Marine Pollution Bulletin 215 (2025) 117915

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Review

Chemical emissions from offshore wind farms: From identification to challenges in impact assessment and regulation

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ARTICLE INFO

Keywords:
Offshore wind farms
Environmental monitoring
Numerical modelling
Impact assessment
Offshore wind farm regulations
Coatings
Anodes

ABSTRACT

Offshore wind energy may offer many advantages: next to the aim of renewable energy production, offshore wind farms (OWFs) enable multi-purpose opportunities with nature conservation and aquaculture. OWFs may also affect the marine ecosystem. The environmental impact of OWFs is starting to be investigated regarding the effect of novel habitat introduction, underwater noise, electromagnetic fields, or exclusion of fisheries. However, the impact of chemical emissions from OWFs remains largely unknown. It is essential to account for these emissions at an early stage, to comprehensively assess the environmental impact with the objective of developing a future fit-for-purpose regulatory framework to protect the marine environment. This review compiled a literature-based list of potential OWF-related chemical emissions containing >200 organic and inorganic

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https://doi.org/10.1016/j.marpolbul.2025.117915
Received 20 February 2025; Received in revised form 28 March 2025; Accepted 28 March 2025
Available online 5 April 2025
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contaminants, including polymers. Compounds are categorised according to data source and emission type. Major gaps in assessing the impact of the compounds are identified, including challenges in environmental monitoring, numerical modelling and assessing the toxicity of individual and mixtures of chemical contaminants on marine organisms and humans consuming potential OWF aquaculture products. A risk-based prioritisation is essential to target the compounds of higher concern and overcome costs linked to assessing a wide variety of chemical contaminants. Although some countries have regulations to reduce OWF chemical emissions, standardized impact assessments or monitoring requirements for OWF-based chemical contaminants have not been established. This stresses the importance of providing more detailed information on occurrence, distribution and impact of OWF chemical emissions as an essential step towards sound ecosystem-based management of OWF installations.

1. Background

Offshore wind energy production is a fast-growing industry. Globally there were 80.9 GW of offshore wind turbines deployed by the end of 2024, with a further 22.7 GW undergoing offshore construction (RenewableUK, 2025). In Europe, the total offshore wind power capacity was 32 GW in September 2023. In terms of the number of structures, the number of operational offshore wind turbines in the OSPAR region rose from 1471 in 2013 to 5126 by January 2023 (OSPAR Commission, 2024). Along the increase in the number of turbines, the average size of the turbines has greatly increased from approximately 3.6 MW in 2013 to 12 MW in 2022, in turn these larger turbines require much larger structures to support them (Orsted, 2023). As of May 2024, the planned United States (US) offshore wind energy project development and operational pipeline reached a potential generating capacity of 80.5 GW (McCoy et al., 2024). China had installed 31 GW of offshore wind capacity by June 2023 (Mei et al., 2023). European Union (EU) governments target an increase to >150 GW by 2030 (Windeurope, 2024). The UK recently announced revised targets of 43–50 GW by 2030 (UK Government, 2024). The aim of offshore wind energy production is to offer renewable energy while reducing the need for fossil fuels. Although this overarching goal supports actions to mitigate anthropogenic climate change, offshore wind farms (OWFs) exert effects on the marine ecosystems which can be either positive or negative and might increase due to the global expansion of OWFs. To fully assess the impact of OWFs, there is a need for a multidisciplinary approach, as many different aspects should be considered. One example is the introduction of hard substrates, such as piles and scour protection, leading to the formation of artificial reefs. In combination with the exclusion of fisheries in the vicinity of OWFs, this stimulates a diverse ecosystem with an increased biomass and biodiversity (Buyse et al., 2022, 2023). OWFs may also provide multi-use opportunities with nature conservation, e.g. through the restoration of habitats and communities (e.g. ter Hofstede et al., 2022) or with aquaculture (Maar et al., 2023). However, OWFs also have negative effects such as noise from piling activities impacting marine mammals, and rotor blades exerting collision risks for seabirds. These negative effects have already been investigated in many studies (e.g. Lefaible et al., 2023; Li et al., 2023; Watson et al., 2024 and references herein) and have even been taken up in routine monitoring and approval procedures in different European countries (BSH, 2013; Rijkswaterstaat, 2016; Rijkswaterstaat., 2022; Danish Energy Agency, 2019; Danish Maritime Authority, 2021; Lindeboom et al., 2015; NVE, 2012). Chemical emissions from OWFs have received comparatively little study, although it is not entirely clear why. Anecdotal conversations with regulators around Europe and first studies suggest a presumption that chemical emissions were negligible compared to other sources like oil and gas structures (Kirchgeorg et al., 2018) and a greater perceived licensing constraint from impacts on species and habitats directly protected by legislation such as the European Birds and Habitats Directives (European Council, 1992, 2009). The lack of assessment of chemical emission in turn has resulted in a lack of monitoring. The effects of OWF chemical emissions are much less studied and depend on the type of chemical belonging to different potential categories, i.e., dissolved organic chemicals, inorganic chemicals or plastic particles. Another option to categorise OWF chemical emissions could be based on their potential sources. An OWF includes multiple sources of chemical emissions depending also on the kind of facility like wind turbines (OWTs) for energy production, offshore platforms as substations (OSS) for collecting/transforming the energy, converters (High voltage direct current or HVDC station) for energy transformation and possibly accommodation platforms. For example, paints or corrosion protection systems from steel structures of any of these facilities cause a continuous leaching of chemicals into the marine environment. Other emissions are discontinuous or accidental, resulting from repair, maintenance and safety training activities (e.g. firefighting foam agents, oils, lubricants) (Kirchgeorg et al., 2018).

The extent of chemical emissions to the marine environment is unclear. First studies show that specific compounds may be leached from materials used for corrosion protection in OWFs, but data is scarce and mass data on emissions remain difficult to estimate. Reese et al. (2020) and Ebeling et al. (2023) showed that a wide range of metals is present in sacrificial anodes from OWFs as a major constituent or impurity. Although these compounds will continuously enter the environment, it remains unclear to what extent this impacts the marine ecosystem (Ebeling et al., 2023, 2025). Moreover, the field of OWF corrosion protection is continuously evolving, with novel developments on bio-based anticorrosive coatings (Sørensen et al., 2009; Wang et al., 2020) and a trend from sacrificial anodes towards impressed current cathodic protection (ICCP) systems, which reduce total metal emission rates but with the risk of inducing overpotential effects such as pH changes (Hu et al., 2019).

Even less information is available on the emissions of organics. Studies on leachates from paints provide initial insights into potential chemical emissions (e.g. Bell et al., 2021; Brand et al., 2020; Luft et al., 2017), but the high diversity in available paints and the limited information on their formulation complicate the mapping of all potential organic chemical emissions. Moreover, laboratory-based experiments do not accurately mimic the true environmental leaching ratio and dilution effects in the field. A comprehensive overview of compounds originating from corrosion protection systems was provided by Kirchgeorg et al. (2018).

OWFs are also a source of plastic pollution due to the release of paint particles from offshore structures and/or polymer particles from the rotor blades of turbines (Mishnaevsky et al., 2025, Panayotova et al., 2010, Czerner et al., 2025). The particulate release is created by fatigue, cracking, leading edge erosion (LEE), abrasion or deterioration processes that are enhanced by environmental factors such as lightning, rain, wind, waves, and currents (Czerner et al., 2025; Wang et al., 2018).

To comprehensively assess the impact of chemical emissions from OWFs on the marine environment, identifying the chemicals/consumables in use and potentially released substances is a necessary first step, including the evaluation of the risk of each substance to reach the marine environment. Next, it is important to assess the relevant exposure and the effects on marine organisms and their consumers in an environmental risk assessment. This involves determining environmental concentrations as well as the toxicity and mode of action of the individual substances. This review aims to provide a comprehensive overview of current knowledge on chemical emissions from OWFs and

existing related knowledge gaps, research needs and challenges. In the first part, we provide insights on the potential chemical emissions from OWFs, following a broad approach including a detailed description of the substances (or mixtures in some cases) that may potentially be released from any of the identified OWF infrastructure sources. This compilation of OWF chemicals is used as the basic list for a later prioritisation for field assessment and monitoring, based on their hazardous properties such as toxicity, persistence, bioaccumulation and endocrine disruption potential. Moreover, the compiled compound list can be an essential input for future regulation and monitoring. Subsequent parts of this review focus on how to measure and model these emissions in the marine environment, assessing the environmental impact of these emissions, the current status of available legal frameworks on OWF chemical emissions, and the potential technical solutions to minimise chemical emissions. The focus is on organic and inorganic chemicals that can dissolve or disperse in the marine environment, excluding emissions from supporting activities such as shipping towards OWFs. Release of particulates such as paint flakes or rotor blade particles is relevant but considered outside the scope of this review. A comprehensive review of the latter topic was made by Czerner et al. (2025).

