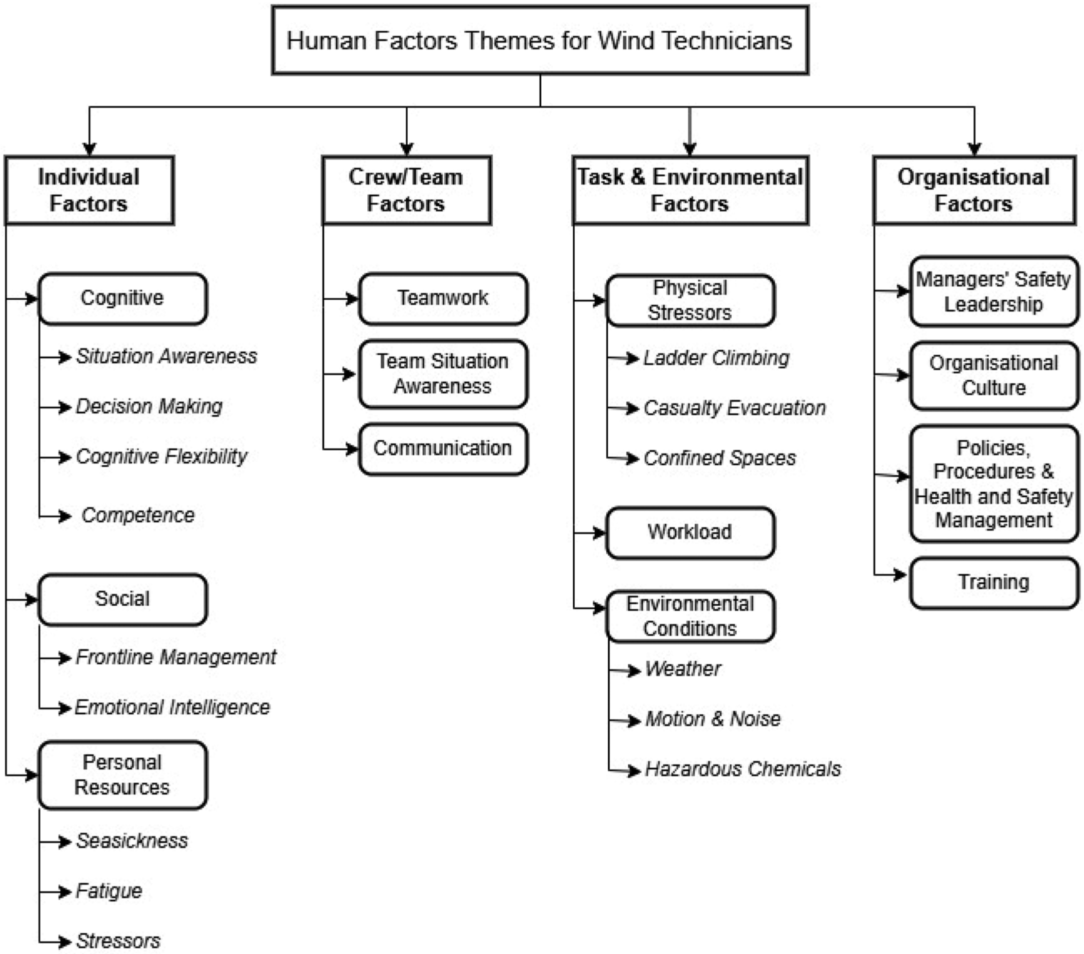

Figure 2. Summary of the human factor themes identified in the scoping review.

4.1.3. Personal resources

Three personal resource sub-factors were identified in the scoping review, consisting of skills that allow technicians to cope with seasickness, fatigue and stressors as shown in Figure 2.

Offshore, technicians' individual response to, and ability to cope with, *seasickness* was discussed. Whilst linked to environmental factors, such as vessel motion and mast sway, seasickness is grouped as a personal resource skill as it relates to how the individual learns to deal with it. Symptoms comprising nausea, dizziness, sweatiness, irritability and headaches were identified, typically worst during the transit to the turbine before commencing work (Earle et al. 2022 A research project examining offshore wind technicians' experience of seasickness and wellbeing during transit on crew transfer vessels emphasised the negative influence that it can have on safety and productivity (Earle et al., 2022). With effects of seasickness including anxiety, fatigue and readiness to work, the authors indicated that there may be implications for safety. Some interviewees reported that the time given to recover from the transit was shorter than they required which may potentially increase safety risks (Earle et al., 2022). Furthermore, seasickness can impact on cognitive function, such as causing distractions and annoyance, increasing human reaction time and impairing balance (Uzuegbunum 2023a –4.3.3. Environmental Conditions).