2. Methodology

The available scientific literature on the topic of chemical emissions from OWFs, including leaching experiments, was searched manually

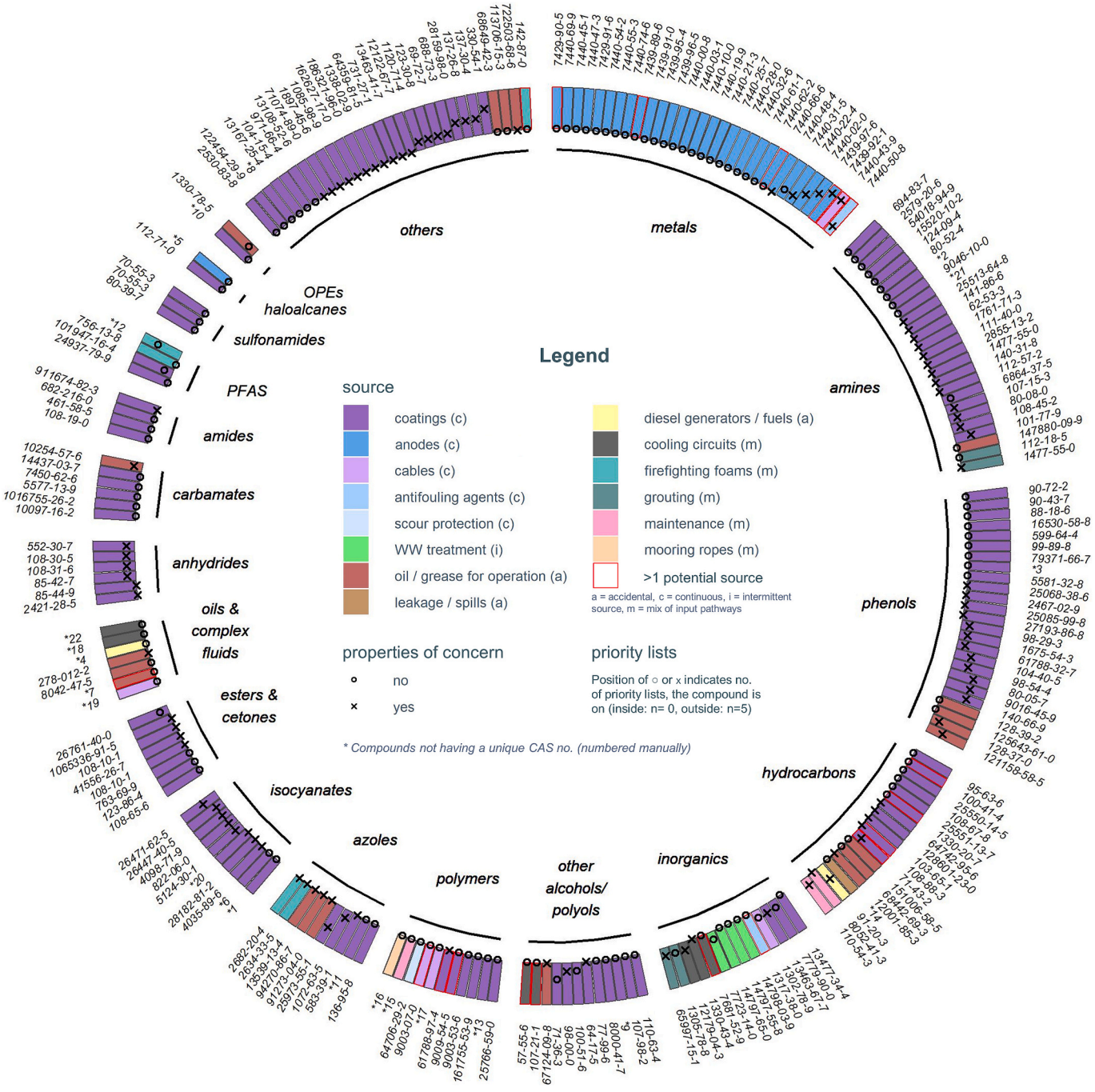

Fig. 1. Overview of chemical compounds (n = 228) and their potential sources identified in this review. For more information on individual compounds, CAS numbers can be used to find the respective compound in Zapata Corella et al. (2025).

through Web of Science, Scopus, and Science Direct in September and October 2023. The focus was on corrosion protection measures (including coatings and sacrificial anodes) as these are continuous sources for chemical emissions. The following keywords, as well as different combinations by Boolean operators, were used as search terms: 'marine environment', 'marine structure', 'offshore wind farm', 'pollution', 'contaminant', 'corrosion protection', 'antifouling', 'coating', 'polymer', 'prepolymer', 'polyurethane', 'epoxy', 'leachate', 'additive', 'seawater resistant', 'sunlight resistant', 'sacrificial anodes', and 'metals'. One researcher screened the results and duplicates and studies published before 2003 were discarded. Following this, titles and abstracts were checked to select only documents containing relevant information on the chemical composition of corrosion protection systems and other potential sources and on leachates or released compounds of corrosion protection systems. These documents included research articles, literature reviews and reports, as well as specific material safety data sheets (MSDS) for commonly used paints and coatings in offshore industries in Europe. The documents were examined more closely by two researchers from different institutions independently to gather information on chemicals potentially emitted to the environment from OWFs. Only those unambiguously presenting information on the chemical identity of substances were retained. The final selection comprises 51 documents which are listed in Supplementary Information (SI). The results of both researchers were merged and harmonized. A list containing 228 compounds identified as being potentially emitted by OWFs was established and published in Zenodo (Fig. 1, Zapata Corella et al., 2025). This and the Chemical Abstracts Service (CAS) registry number was added for unique identification and to prevent the addition of the same chemical again when used names in the documents differ. For all compounds, additional data, such as information on properties of concern according to the information collected on the European Chemicals Agency (ECHA) website and on hazard classification according to the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) were added. Additionally, it was noted whether the compound is listed on a priority list for chemicals of concern. The priority lists considered are compiled in Table 1. Compounds were assigned to one or more sources of chemical emissions from OWFs. Three overarching categories were defined: (i) continuous, (ii) intermittent, and (iii) accidental emissions. For continuous sources, a non-interrupted mass transfer of compounds from the material that is in permanent contact with the surrounding environment or continued discharge is expected. In contrast, accidental releases occur inadvertently and rather from supposedly closed systems (e.g. by leaks and spills or operational and maintenance activities related to unexpected events). The intermittent category describes sources where emissions to the environment are discontinuous (start-stop) in nature but, compared to accidental sources, are intentionally released on a periodical basis during the operation of the installation, like during routine maintenance, fire drills or sewage treatment.

Regulatory frameworks on OWF chemical emissions were investigated for the North-Atlantic, more specifically for countries bordering the North Sea, including the UK, Germany, The Netherlands, Denmark, Belgium, France, and Norway, which contribute to a majority of European offshore wind energy production (Windeurope, 2024), as well as for the US. Further, regulatory aspects from the regional sea conventions OSPAR and HELCOM were reviewed. As a starting point, publicly available resources, e.g., national websites, reports from authorities, research institutes, legal documents, and reports from individual wind farm projects were investigated. Furthermore, national and local authorities, as well as offshore wind stakeholders were directly contacted to ask for more information on regulations for chemical emissions from OWFs.