Attention has also been given to offshore wind workers' experience of, and ability to cope with, fatigue, and the potential impact that it can have on their physical, cognitive and social abilities (McMaster 2020; Mette et al. 2018a, 2018b). Climbing up multiple installations in a day, high workloads, and up to 14 day rotations were found to contribute to feelings of fatigue in German offshore wind workers (Mette et al. 2018a, 2018b) (4.3.1 Task & Physical Stressors). Those who live on service and operations vessels (SOVs) are likely to experience higher levels of fatigue than those who use CTVs (McMaster 2020), often describing the build-up of fatigue in the second week on the SOV (McMaster 2020; Mette et al. 2018b). The consequences of fatigue, and poor management of it, have been associated with unsafe behaviour, in addition to poor physical and mental health (McMaster 2020). A 'macho culture', that discourages speaking up about feeling tired may create a stigma around discussing and reporting fatigue in both onshore and offshore wind (McMaster 2020). That the wind industry is currently male dominated, often with technicians having a military background, may perpetuate this attitude (McMaster 2020).

Stressors such as a lack of control of work, isolation from family and friends, employment uncertainty, high workload and potential emergency situations may impact on wind worker performance (Cunha, Silva, and Macedo 2024; Mette et al. 2018b). Weather days (which stop work) were identified as being stressful with operators describing feeling stuck (Mette et al. 2017). High levels of stress and difficulties detaching from work were mentioned (Mette et al. 2018a), particularly for those with management duties (Mette et al. 2018b). Adopting a self-determined attitude and a perceived sense of control was found to be a valuable strategy for coping with stress and work demands (Mette et al. 2018a). Seeking social support from colleagues and superiors, as well as at home from partners and family (e.g. daily contact), was also found to be helpful for coping with stress, as well as nutrition, and actively seeking detachment from work (Mette et al. 2018b).

4.2. Crew factors

Three categories of crew/team factors were identified consisting of teamwork, team SA, and communication.

4.2.1. Teamwork

Teamwork is a key social skill for individuals working in the wind sector for reducing human error, particularly when working with limited supervision in remote locations (Mentes and Turan 2019; Safety On 2021). It relates to the ability of individual crew members to work together to complete workload and cope with unexpected situations, including sharing tasks, supporting others when they need it, and an awareness of each other's performance (Mentes and Turan 2019; Mette et al. 2018b).

4.2.2. Team situation awareness

Team SA relating to the crew's shared understanding of the situation is important. It may include sharing information and mental models, awareness of team members' tasks, and questioning assumptions to develop a shared awareness of the situation (Mentes and Turan 2019). For example, effectively communicating and building up shared awareness before and during work (e.g. of work plans, potential hazards, and emergency response; Safety On 2021). Accurate team SA, and rapid decision making are also pertinent for emergency response (Pedersen and Ahsan 2020).

4.2.3. Communication

Team communication, including reference to potential hazards, work plans and potential future issues is an essential competency. Technicians' communication skills include seeking confirmation of understanding when issuing verbal instructions and providing concise written instructions for team members (Safety On 2021). For example, being able to communicate potential hazards to the crew when working at height (G+ 2018a). Ineffective coordination and poor communication between team members is a potential risk factor, and an area for improvement in maintenance and operations (Mentes and Turan 2019; Ahsan et al. 2019).

4.3. Task & environmental factors

Working on turbines in confined spaces within remote environments introduces various task-related, workload and physical environmental challenges, all of which can affect worker safety, wellbeing, cognitive function and productivity. While the primary focus of the scoping review was on psychological and organisational factors influencing technicians, it became evident that these are closely interlinked with task and environmental conditions (e.g. vessel motion, seasickness and cognition). To provide a comprehensive understanding of the factors shaping wind technicians' performance during O&M, the key task and environmental themes are summarised below. Three categories of task and environmental factors were identified consisting of physical factors, workload and the environment, including six sub-factors.

4.3.1. Tasks & physical stressors

Three task and physical stressor sub-factors were identified in the scoping review, consisting of ladder climbing, casualty evacuation, and confined spaces as shown in Figure 2.

Ladder climbing, as well as lifting and completing complex job tasks in confined spaces have the potential to impact on wind technician performance, wellbeing and safety (Mette et al. 2017; National Academy of Sciences 2013). Transferring from a vessel to the base of the turbine can be physically demanding with technicians carrying an additional ~8.8 kg from lifejackets, PPE, harnesses and attachments, in addition to potentially a ~2.5 kg sea survival suit as well as equipment needed to complete the tasks (Milligan, O'Halloran, and Tipton 2019). Design and current condition (e.g. wet, build-up of deposits) of the external ladder, seasickness, worn clothing, environmental conditions (e.g. light conditions, sea state), vessel motion and fatigue from previous climbs add to the demanding nature of the transfer (Milligan, O'Halloran, and Tipton 2019).

Job task analysis found that *casualty evacuation* was the most physically demanding task undertaken by technicians (Milligan et al., 2024). However, ladder climbing is the most widely discussed physical stressor with technicians ascending and descending 80-120 metre turbine tower ladders (dependant on turbine size), typically carrying tools, replacement parts and equipment (Fischer, Koltun, and Lee 2021; Karanikas et al. 2021). Ergonomic analysis of ladder climbing activities found that it is physically demanding due to routine exposure to repetitive movements, unfavourable postures, forceful exertion, temperature extremes, static loading and duration related risk factors (Fox 2019). Research suggests that wind farm workers may be at risk of musculoskeletal injuries and disorders (MSD) (Fischer, Koltun, and Lee 2021), particularly when working in smaller turbines given the smaller, more confined spaces, requiring technicians to work in awkward positions (Oestergaard et al., 2022). Furthermore, ergonomic issues related to ladder climbing can have financial implications with 52% of survey respondents reporting missing between three and 12 days of work per year due to MSD symptoms (Fox 2019).

Once in the *confined space* of the nacelle at the top of the turbine tower housing the main components (e.g. gear box, generator), technicians may be working in awkward, uncomfortable positions with limited supervision (Cunha, Silva, and Macedo 2024). However, confined spaces may be less of an issue in newer, larger generation wind turbines. There may be additional risks in the confined space (e.g. fire from electrical parts, lubricants and insultation; Mustafa and Al-Mahadin 2018). Analysis identified a wide range of physically demanding tasks in the turbine such as negotiating hatches, bolt torquing and tensioning, manual handling, and working in poor postures due to confined space (Milligan, O'Halloran, and Tipton 2019; O'Halloran, Tipton, and Milligan 2024). Consequently, physical stress represents a significant health hazard (Milligan, O'Halloran, and Tipton 2019, 2024).

4.3.2. Workload

Technicians may be working long shift patterns to stay on schedule and to align with favourable weather windows with 12-hour shifts including three transfers, and 14 day rotations typical, contributing to perceived workload (Mette et al. 2018a, 2018b; Milligan, O'Halloran, and Tipton 2019). Wind workers have described workload intensification in response to weather windows and customer demands (Cunha, Silva, and Macedo 2024) with additional overtime hours in the summer due to improved weather conditions (Fox 2019). Time pressures and unusual working hours have also been identified as potential organisational hazards during operation (Tveiten et al. 2011). Excessively long shift patterns may result in exhaustion, impacting on cognition, increasing the possibility of workplace errors, accidents and injuries. It may also expose workers to duration related risks, increasing the likelihood of MSD symptoms (Fox 2019).

4.3.3. Environmental conditions

Three environmental sub-factors were identified in the scoping review, consisting of weather, motion and noise, and hazardous chemicals as shown in Figure 2.

Working in adverse weather conditions, and under extreme hot and cold temperatures, on turbines can impact on worker safety and productivity. For example, excessive heat stress represents a significant risk factor with symptoms including headaches, dehydration, nausea and sickness (Fox 2019). Such temperature exposure has been found to impact on cognitive and physical functioning in other contexts, increasing the likelihood of accidents and injuries (Karanikas et al. 2020). Risks may be exacerbated if combined with over exertion and inappropriate PPE (Karanikas et al. 2020).