3. Results and discussion

3.1. Chemical emissions characterization

3.1.1. Potential chemical emissions from OWFs and their sources

The list presented in this review summarizes the potentially emitted compounds by OWFs depending on the state of scientific knowledge at the time of evaluation. The 228 identified compounds belong to a wide variety of chemical families (Fig. 2a), whereby organic compounds comprise 64 % of the identified compounds (especially phenolic compounds), followed by inorganic compounds (19 %), among others. In the consulted literature, also complex mixtures such as the Stoddard solvent, naphtha or silicon fluids, specific compound groups such as polycyclic aromatic hydrocarbons or *per*- and polyfluoroalkyl substances (PFAS), as well as polymers, such as polystyrenes or polyacrylates, are described, although these represent a smaller contribution to the total number of possible emissions from OWFs. A more detailed classification of identified compounds is provided in Zapata Corella et al. (2025). From the list, 62 are included in priority lists from international organisations and regulatory bodies such as ECHA, OSPAR, REACH or the EU Water Framework Directive (Zapata Corella et al., 2025). Since many other of the listed compounds have known hazards and properties of concern (Zapata Corella et al., 2025), prioritisation based on emission rates and chemical characteristics such as persistence, bioaccumulation potential and toxicity (PBT-properties) will be essential to accurately assess the risk of OWF chemical emissions. Thirteen different sources of chemical emissions were identified, with coatings accounting for the majority of substances potentially released into the environment (58 %), followed by anodes (12 %), and oil and grease for operation (10 %) (see Figs. 1 & 2b). These emissions are mainly linked to the operational phase of OWFs, indicating that emissions during construction and decommissioning are less studied. Moreover, the literature sources consulted to compose the list of chemical emissions (Zapata Corella et al., 2025) mainly focus on short-term impacts. Even though the need for continuing monitoring and on-field data is underlined by several studies (e.g., Bell et al., 2020; Ebeling et al., 2023; Kirchgeorg et al., 2018), long-term monitoring, emission and leaching studies are still lacking, own to the relatively new and fast expansion of OWFs over the last decade and the higher complexity to set up long-term research studies.

The location of the source, the input pathway, and the physico-chemical characteristics of the individual chemicals will determine the

Table 1
Priority lists considered to identify chemicals of concern.

CoRAP: Community Rolling Action Plan. https://echa.europa.eu/information-on-chemicals/evaluation/community-rolling-action-plan/corap-table
ECHA ED Priority List: ECHA's endocrine disruptor (ED) assessment list. https://echa.europa.eu/ed-assessment
EQS-WFD: Environmental Quality Standards (EQS) set for the priority substances in the Water Framework Directive (WFD). https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:226:0001:0017:en:PDF
OSPAR LCPA Priority List: OSPAR List of Chemicals for Priority Action. https://www.ospar.org/work-areas/hasec/hazardous-substances/priority-action
OSPAR LSPC Priority List: OSPAR List of Substances of Possible Concern - Annex to the List of Chemicals for Priority Action. https://www.ospar.org/work-areas/hasec/hazardous-substances/possible-concern/list
PLONOR: OSPAR list of substances used and discharged offshore which are considered to Pose Little Or No Risk to the environment. https://www.ospar.org/documents?d=32939
REACH (Annex XIV): Authorisation List. List of substances included in Annex XIV of REACH. https://www.echa.europa.eu/authorisation-list
REACH (Annex XVII): Substances restricted under REACH. List of substances included in Annex XVII of REACH. https://echa.europa.eu/substances-restricted-under-reach
Stockholm Convention: List of substances proposed as POPs. https://echa.europa.eu/list-of-substances-proposed-as-pops
SVHC Priority List: Candidate List of Substances of Very High Concern for authorization. https://echa.europa.eu/candidate-list-table

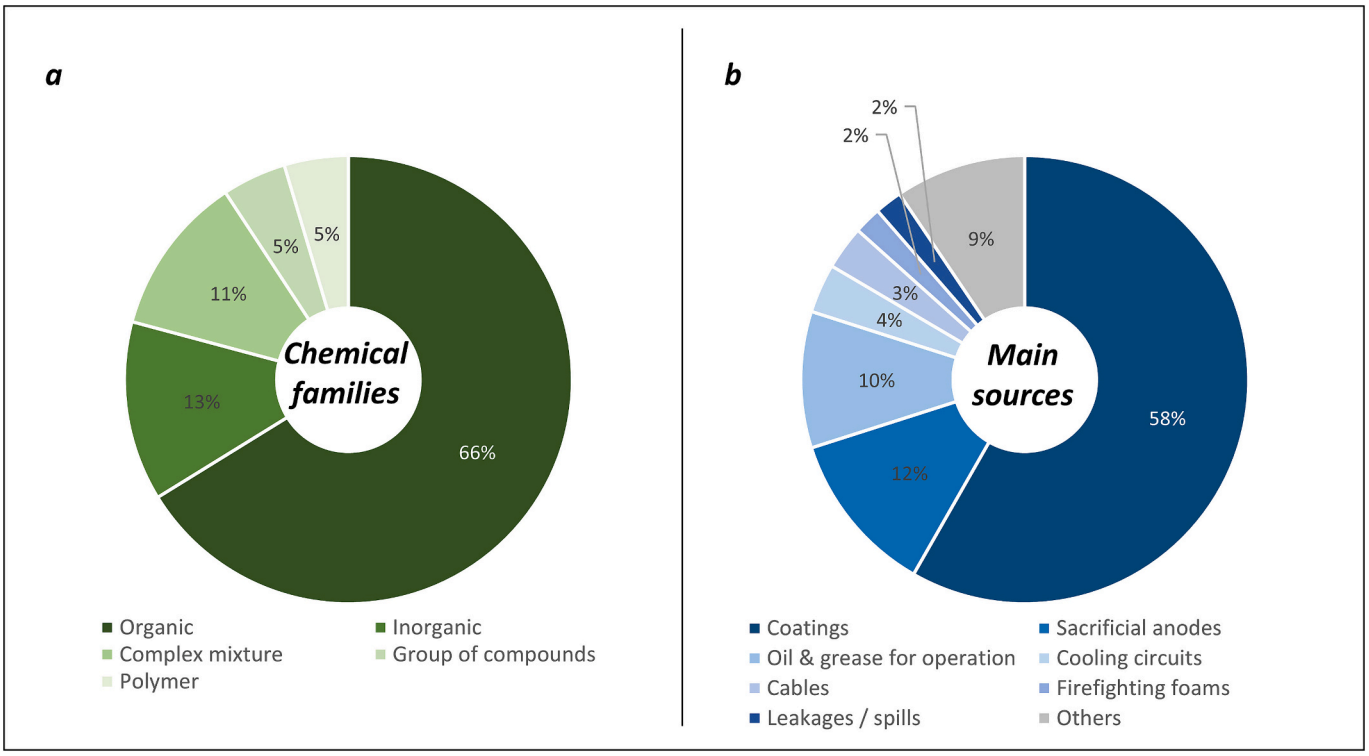

Fig. 2. Percentages of (a) chemical origin and (b) main sources for chemical compounds potentially emitted by OWFs. All 228 identified compounds were assigned to at least one group.

environmental fate after being emitted. Volatile or semi-volatile compounds (e.g. toluene), as well as substances from OWF structure parts not directly in contact with water (e.g. eroded particles from blades), may be introduced into the air and transported over long distances, while polar chemicals and substances emitted from sources with direct water contact may be dissolved into the water column (e.g. ethylenediamine, metals) and may also be transported through water currents over longer distances. Less polar compounds (e.g. naphthalene), as well as particles with high densities (e.g. resulting from coatings), may sink through the water column and accumulate in the sediment (Czerner et al., 2025). Finally, the more persistent and lipophilic chemicals may enter and accumulate in marine trophic food webs.

3.1.2. *Continuous release of chemicals by corrosion protection systems*

Corrosion protection systems are highly important for preserving the structural function of steel-based materials. The marine environment is an aggressive medium that can deteriorate these materials through physical (e.g. wind and sea erosion), chemical (e.g. electrochemical oxidation) or even microbially induced corrosion processes, which can in sum remove up to 200 μm of surface thickness per year from an unprotected layer (Momber, 2011). Different strategies to avoid or minimise such corrosion are applied, often in combination, to protect OWF structures. Options for corrosion protection systems include (organic and biobased) coatings, galvanic anode cathodic protection (GACP) or impressed current cathodic protection (ICCP) systems (Kirchgeorg et al., 2018). Each of these protection systems represents a potential source of chemical emissions to the surrounding marine environment.

3.1.3. *Coatings as major source of continuous organic chemical release*

As illustrated in Fig. 2b, 58 % of the identified chemicals potentially emitted by OWFs come from coatings, which comprise protective layers of different materials covering the whole structure. Three layers are commonly present in these coatings, with differing compositions depending on the area of the structure to be protected: priming coat, intermediate coat and topcoat. Although direct emissions from coatings are minimised by hardening the coatings onshore before steel structures are deployed offshore (Kirchgeorg et al., 2018) the topcoat is of highest importance with respect to potential emission of chemicals leaching from the coating as this layer is in permanent contact with the surrounding environment and will, therefore, be degraded first. In offshore wind energy devices, topcoat layers are commonly based on polyurethane (PU) and/or epoxy resins (EP) (Momber and Marquardt, 2018), and the chemical emissions are expected to be related to the polymeric composition and additive chemicals present in these two materials. In the case of the bulk polymer matrix, mechanical and chemical degradation processes are necessary to break down the polymer chains into small molecules that can be released into the surrounding environment. Oxidation and/or hydrolysis reactions start in the polar groups of the polymeric chains, breaking the cross-linked tridimensional structure, which leads to the deterioration of the material properties and the emission of the degradation products, the composition of which are dependent on the original composition of the polymer (Allen et al., 2022; Powers, 2009). Moreover, the chemical degradation reduces the resistance of the coating to further mechanical erosion. This process and physical disturbance due to damage by ships, wear and tear due to waves and tides, as well as biofouling may lead to emissions of micro-, macroparticles and/or flakes from the different coating layers (Hildebrandt et al., 2024; Turner, 2021).