Vessel motion has been found to be a key source of discomfort for offshore wind technicians during transfer to the turbine (Uzuegbunam, Uzuegbunam, and Ibem 2023b), as they experience vibrations from the vessel in the form of whole-body accelerations. These accelerations have the potential to result in discomfort, fatigue (personal resources skills), sweating and reduced cognitive function (Scheu et al., 2018). Consequently, a vessel motion monitoring system (incorporating sea state data) was developed as part of decision support model to support sail/not-sail decisions (Uzuegbunam et al., 2023a, 2023b). Wave height and motion sickness were found to be significantly related (Uzuegbunam, Uzuegbunam, and Ibem 2023b). Vessel vibration can also have effects on worker health including both long-term (e.g. back pain) and short-term exposure (e.g. seasickness) which even experienced offshore wind technicians can suffer from (Mette et al. 2018a). There may also be differences in how technicians experience vessel motion depending on whether they travel to the turbine via a CTV each day or whether they stay aboard the SOV for several weeks at a time. Those on SOVs may experience increased exposure to vessel motion given the increased length of time on the vessel, impacting their health. For example, poor sleep quality for those living on the SOVs, as a result of noise and vibration, as well as uncomfortable conditions (e.g. poor mattresses, confined spaces), was found to be a major cause for increased tiredness and decreased work performance (Mette et al. 2018a).

Both onshore and offshore technicians may also be exposed to turbine motion risks in which the turbine mast can sway in response to weather conditions (Scheu et al., 2018), resulting in nausea or movement-induced illness, with associated reduction in performance or risk of errors (Hanson 2013; Hanson and Thatcher 2019).

Noise exposure risks relate to the use of power tools, weather and from equipment inside the turbine. In the offshore sector, noise can also be generated from power generators as well as during transfer (e.g. helicopters, CTVs; Karanikas et al. 2021). Similarly, the technicians may be at risk of injury due to hand-arm vibration (e.g. Hand Arm vibration Syndrome, HAVs) or whole-body vibration (WBV) through the repetitive use of power tools (e.g. grinders). Exposure to *hazardous chemicals* (e.g. styrene and epoxy resins) have also been identified as key hazards (Cuhna et al., 2024; Karanikas et al. 2021).

Despite calls for HF and ergonomics principles to be considered in the design of the wind turbines (Fischer, Koltun, and Lee 2021), with poor design flagged as a key performance shaping factor (Safety On 2021; National Academy of Sciences 2013), there does not appear to be specific guidance from a HF perspective. During a stakeholder webinar, workers highlighted that there is a need for better design of turbines and equipment that eliminate risks, rather than mitigating existing risks, by actively engaging with workers during the design process (Rosenburg and Stavrakakis 2021).

4.4. Organisational factors

Four organisational factors were identified consisting of (i) managers' safety leadership, (ii) organisational culture, (iii) policies, procedures & health and safety management, and (iv) training.

4.4.1. Managers' safety leadership

Managers' commitment to health and safety, including behaviours that foster a positive safety culture, is essential for establishing a safe and efficient wind sector. Renewable (2015) has recognised that senior leadership failure to value safety can have an impact not only in terms of employee health and safety but commercial success (e.g. legal and contractual implications, project delays). Pressure from leadership, including a lack of senior management trust in worker performance, has been flagged as a concern by onshore wind workers (Cunha et al., 2024). Whilst Renewable UK's guidelines highlight that managers' failures have been identified as root causes in serious accidents, no other examples of managers' safety leadership characteristics for offshore wind were identified.

4.4.2. Organisational culture

Organisational culture was discussed in the literature in relation to safety culture, a just culture and the prioritisation of safety as well as the overarching culture of the emerging wind industry.

Safety culture has begun to be recognised by key industry bodies as an important health and safety management approach across the life cycle phases (e.g. G + 2018a, EI 2018; Renewable 2015). Selecting contractors who have a compatible safety culture has been offered as a route to a positive safety culture (Renewable 2015). Operations and maintenance contracts are typically longer than those for wind farm construction. The former are typically between five and 10 years but can be up to 20 years, compared to 2-8 years for construction depending on wind farm size. The longer contracts provide the opportunity to foster a positive safety culture, and the O&M work often involves smaller, self-managed teams. This can make it a challenge for managers to encourage positive safety behaviours in the workforce, particularly when faced with time pressures and high workload. Recognising the relatively immaturity of the safety culture in the wind industry, Hussain, Khan, and Mover (2022) developed a preliminary safety culture measure for onshore wind. This was a valuable step towards the introduction of safety culture assessment. However, the questionnaire appears to be largely based on the Score your Safety Culture checklist developed for aviation (Reason 2000, Transport Canada), with minimal adaptation for the specific characteristics of wind industry.