PUs are copolymers synthesized by the reaction of diisocyanates with dialcohols. However, a variety of additive chemical modifiers, such as crosslinkers, fillers, and surfactants are often included in the process to improve the properties of the resulting PU for a desired application (Maurya et al., 2023). Potential marine environmental contaminants released from PU coatings may include non-intentionally added substances (NIAS) such as unreacted alcohols (e.g. glycols, butanediol, and bisphenols), unreacted diisocyanate comonomers (e.g. methylene diisocyanate, toluene diisocyanate, or isophorone diisocyanate) and the corresponding diamine hydrolysis products (methylenedianiline, toluenediamine, and isophorone diamine), non-evaporated solvents (e.g. furfuryl alcohol and benzyl alcohol), chain modifiers (e.g. phenols and

amines), as well as a wide range of chemical additives that serve a specific function (e.g. fillers, pigments, plasticizers, flame retardants, ultraviolet (UV) stabilizers, or antioxidants) (Zapata Corella et al., 2025). Degradation mechanisms can act upon the polymer, additives, and NIAS, leading to the formation of many other chemical transformation products that could potentially be released into the surrounding water. Experimental studies on the leaching of chemical compounds from PU coatings are scarce. Luft et al. (2017) used a non-target approach to evaluate the chemical leaching of a PU coating to milliQ and river water for up to 14 days. A total of 48 chemicals representing five major chemical groups were identified in the aqueous leachates: N-(tosyl)carbamate derivates, toluenesulfonamide derivates, methylenediisocyante derivates, toluenediisocyanate derivates and oligoethylene derivates.

EP polymers are prepared by reacting epoxy rings containing precursors (e.g. epichlorohydrin) with a difunctionalised molecule such as dialcohols (e.g. bisphenols), to form a diglicidylether that can continue reacting to increase the chain length. Hereafter, a curing process is performed where crosslinkers and/or chain terminators react with the remaining epoxy rings, creating tri-dimensional branched structures which harden the polymer. This process occurs through the addition of curing agents such as amines or phthalic anhydrides and/or through chemical reactions activated with heat or light (photo-curing) (Jin et al., 2015). A variety of additives (e.g. imidazole derivates, benzophenone antioxidants, UV filters, zinc and titanium oxides and phosphates, pigments) are typically incorporated to improve key properties such as oxidation and photooxidation resistance, flexibility, or tensile strength of the final EP coating (Allen et al., 2022; Verma et al., 2020). Similarly, residual production chemicals such as monomers/oligomers and related compounds, hardeners, and curing agents (e.g. phenolic compounds like tertbutylphenol, nonylphenol, and bisphenols) are also present in the final EP coating (Kirchgeorg et al., 2018; Shi et al., 2023; Zapata Corella et al., 2025). As with the PU coatings, degradation mechanisms can potentially form other chemicals that could leach into the surrounding water. Several of these compounds are listed in catalogues for prioritized hazardous chemicals (Zapata Corella et al., 2025). Bell et al. (2020, 2021) identified different phenolic compounds in leachates from EP coatings, with and without exposure to UV-A radiation for up to 65 h. Bisphenol A (BPA), 4-tert-butylphenol, and BPA bis(2,3-dihydroxypropyl) ether were found in all leachates. Leachates from the irradiated EP coating also contained 4-cumylphenol, BPA-I11 and BPA—I10, and the release of BPA was six to 19 times higher. Vermeirssen et al. (2017) also characterized the composition of leachates derived from four commercial EP corrosion protection products, using target screening to look for the presence of BPA, BPA diglycidyl ether (BADGE), and bisphenol F (BPF). Significant differences were observed among the coatings tested, with one coating formulation releasing 100 times more BPA than the other coatings and releasing more BPA after a seven-day curing process compared to a one-day curing. The leachate from the same coating did not contain BADGE concentrations above the limit of quantification (LOQ), while another coating released detectable quantities of BADGE but no BPA. BPF was below the LOQ in all of the coatings studied.

3.1.4. Anodes as a source of continuous metal release

GACP systems are frequently used in OWFs for the corrosion protection of steel structures. The galvanic anodes are designed to be oxidised and dissolved over a lifetime as part of a galvanic cell, preventing oxidation of the structural steel, which is why they are often called “sacrificial anodes”. This leads to a continuous emission of metal ions into the marine environment (Deborde et al., 2015; Kirchgeorg et al., 2018; Tornero and Hanke, 2016). Sacrificial anodes were identified as the second most important source of chemical emissions from OWFs in this review (see Fig. 1b).

The composition and amounts of released metals are dependent on the composition of the anodes. Main components of commonly used aluminium-zinc-indium and zinc-based anodes are aluminium and zinc (Kirchgeorg et al., 2018; Tornero and Hanke, 2016). In addition to the main elemental components of galvanic anodes, indium is added for aluminium-based anodes and gallium, cadmium, and lead may occur in anodes to a limited amount (according to national or international standards like DIN EN 12496:2014 (DIN, 2014) or NORSOK M-503 (NORSOK M-503, 2016) and a study of anode composition by Reese et al. (2020) and may have the potential to serve as tracers for OWF-derived metal release (Reese et al., 2020; Ebeling et al., 2025). Other heavy metal impurities in galvanic anodes, such as mercury, nickel, and manganese, may also be released into the marine environment in very small amounts (Gomiero et al., 2011, 2015; Plenker et al., 2024; Reese et al., 2020). Several of these heavy metals are included on priority lists for hazardous chemicals (e.g. cadmium, lead, mercury, and nickel) (Zapata Corella et al., 2025). In contrast to GACP systems, an active current is used to protect steel structures from corrosion in ICCP systems. Typically, titanium, indium, or mixed iridium/ruthenium oxide coatings are used, or titanium-, niobium- or tantalum-coated magnetite or platinum is applied for electrodes used in this kind of corrosion protection systems (Kirchgeorg et al., 2018). Due to the materials used, small quantities of niobium, tantalum, or titanium could potentially be emitted, but this has not been demonstrated to date (BSH internal communication). Although there is no large metal emission associated with ICCP (Kirchgeorg et al., 2018; Plenker et al., 2024), halogenated by-products may be produced in situ due to the ongoing electrolytical processes (Michelet et al., 2020). Studies on ICCP emissions are rare and further assessment is needed in the future.

3.1.5. Other continuous sources of chemical emissions

Other OWF sources that may lead to a continuous release of chemicals into the marine environment include rotor blades, cables and the material used for grouting. Surface erosion of rotor blades of wind turbines and especially LEE can lead to damage and degradation of the material (Mishnaevsky et al., 2021). To minimise the effects, protection measures are applied, mostly consisting of coatings and tapes (Law and Koutsos, 2020). LEE may result in cracks in these coatings, as well as peel-off and release of the underlying composite material (Mishnaevsky et al., 2021). Therefore, particulate matter and substances from protecting coatings and/or the blade material itself (normally glass- or carbon fibres in combination with epoxy resins for reinforcement (Otto et al., 2023; Solberg et al., 2021)) may be released into the environment (Plenker et al., 2024). Importantly, the release of such particles with a higher surface area to volume ratio than the original coatings, can result in increased leaching of the chemicals they contain since leaching mainly occurs at the particle surface (Galloway, 2015).

Under regular conditions, cables need to be buried in sediment and hence chemical emissions to their surrounding environment are considered to be negligible (Ardelean and Minnebo, 2015; Plenker et al., 2024). However, this might change in case of incomplete burial or damage to cables. Exposed cables may lose material like polypropylene, polyurethane, or bituminous compounds at their surface due to abrasion (Plenker et al., 2024). In case of damage, metals might be continuously released, depending on the kind of cable used (Meißner et al., 2006). The process of cable laying during the construction of OWFs may also result in the remobilisation of contaminated sediment, which can lead to the emission of chemicals into the water column (Kirchgeorg et al., 2018; Tornero and Hanke, 2016).