Concerns regarding a non-reporting culture in wind have been raised (Mentes and Turan 2019). A stakeholder webinar highlighted safety concerns of UK wind workers regarding the extent to which safety is prioritised, the impact of increasing workloads on safety and the wider safety culture in the wind industry (Rosenburg and Stavrakakis 2021). Several speakers flagged concerns regarding workers' ability to speak up and report safety concerns for fear of reprisals, and that this may be in some cases be perpetuated by a blame or not-required-back culture. Whilst these are views of a small group of speakers, the issues are reflected in the wider literature (e.g. blame culture, Ahsan et al. 2019). There are recommendations that the wind industry would benefit from developing a 'just culture' in which discussion and reporting of incidents and injuries, particularly concerns of fatigue, seasickness, and MSD symptoms, is open and without the fear of repercussions (Fox 2019; Earle et al. 2022; McMaster 2020).

4.4.3. Policies, procedures & health and safety management

Unharmonized health and safety management systems are perceived as a key health and safety risk in wind, resulting in the sector struggling to move beyond a 'zero incident' approach (Ahsan et al. 2019). Variation in company specific risks, and consequent health and safety management procedures, have the potential to introduce further complexity into the wind system, particularly for sub-contractors (Ahsan et al. 2019). Whilst safety standards appear to be in use across the wind industry (e.g. OHSAS 18001), with additional safety guidelines (e.g. Renewable 2015), there does not appear be a wind-specific standard, resulting in companies developing their own standards. Different health and safety standards across wind companies, too many documents, and overly complex health and safety guidance were all identified as potential risks by offshore wind technicians (Ahsan et al. 2019). Similarly, inadequate policies and procedures for maintaining offshore wind turbines, as well as lack of oversight and training and/or delayed preventative maintenance, can result in unsafe working conditions and technical failure of the turbines (Mentes and Turan 2019).

Over a decade ago, Albrechtsen recommended implementing an industry wide incident reporting system (2012). Whilst the organisation G+annually publishes incident statistics provided by their membership, it is not mandatory and has been subject to criticism for its limitations (e.g. restricted to membership, variation in quantity and quality of data) (Rowell, McMillan, and Carroll 2024 for review). At an organisational level, there appears to be variation in how different companies record and investigate incidents, nor do human factors appear to be widely coded in these investigations. Rowell, McMillan, and Carroll (2024) have continued to flag the need for improved health and safety reporting procedures by proposing a stronger focus on leading indicators, with a broader range of indicators, including safety culture.

4.4.4. Training

There continues to be a call for standardised training in the wind sector (Albrechtsen 2012; Rowell, McMillan, and Carroll 2024). Company specific approaches to training and variation in quality/type of training across the industry have been flagged as potential risks, particularly in relation to emergency response (Pedersen and Ahsan 2020). Given the physical hazards discussed above, it is notable that technicians have reported not receiving adequate training for ladder climbing (Fox 2019). Shortages of health and safety training (e.g. when a technician becomes supervisor) have also been identified as a health and safety management risk with the introduction of leadership training for technicians, supervisors, and leaders being proposed as a valuable risk management strategy (Ahsan et al. 2019).

5. Discussion

To ensure the long-term success of the onshore and offshore wind industry as it grows to meet increasing energy demands, it is essential that safety remains a top priority. A fundamental component of safety management is recognising that HF impact on worker performance. This then offers an evidence base to support safety standards and training at scale (Teperi et al. 2023). This is particularly pertinent for wind technicians as a consequence of the demanding work environment characteristics. Yet, there is a limited understanding of HF in the emergent wind energy industry, typically taking an ergonomic approach. Our review aimed to address this gap by identifying the psychological and organisational aspects of HF that impact on wind technician safety, wellbeing and performance during O&M activities and these are discussed below.

5.1. Preliminary framework & wider context

Given the early stage of study for HF in the onshore and offshore wind industry, our review contributes to the literature by providing an initial set of 13 HF for wind operations. These consist of individual (cognitive, social, and personal resource), crew/team (teamwork, team situation awareness and communication), task and environmental (physical stressors, workload, and environmental conditions) and organisational (managers' safety leadership, organisational culture, policies, procedures & health and safety management, and training) factors. In addition, there are 15 sub-factors as shown in Figure 2. Whilst a physiological and ergonomic design perspective focusing on task and environmental factors has typically been taken in the research to date, this review identifies that 10 (out of 13) HF related to individuals and the wider organisations that they work in. The other three factors relate to task and physical stressors, workload, and the environmental conditions. Consequently, the initial framework shown in Figure 2 provides a more comprehensive understanding of the HF impacting on wind technicians, compared to the focus on task and environmental conditions as in earlier research. The following will discuss the key psychological and organisational factors identified in the review with reference to the wider HF literature.

A range of individual cognitive, social and personal resource skills were identified in the literature as important for wind technician safety and performance. SA is a key cognitive skill for wind technicians, providing the foundation for subsequent fault finding and decision making essential for day-to-day operations and emergency situations. Consequently, it is encouraging that an introduction to SA and decision making are included in HF guidelines for the renewables sector (G+ 2018b; Safety On 2021). However, reference to these skills, are typically high-level and existing research does not appear to specify them, nor do they appear to be grounded in accepted models (e.g. Endsley's (1995, 2015) three level model of SA). Although SA related training for technicians has been suggested for reducing maintenance errors (Mentes and Turan 2019), this recommendation has not yet been specifically examined in the offshore wind context. Research examining personal resource skills for coping with seasickness, fatigue and stress, is a key topic in the wind literature, providing valuable understanding of how these impact on wind technician wellbeing, safety and performance. However, the studies to date are preliminary with limited sample sizes focusing on the short-term impacts of seasickness rather than long-term health effects.

The review confirmed the importance of recognising the crew/team category. Working in small crews of three-four technicians, teamwork, team SA and communication were found to be key skills (Mentes and Turan 2019; Safety On 2021). Whilst there are indications of what these may include, these specific skills have not been examined in depth to date for wind technicians, although social skills are recognised in similar sectors as being critical for safe and efficient performance (e.g. forestry, Irwin et al. 2023). For example, having feedback loops between team members may help workers to recover from, or mitigate, failures (Mentes and Turan 2019).

The risks relating to tasks and the environment that wind technicians work in were identified yet there is limited research examining how these factors impact on worker performance in the wind context. For example, in other domains cognitive skills have been shown to be impacted by extreme environmental conditions (e.g. Taylor et al. 2015).

Compared to other energy sectors (e.g. nuclear Orikepete & Ewin, 2024) which recognise the organisational factors as part of safety management approaches, these appear to be less well understood in the wind context. Typically, topics such as managerial leadership, organisational culture and training are discussed as part of other factors (e.g. fatigue reporting; McMaster 2020), rather than as standalone research areas. Elements of organisational culture, particularly safety culture, are being discussed (G + 2018a, Renewable 2015; Rosenburg and Stavrakakis 2021), yet the key attributes of a positive safety culture in wind have not been identified as has been done in other sectors (e.g. in oil and gas Mearns et al. 1998; Rocha et al. 2024). Although management commitment to safety is a fundamental component of a positive safety culture (Fernández-Muñiz, Montes-Peón, and Vázquez-Ordás 2007), there was minimal reference to management or leadership in the literature or industry documents on HF (e.g. Renewables UK, 2015). Nor does there appear to be a set of guidelines for wind organisations to implement safety culture approaches. As incident reporting continues to be an issue in the wind sector (Ahsan et al. 2019; Rowell, McMillan, and Carroll 2024) and since accident prevention is critically linked to HF investigation (Harle 2017), the scoping review suggests that HF incident investigation has been somewhat overlooked in offshore wind industry to date. Given the lack of standardised safety management systems, such as incident analysis tools in wind and safety culture questionnaires (Ahsan et al. 2019; Hussain, Khan, and Mover 2022), a HF incident tool kit such as developed in other sectors may be valuable (e.g. H-FACS, Shappell et al. 2006).

5.2. Supplementary factors

There may be additional HF that were not identified in the review which are relevant to the wind context. Given indications of stress, emotional demands, social isolation, and long working hours (Cunha et al., 2024; Mette et al. 2018a), addressing mental health issues in the wind technician population may be value. Particularly as workers in similar occupations have been found to experience higher levels of anxiety and depression, especially those on long rotations offshore (e.g. oil and gas workers; Pavičić Žeželj et al. 2019). More recently mindfulness approaches have been identified as a potential mechanism for supporting workplace safety (Liu, Tsai, et al. 2023 for a review) through enhanced situation awareness (Chmielewski et al. 2021). Psychological safety will likely also be pertinent (Edmondson 2018) given links with safety climate and safety voice (Sun et al. 2022).