Furthermore, a transition piece can be required between the structural foundations on the seafloor and the support structure of the offshore wind turbine. To form a solid connection, grouting material is pressed into the transition piece and is compacted until it spills over, with the consequent release of Portland cement and calcium oxide into the surrounding environment (Plenker et al., 2024). In addition, the foundations of the turbine have to be stabilized on the seafloor. The presence of monopile or jacket foundations cutting into the marine soil causes erosion and sediment transport around the foundation due to

wave−/current-induced velocities, often referred to as scouring (Welzel et al., 2020; Schendel et al., 2018). To keep the stability of the structure, different materials are used as scouring protection. Stone or rock rubble is the most commonly used material for this purpose, but geotextile sand or stone containers, geosynthetics, concrete or rubber mats, nylon mesh bags, or even old car tyres are also in use, all of which may release particles and degradation products (Brüggemann et al., 2025; Glarou et al., 2020; Plenker et al., 2024).

Another source of chemical emissions may be mooring ropes in the case of lines used for anchoring or attaching vessels (intermittent) or floating turbines (continuous). This more recently developed technology represents an alternative to bottom-fixed turbines in shallow waters and offers the opportunity to locate OWF in deeper waters further from the coast, as well as on different types of seabeds, although it requires complex mooring designs (Campanile et al., 2018; Rezaei et al., 2023). Synthetic ropes, made of polymeric materials such as nylon, polyester, or aramid, have been demonstrated to exhibit enhanced performance and physical properties with lower economical costs in contrast to steel chains and wires frequently used (Weller et al., 2015). Therefore, the expected chemical emissions are related to the chemical additives, NIAS, and the degradation of these polymers. However, the specific surface in contact with the surrounding environment is relatively low compared to e.g. the coated surface of turbines.

3.1.6. *Intermittent and accidental sources of chemical emissions*

Intermittent and accidental releases of chemicals may originate from a diverse range of sources at the turbines but especially also at OSS and HVDC stations, and include maintenance operations and products, closed cooling circuits, firefighting foams, diesel generators and fuels and wastewater treatment. Of these, oil and grease for operation represent the largest number of chemicals potentially emitted, followed by cooling circuits and firefighting foams (see Fig. 1b).

Compounds that may be introduced accidentally into the marine environment by the use of oil, grease, and/or lubricants for the maintenance and operation of devices on OWF structures include different phenols and hydrocarbons (Zapata Corella et al., 2025), which are natural components in the oils and lubricants, as well as additive chemicals that are included to improve performance (Tornero and Hanke, 2016; Plenker et al., 2024). Oils, grease and lubricants are particularly used in the technical equipment during installation, and then the chance that compounds leak into the environment is higher than during the operational phase, when these substances are mainly used in closed systems or routine maintenance only (Plenker et al., 2024).

Cooling circuits may be installed on offshore platforms for the smooth operation of technical processes. Cooling circuits may be open using seawater or closed using external cooling units. Especially in the case of open circuits, antifouling agents may be applied to prevent marine growth, and, in this case, continuous chemical release into the environment occurs (Plenker et al., 2024). Chemicals would only be released accidentally in closed circuits on platforms and turbines, where leaks could occur. The primary chemicals associated with this source are the cooling agents ethylene glycol, propylene glycol, and disodium tetraborate (for closed systems), as well as the antifouling agents copper, copper oxides, and sodium hypochlorite (for seawater cooling systems) as listed in Zapata Corella et al. (2025) (Tornero and Hanke, 2016; Plenker et al., 2024).

Another source potentially releasing chemicals into the marine environment are firefighting foams when these need to be used on platforms (Kirchgeorg et al., 2018; Tornero and Hanke, 2016). Substances contained in firefighting foams that may be released in case of an emergency or possibly during fire drills include fluorosurfactants, thiazoles, and sodium decyl sulphate (Plenker et al., 2024). Although aquatic film forming foams often contain PFAS, some chemicals of this group like perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) are already restricted by EU Directives (European Commission, 2020) and PFAS in general can be expected to be absent in the near future (Plenker et al., 2024), especially as alternative chemicals are being studied (e.g. Nicol et al., 2022) to avoid the introduction of these contaminants into the environment.

The use of fuels, such as diesel, for running auxiliary and emergency generators on connecting platforms may lead to chemical emissions from OWF structures in case of spills or accidents, especially during bunkering processes (Plenker et al., 2024). Diesel itself, but also specific components like naphthalene may enter the marine environment (Plenker et al., 2024; Tornero and Hanke, 2016). Additionally, atmospheric chemical emissions derive from the operation of diesel generators but are also linked to ship traffic in the installation phase and maintenance in the operating phase (Kirchgeorg et al., 2018; Wang et al., 2019). Atmospheric chemical emissions were not considered in this review, though, and are therefore not listed in Zapata Corella et al. (2025).

Another intermittent source of chemical emissions from OWFs that could be identified in this review are discharges from wastewater treatment plants located on manned platforms (Kirchgeorg et al., 2018). Even though offshore wastewater treatment is already regulated by MARPOL (e.g. MARPOL, 2012) to reduce the entry of nutrients derived from the decomposition of organic matter, chemicals such as ammonium, nitrite, nitrate (together total nitrogen), and phosphorus still represent a major emission (Plenker et al., 2024).

3.2. *Impact assessment of OWF chemical emissions on the marine ecosystem*

Understanding the impact of chemical emissions from OWFs on the environment is important to protect the marine ecosystem. Moreover, OWFs are in close proximity to economically important fisheries and in case of multi-use scenarios, aquaculture products are cultivated within wind farms. It is therefore essential to also take into account secondary poisoning and effects on humans via the environment for risk assessments, including the concept of mixture toxicity (Caplat et al., 2012). Many of the compounds listed in Zapata Corella et al. (2025) have toxic properties of concern according to the ECHA registered substance factsheets or are labelled as hazardous within the GHS and its application in Europe under the Classification, Labelling and Packaging (CLP) regulation (EC No 1272/, 2008) (European Parliament, 2008). From this perspective, compounds which may raise the largest concern due to their toxicity on (marine) species and humans (via oral exposure route) are those classified as (1) carcinogenic and/or mutagenic, (2) toxic for reproduction, (3) specific target organ toxicity by repeated exposure (STOT RE), (4) toxic for the aquatic environment, and/or (5) as endocrine disruptors. Following ECHA substance factsheets and GHS labelling, 25 substances from the literature list are listed as proven or suspected carcinogenic or mutagenic, 17 substances are toxic for reproduction, 93 substances are toxic for the aquatic environment and 14 have endocrine disruption properties. However, it is important to stress that the degree of information can be strongly substance dependent, and more substances may be classified as substance of concern if more data on hazard properties will become available. Phenols and bisphenols are applied in OWF epoxy resin-based coatings (Kirchgeorg et al., 2018) and are examples of OWF chemical emissions for which the chemical properties are mostly well known, such as for nonylphenol or bisphenol A. They occur on the REACH SVHC list for substances of very high concern and detailed information is available on persistence, bioaccumulation potential, acute and chronic toxicity, and other properties of concern such as endocrine disruption potential. However, for other relevant OWF emissions, data is incomplete to perform a full risk assessment. Indium, for example, is present in galvanic anodes and may leach in the marine environment (Ebeling et al., 2023, 2025; Reese et al., 2020). Although ecotoxicity data is available on the crustacean *Hyalella Azteca* (Borgmann et al., 2005), ecotoxicity data on different trophic levels is missing to allow for a full risk assessment. It is important to note

that next to the parent substances listed, also degradation products of organic substances can have such negative properties and might be of concern. However, information on substance degradation in the environment, and especially in the marine water column and sediment, is often very limited or non-existent which represents a significant challenge for a comprehensive assessment of the substance impact in these ecosystems.