The wind industry is international with an increasingly mobile workforce who may move between countries as well as between onshore and offshore working environments. This has the potential to introduce additional HF issues such as language and communication challenges (Alsamadani et al., 2013), or differences in national culture which may impact on subsequent safety culture (Tear et al. 2020). It is also possible that as technicians move between onshore and offshore wind, they may transfer elements of company culture (e.g. safety culture). With a global workforce, onshore and offshore technicians complete many of their training courses through Global Wind Organisation (GWO) accredited training centres. Yet beyond this, there can be variation in training type, access and quality across different countries, impacting on worker health, safety and productivity. From a training and safety perspective, identifying the cognitive, social and personal resource skills - known as Non-Technical Skills (NTS) - required for wind technicians would be pertinent. Sectors operating in similar environments have recognised NTS as vital for productivity and safety (O'Connor 2011; Moffat and Crichton 2015, Irwin and Poots 2015) with lapses in NTS being linked to adverse events (Naweed and Murphy 2023). Yet NTS in wind remain unspecified, and it is likely that there are additional NTS for wind technicians (e.g. coping with seasickness).

5.3. Limitations & future research

The preliminary framework provides the first outline of the key psychological and organisational factors influencing wind technicians during O&M that have been studied to date. However, there are limitations with the scoping review. The spread of factors across a small number of papers (most published in the last five years), indicates that HF in wind is a relatively under explored research area but as it is a relatively new industry, this is not surprising. Many of the empirical papers have limited sample sizes. Furthermore, it is possible that there is a greater understanding of HF in the wind industry, including safety interventions, represented in documents that have not been published.

Future research would benefit from direct stakeholder engagement, such as with safety and operational managers, health and safety, and human resources professionals to bring their expertise into research design and implementation studies, such as conducting stakeholder focus groups. Conducting a large-scale worker survey on perceptions of the HF influencing their performance, may provide a valuable perspective on safety in the wind industry. For example, conducting a global online survey in conjunction with an industry body could have the benefit of moving beyond the current limited industry safety incident data. As mentioned above, this review only provides an early listing of the relevant HF for wind technicians. As the industry rapidly evolves and expands, it is likely that other factors will become relevant (e.g. automation, remote inspection). For example, examining how HF differ between the onshore and offshore wind environments may be valuable for researchers, practitioners and regulators alike, particularly as technicians move between the two contexts.

6. Conclusion

Global wind energy is a crucial component in the endeavour to reach our climate goals and net zero targets. The long-term success of the industry necessities that protecting the health and safety of technicians remains a top priority, but industry data indicate shortcomings. Given the impact that HF approaches have had on similar sectors as a safety management approach, there are considerable opportunities for lesson sharing across industries. Our review developed a preliminary framework of the HF that impact on wind technician safety and performance during operations and maintenance activities, contributing to the early stage of knowledge building regarding HF in the onshore and offshore wind industry. Despite the limited number of studies, the review illustrates the importance of HF, not only for supporting worker safety and health but also for efficiency. This sentiment is beginning to be reflected in the industry. In light of recent industry safety data (e.g. G+. 2024), the preliminary list of factors presented here may offer a framework from which to start to address safety and health issues, alongside technical factors. This framework can be used to direct future research, as well as support practitioners to develop effective interventions in the wind industry and wider renewable energy sector.

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Ethical statement

A safe and competent workforce in the wind power industry is essential for meeting climate goals and energy needs. However, wind industry incident data indicate safety concerns. Despite behavioural issues significantly contributing to these wind incidents, the limited human factors research in offshore wind typically focuses on design and physiology. A scoping review was carried out to examine the psychological and organisational factors that impact on wind technician safety and performance. It did not involve human participation. In total, 13 research articles examining human factors in wind were identified from public datasets, as well as 8 items from the grey literature. A preliminary human factors framework was produced (consisting of individual, crew/team, organisational and task & environmental factors) which can be used to direct future research, as well as support practitioners to develop effective interventions in the wind industry and wider renewable energy sector.

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