By referring to ecotoxicological tests with regard to the marine environment, caution must be taken as the toxicity assessment under the chemical regulatory frameworks is mostly performed on freshwater species. Therefore, modulation of the toxicity by marine environmental parameters (e.g. hardness or $CaCO_3$ content, dissolved organic carbon content, and pH) might not being taken into consideration, which is of concern for certain substances such as metals (Cui et al., 2023). The bioavailability of copper, for example, is recognized by the water quality criteria issued by the U.S. Environmental Protection Agency (EPA)., 2016 to be affected by salinity, dissolved organic carbon, pH, and temperature. In the marine environment, these factors interact, and the effects of those interactions are still poorly understood (Cui et al., 2023) especially with regards to metals that are chronically released in small quantities from galvanic anodes. In addition, the progression of climate change can further negatively impact marine life as not only the toxicity of several high-risk pollutants may increase with increasing levels of climate change drivers, but also the bioaccumulation of contaminants in marine organisms may be enhanced (Jeong et al., 2023; Kibria et al., 2021; Sokolova and Lannig, 2008). Although not examined on the interaction with environmental factors, Levallois et al. (2023a, 2023b, 2023c) conducted a series of experiments on the effects of toxicity of galvanic anode derived metals individually and in metal mixtures on various marine organisms. In larvae of the oyster *Crassostrea gigas* aluminium and zinc had additive and synergistic toxic effects, emphasizing the importance of studying metal mixtures (Levallois et al., 2023a). In the abalone *Haliotis tuberculata*, extreme exposure to leachates from aluminium-based galvanic anodes (mixture of seven metals) impacted growth, immunity, and reproduction while no significant effects were observed at environmentally realistic concentrations. In this study, abalone were also fed with metal contaminated algae, incorporating relevant cascading trophic effects (Levallois et al., 2023b). Microphytobenthos accumulated aluminium and a reduced biomass as well as a reduced photosynthetic efficiency was observed at increased but environmentally realistic aluminium and zinc concentrations, suggesting potential long-term risks to primary producers in marine ecosystems (Levallois et al., 2023c). These studies focussed on physiological vulnerabilities that drive species' vital rates. Regulatory hazard assessments often overlook benthic organisms, relying on limited species and pelagic data and typically focus on vital rates only (Tornero et al., 2022; ECHA, 2023). In addition, most toxicity data are from adult organisms, which is often the least sensitive life stage. Recently, toxicity tests with early-life stages are gaining interest for their ability to capture developmental vulnerabilities which addresses data gaps for a growing number of emerging chemicals under increasingly stricter legal trends for animal experimentation (Capela et al., 2020). Blanc-Legendre et al. (2025) have demonstrated the absence of acute toxicity of aluminium salt and the cocktail of elements released by galvanic anode cathodic protection on embryo-larvae development of marine medaka (*Oryzias melastigma*). In the same study, they found no modification of growth and reproduction of adults after chronic exposure to the same solutions but some behavioural disruptions at the highest concentrations highlighting the importance of the exposure duration and the sensitivity of the effect endpoint.In addition to interactive effects among metals, several other toxic substances that might be released by OWFs simultaneously may also interact. The multitude of potential chemical emissions from OWFs makes it complex to estimate the risk of these emissions. A prioritisation exercise based on potential occurrence and PBT properties is deemed necessary to focus on the substances of higher concern. In addition, the risk assessments based on single substances must be completed by a hazard assessment on identified mixtures in OWF leachates to identify or disregard any potential interactions, i.e. antagonistic or synergic effects (Crowther et al., 2023; Morais et al., 2023).

Another approach to assess the impact of chemical mixtures from OWFs is by determining bioaccumulation and/or the health of marine species collected from within OWFs. Good model species for this are *Mytilus* spp. because they are one of the dominating species colonizing the subtidal structures of OWFs and because of their highly sedentary and filter-feeding life strategy (Degraer et al., 2020). Wang et al. (2023), for example, showed that the metabolic pathways of blue mussels and oysters from OWFs were significantly different to that of individuals collected from marine ranches. The authors conclude that therefore the immune responses, oxidative stress, energy metabolism, and osmotic pressure regulation of mollusks may be affected by exposure to chemical leachates from OWFs (Wang et al., 2023). In a study on metal accumulation in *Mytilus galloprovincialis,* not from OWFs but offshore gas platforms, in which similar sacrificial galvanic anodes are used, Gomiero et al. (2015) found increased levels of zinc, cadmium, and nickel in the tissues of mussels that were collected near platforms. The bioavailable fraction of such metals triggered the biological response of the native bivalves with increased metallothionein content and destabilized lysosomal membranes. No studies on contaminant concentrations from OWFs in marine species have been published. Yet, reports about good environmental status emphasise recommendations on determining baseline levels of contaminants in marine organisms for future studies near OWFs (Abramic et al., 2022).

3.3. Identification and quantification of OWF chemical emissions

3.3.1. Analytical challenges to identify OWF chemical emissions

To perform a full impact assessment on OWF chemical emissions, not only the hazards and properties of concern of individual or mixtures of substances (section 3.2) should be determined but there is also the need to obtain environmental concentrations and distributions. The chemical complexity of OWF chemical emissions means that no single analytical technique is able to comprehensively quantify emitted chemicals, but a variety of analytical methods is required. Inductively coupled plasma-mass spectrometry (ICP-MS) or ICP-optical emission spectroscopy (OES) is necessary for analysing metals, trace elements and metal speciation. Gas chromatography (GC)-MS-based techniques are required for more volatile and apolar organic compounds, while liquid chromatography (LC)-MS-based techniques allow the identification of larger and more polar compounds. From a technical, time, and cost perspective, monitoring all of the chemicals potentially emitted by a given OWF is not feasible. For example, accurate quantification ideally requires sourcing high-purity isotopically labelled or deuterated reference standards for each chemical. Additionally, the wide range of physicochemical properties among the different OWF chemicals requires multiple extraction and sample processing approaches. The sample matrix, which can be seawater, sediment or even biota, represents the next challenge for most analytical methods, causing interferences (for ICP techniques) or signal suppression (for electrospray ionisation) during analysis. As such, cost-effective monitoring of these emissions in the marine environment requires a risk-based selection of a small number of target compounds that factor in emission levels, rates, and chemical toxicity.

In addition to the wide range of analytical instrumentation required for chemical quantification, the need to determine low environmental concentrations resulting from dilution and transport of the emissions over large areas in the marine environment poses further analytical challenges (Vanavermaete et al., 2023). Moreover, OWFs are mostly built outside the 12 nautical mile area, often characterized by coarse sediments with low binding capacity for contaminants. Therefore, coarse sediment samples will contain lower concentrations of chemical compounds compared to muddier sediment samples, which may hinder the detection of contaminants in OWF site samples (Horowitz, 1991;

Szava-Kovats, 2008).

Even when focusing on a selection of the highest-risk OWF-associated chemicals, state-of-the-art instrumentation and advanced multi-step analytical methods will be needed to provide an accurate picture of environmental concentrations originating from OWF emissions. Two main strategies can be adopted to assess contaminants in the marine environment. Target screening employs specific methods to analyse one or more known chemicals with high accuracy while minimising the matrix effect and filtering out any signal from non-targeted chemicals. This approach, however, assumes the knowledge that the expected contaminant(s) is/are present with a certain probability and typically overlooks other possible contaminants. Non-targeted screening (NTS) is less biased, as a wide range of compounds can be detected. However, the instrumentation and analytical procedures generally limit the range of detectable compounds, and NTS methods are less sensitive than targeted ones and often allowing qualitative or semi-quantitative analyses only. As thousands of compounds may be detected in a NTS approach, a suspect list may help to prioritise the detection of certain compounds (González-Gaya et al., 2021). It is also important to consider biotransformation and degradation processes that change the native chemical structure. These degradation products were not originally used in the OWF infrastructure but may be important from a hazard and persistence perspective. For example, diisocyanates from organic coatings can be degraded into diamines (Pantelic et al., 2023). Both the isocyanates and respective degradation products have been classified as carcinogens (Luft et al., 2017; McQueen and Williams, 1990; Utomo et al., 2020) and are strong candidates for inclusion in targeted screening.

A key issue for many of the chemicals known to be associated with OWFs is that they have multiple other applications directly at sea, as well as on land which may also lead to emissions to the marine environment. As a result, their detection in environmental samples often cannot be exclusively attributed to OWFs and may be background contamination from other sources. For example, zinc-based galvanic anodes used on ships might lead to similar emissions as galvanic anodes installed in OWFs. Next, phenols, phthalates, or organophosphate esters can be emitted by paints and plastics at OWF (Hahladakis et al., 2018). Yet, plastics and polymer-based coatings are also widely used in other marine sectors. An appropriate sampling strategy, considering areas impacted by OWFs, areas under other suspected chemical pollution sources and reference sites could help apportioning the OWF-related emissions (see below). Furthermore, targeting such chemicals for analysis is complicated by the need to minimise contamination through the use of plastic-free sampling equipment, storage containers, and laboratory equipment during sample processing and analysis.

3.3.2. *Challenges for OWF emission monitoring*

A common goal of environmental monitoring is the establishment of baseline contamination levels and the ability to measure spatiotemporal changes. This requires a carefully considered and robust monitoring design, obtaining the maximum degree of information in a cost-effective way. Cost reduction involves not only selecting prioritized chemicals for analysis, selecting the best analysis matrix and optimising sample preparation and untarget and multi-target analysis methods, but also optimising sampling design. The minimum number of samples depends on the statistical power that is required to detect spatial-temporal trends. In the marine environment, a high variability is expected, and thus, a higher number of samples will be required to achieve statistical significance (Garman et al., 2012). The number of sample locations can be reduced by using repeated measurements. This also reduces the variance between samples, which increases again the statistical power. However, if the number of stations is too low or poorly selected, the resulting concentrations might be under-representative or biased (Tuit and Wait, 2020).

Detecting spatiotemporal trends in OWF chemical emissions can be challenging due to the natural background levels of individual chemicals, which can demonstrate a high degree of spatiotemporal variability. For example, Reese et al. (2020) calculated a release of >80 kg of aluminium-anode material per monopile per year for OWFs in the German Part of the North Sea. Even higher values were reported by Kirchgeorg et al. (2018). Although this can lead to high emissions of aluminium and a multitude of other (toxic) metals present as impurities (Reese et al., 2020), natural variability in the background levels of aluminium as well as its general high concentration/mass fraction in the marine environment currently hampers the identification of environmental trends (Ebeling et al., 2023, 2025).

OWF chemical emissions are subject to local and regional hydrodynamic patterns, which strongly influence the distribution of individual contaminants. With respect to seawater, water that resided for some time in the windfarm area should be targeted making factors such as the current direction during sampling and the residence time of the water mass in the OWF area of importance. Backtracking simulations (Dulière et al., 2012) and marine current forecast models (Royal Belgian Institute of Natural Sciences, 2024) are useful tools to prepare the sampling program. The amount of suspended particulate matter will strongly impact the contaminant concentration in unfiltered water samples as well as the general distribution between the suspended particulate matter and the dissolved phase. Levels in seafloor sediment are influenced by the erosion and deposition pattern at the chosen sampling locations. In that sense sediment transport models, or other information like residual currents and bathymetry can be consulted. In addition, changes in currents around an OWT can lead to local accumulation and erosion zones (Aminoroayaie Yamini et al., 2018; Neill et al., 2017). The presence of small grain size sediment and organic matter (ICES, 2009) also determines the sorption capacity of the sediment especially towards non-polar compounds. A biased monitoring design that does not take into account these factors has the risk of overestimating or underestimating the true extent of OWF emissions.

An alternative for frequent, highly resolved sampling within the OWF regions represents the so-called passive sampling approach. Passive sampling techniques have been developed for either organic compounds or metals. Applied devices often consist of a sorption phase, which is separated from the environment via a membrane. The sorption phase is exposed in a medium (e.g. water, sediment), where it samples the target compounds at a rate that is proportional to the difference in chemical activity between the sampler and medium and where the uptake kinetics is controlled by passive processes (diffusion and ambient convection) until equilibrium is attained. Upon calibration of the devices, this allows the time-integrated measurement of the freely dissolved compounds present in the sampled environment during the exposure period. Such devices can be easily deployed for monitoring activities, providing information about the average emission level during the exposure period. These techniques are beneficial since they enrich the targeted compounds and separate them from the environmental matrix. However, also, such alternative approaches create certain costs and require logistics (ship time for deployment and recovery) as well as efforts in the lab. In addition, deployment might be hindered due to biofouling and general physical damage due to the sometimes harsh marine condition (Alvarez, 2010; Harman et al., 2009). Last, although passive sampling techniques for metals are well developed, the existing approaches for organics often consider well-known compounds only and the development for an important number of the chemicals potentially emitted from OWFs could be very time-consuming.

Comprehensive OWF monitoring needs to distinguish OWF emissions from other marine and land-based sources. A BACI design, where samples are taken Before (B) and After (A) the commissioning of the OWF, while during the operational phase, samples should be taken in Control (C) and Impact (I) areas (Underwood, 1994), can be of help. In this design, it is important to consider multiple control areas: next to low-impact areas and areas where emissions from other sources, such as shipping, oil and gas, or land-based pollution are expected, should be included to allow thorough conclusions. The implementation of a BACI

design is, however, not always straightforward as it is limited by the spatial homogeneity of the contaminant dispersion. Due to the dynamic systems at play in the marine environment, contaminants may be dispersed over long distances, resulting in a heterogeneous distribution (Osuna and Monbaliu, 2004). Moreover, at existing OWFs, the assessment before commissioning is no longer possible, and in a marine environment, where many activities are taking place, the selection of appropriate control areas can be challenging. Different alternatives have been proposed to tackle these limitations. Distance-stratified control-impact (CI) and after gradient (AG) designs can be used in cases where no data from before the construction of the OWF is available (e.g. Ellis and Schneider, 1997). A Before After Gradient (BAG) allows to distinguish the impacts from other operating factors to be distinguished without the need for control areas as long as data are available for each operating area (Christie et al., 2020; Methratta, 2021). The BACI system can be combined with distance-based sampling, considering the heterogeneous spatial distribution of contaminants over a longer distance (Methratta, 2021). Moreover, statistical methods such as principal component analysis may help to identify sources by clustering sample locations with similar chemical contamination profiles (DelValls et al., 1998). Finally, the sampling design and field monitoring can further be strengthened with the modelling of chemical emissions and their distribution (e.g. Rivas Casado et al., 2009). Aside from the mentioned approaches, new analytical possibilities such as precise isotope ratio measurements provide the potential for source appointment and differentiation even in complex environmental settings e.g. to distinguish metal emission sources (Wiederhold, 2015).

3.3.3. *Numerical modelling for predicting environmental fate of OWF emissions distribution*

To facilitate a holistic assessment of the environmental impact of OWF chemical emissions, numerical models can aid in gaining an understanding of the driving processes and complement monitoring and analytical investigations. Furthermore, from modelled distribution patterns and transport pathways, risk of exposure to potentially harmful substances can be directly assessed, which can aid in the development of mitigation measures (Avens et al., 2011). Numerical transport models are versatile tools which can be used for a wide range of environmental applications. Organic contaminant simulations investigating the atmospheric transport, transport in rivers and oceans, or sorption of contaminants to sediment can be found in the pertinent literature, just to name a few examples (Koziol and Pudykiewicz, 2001; Lindim et al., 2016; Pietrzak, 2021; Wu and Gschwend, 1988). The results of this work indicate that OWFs are potential sources of many soluble and particulate substances, so a thorough understanding of the transport mechanisms of these substances is important in order to monitor them or to identify mitigation measures.

In the context of OWFs, scenario testing and forecasting can aid in assessing the environmental impact of planned or newly installed farms, which will be increasingly important given the enormous expansion of the offshore wind industry in the next years and decades. Forecasting can be useful to evaluate possible environmental effects in the future. Scenario testing can be carried out to underpin spatial planning and risk analysis (Hardesty et al., 2017).

Commonly, contaminant transport models are composed of two main parts: a hydrodynamic model, which is solved using for example a depth averaged model or the 3D Boussinesq approximation, and a transport module which solves concentration equations for dissolved contaminant transport through advection and diffusion (e.g. (Dang et al., 2012; Demmer et al., 2022; Mansui et al., 2015)). The transport modules can for example apply Lagrangian particle tracking to simulate particle pathways (e.g., (Demmer et al., 2022; Liubartseva et al., 2018; Politikos et al., 2020). The Lagrangian particle tracking method has the advantage of resolving trajectories, allowing an accurate tracking of substances even at lower concentrations, while the Eulerian approach models particle concentrations and not trajectories, which does not yield accurate results at low contaminant concentrations (Saidi et al., 2014). Therefore, Lagrangian particle tracking is a promising method for modelling OWF emissions, as the expected contaminant concentrations are low.

Contaminants are either modelled in a conservative manner, neglecting changes through environmental factors, or as reactive substances which are subject to decay or degradation (Jiang et al., 2023). The changes through environmental factors are thereby determined by the polluting substance that is investigated, e.g. the physical shape of an oil spill changes through processes like evaporation, emulsification, and dissolution (Dang et al., 2012), whereas microplastics are degraded through sunlight, biochemical degradation, and mechanical abrasion (Andrady, 2011; Waldschläger et al., 2020). These degradation processes can alter the environmental transport of contaminants (Waldschläger et al., 2020) and models need to be chosen and adapted to each individual question in order to ensure that all relevant processes are included with sufficient accuracy. OWFs potentially emit a wide range of dissolved and particulate emissions, the environmental fate and partitioning of which needs to be thoroughly investigated to allow accurate modelling of these compounds.

Different characteristics of hydrodynamic transport models can aid in investigating environmental distributions of contaminants, also from OWFs. Regional scale models with a Lagrangian tracking of the contaminants are promising tools, since OWFs occupy large areas. Some regional models with Lagrangian particle tracking are presented below. Liubartseva et al. (2018) modelled the transport of plastic debris in the Mediterranean Sea from anthropogenic sources. An Eulerian oceanographic model was used in combination with Lagrangian particle tracking. Diffusion was modelled using a random walk approach. Furthermore, sedimentation and beaching of particles was predicted using a Monte Carlo simulation. Another transport model was used by Mansui et al. (2015), who investigated surface transport of marine debris using a Boussinesq type ocean circulation model in the Mediterranean Sea. The particle transport was modelled as surface transport with no vertical movement, using a Lagrangian solver. Politikos et al. (2020) investigated the transport, residence time, and connectivity of floating litter in the Ionian Sea using a 3D circulation model with the free surface. The investigated litter was tracked using Lagrangian particle tracking which modelled the particles as passive floaters without vertical movement. In the context of OWFs, Demmer et al. (2022) investigated the spatial density distribution and connectivity of mussel larvae at offshore renewable energy sites to assess possible locations for a co-location of aquaculture in the Irish Sea. For the simulations, the authors coupled a 2D depth-averaged finite element model to a Lagrangian particle tracking module. The hydrodynamics were validated using tide gauge and velocity measurements by calculating the root mean square error and the normalised root mean square error between the measurements and the simulated results.

For investigations of waterborne contaminants as described above, the hydrodynamic conditions of the investigated area need to be modelled accurately, and it is important to arrive at calibrated as well as validated model stages, as these are the driving forces for the contaminant transport. In a first step, a model is verified against known solutions to test the applied assumptions for correctness. In a next step, models get validated against observational or experimental data to ensure accuracy for real-world scenarios as well (Oberkampf and Trucano, 2002). In this respect, accurate input data such as wind, wave, and/or current conditions are necessary to produce results of high-quality (Armenio et al., 2019). Furthermore, accurate data on emission timing, quantities and sources can significantly improve the quality of the results (Mansui et al., 2015). However, physical sampling of contaminants to produce such data is a demanding task since the applied sampling methods can influence the results, e.g. through sample size limitations introduced by the equipment used (Hardesty et al., 2017), or due to detectability limitations and time and assets constraints in an evolving (emergency) response situation (e.g. van der Molen et al., 2021). Therefore, it is of

high importance for reliable numerical modelling of contaminants to consider the limitations and possible biases of the input data as identified in the previous sections.

Complex problems such as the transport of contaminants through a waterbody are subject to a large number of influencing processes, variables, and parameters (e.g. chemical reactions, temperature, currents, waves, wind forces, contaminant properties). Due to the high underlying complexity, it is a sensible approach to reduce the complexity of the problem by focusing on the most important processes. However, simplifications must be treated with caution since they can reduce the accuracy of the modelled transport. For instance, the vertical transport of solutes from the waterbody to the sediment is underestimated when the deformation of the seafloor induced by waves and consolidation is neglected (Liu et al., 2022).

Another aspect that must be considered in constructing a model to investigate the transport of OWF emissions is model scaling effects. While numerical models offer the benefit of investigating problems on different scales, scalability comes with the downside that scaling effects may occur which can affect the accuracy of the obtained results. For example, basin scale models can be more accurate near open boundaries than regional scale models (Politikos et al., 2020). Therefore, a suitable model scale needs to be found to minimise errors. Additionally, hydrodynamical processes and environmental degradation of contaminants also occur on different scales, which have an impact on the required grid resolution to properly resolve the processes, e.g. grid cell sizes of a few kilometres for hydrodynamics (Piñones et al., 2011; Venayagamoorthy et al., 2011) down to molecular degradation processes (Das and Chandran, 2011; Rosu et al., 2005). Therefore, suitable implementations need to be found, for example, through empirical degradation coefficients, since accurate numerical simulation of chemical reactions at submicrometre scale is computationally too costly (Ryu et al., 2018).

3.4. Legal frameworks and regulatory differences for OWF chemical emissions

The multiplicity of offshore wind installations is accompanied by the use of different types of operating materials and technologies incorporating various environmentally relevant chemical substances, which may lead to emissions. Besides the evaluation of applied technologies, the chemical compounds emitted, and their effects, it is worthwhile to examine the current status of available legal frameworks on chemical emissions regarding offshore wind energy development, which was investigated for the UK, Germany, The Netherlands, Denmark, Belgium, France, Norway, and the US.

In general, all investigated countries have individual authorisation processes with differences in involved authorities and procedures, making it difficult to compare the approaches. For the UK, Germany, and Denmark, the environmental licensing procedures were investigated elsewhere (Vasconcelos et al., 2022). In addition, insufficient public information and differences in regulations between offshore projects in the same country hamper the comparison on a national level. However, some similarities could also be identified. For example, several general aspects and requirements are often mentioned and applied in transnational (UN General Assembly, 1982. Art. 145; OSPAR Commission, 2008; HELCOM, 2021) and/or national regulative practices (countries):

- no hazard for water quality/marine environment by offshore installations
- avoid/reduce emissions and negative effects from offshore installations by using state-of-the-art techniques
- prevention of oil spills
- waste disposal on land

Chemicals used on vessels for installation, support, or maintenance are considered under shipping regulations elsewhere. In addition, for platforms, the International Convention for the Prevention of Pollution from Ships (MARPOL) might be applied for certain aspects (e.g. oil pollution (bilge), sewage).

Environmental assessments (EA) are regulated in a similar manner as well. Most countries require EA before OWFs are approved and constructed. In the EU, the extent to which and at which planning level EAs are to be carried out is primarily specified by Art. 15c, 16a, and 16b of EU Directive 2023/2413 (REDIII) (European Parliament, 2023). These requirements are made more specific by transposing the directive into the national laws of the member states. In principle, an assessment with respect to the environmental impact of a project has to be carried out prior to the construction of OWFs.

If EA and monitoring programs are carried out for OWFs, they predominantly focus on biological and ecological aspects such as bird migration and collision, sediment and benthos disturbance, and underwater noise (BSH, 2013; Danish Energy Agency, 2019; Danish Maritime Authority, 2021; Degraer et al., 2023; Norwegian Water Resources and Energy Directorate, 2012; Rijkswaterstaat, 2016; Rijkswaterstaat., 2022). However, the assessment and monitoring of impacts resulting from chemicals and chemical emissions are only mentioned and addressed occasionally. For example, in France, a monitoring of metallic contamination in water, sediment, and benthos is recommended (Miquerol et al., 2023). For Germany, the UK, and the US more detailed regulations addressing chemical emissions are presented in the following individual case studies.

3.4.1. Legal framework case study: Germany

In Germany, the majority of OWFs are situated in the German exclusive economic zone (EEZ) of the North Sea and the Baltic Sea. The Federal Maritime and Hydrographic Agency (BSH) is the responsible authority for the examination, approval, and monitoring of wind turbines and offshore structures such as converter platforms and offshore substations (WindSeeG, 2017). Moreover, BSH is responsible for maritime spatial and sectoral planning.

Regarding chemical emissions within the framework of licensing, the applicants have to present a specific emission concept in the early design phase illustrating which chemical emissions are expected in the project and how they are reduced and/or avoided. These concepts are assessed with respect to their environmental impacts. After approval, an emissions study is required, which includes a more detailed description and quantification of chemical emissions and their avoidance. Furthermore, waste and operational materials concepts are mandatory for the operational phase of the project, which are regularly updated by operators to ensure, e.g., proper handling of operating materials and waste.

On the maritime sectoral planning level, the ‘site development plan’ defines standard technical and planning principles for OWFs and their grid connections (BSH, 2025). The requirements of the ‘site development plan’ are mandatory for individual offshore projects (turbines and platforms). This plan also regulates the topic of chemical emissions and their avoidance, mainly focusing on environmental technologies and also considering operative experiences from the offshore wind sector regarding the applicability (BSH, 2025) with regard to:

- General aspects (avoid/reduce emissions, environmentally friendly operating materials, structural and operational precautionary measures)
- Waste
- Corrosion protection
- Cooling systems
- Sewage / wastewater
- Drainage / oily water separator
- Firefighting foams, especially on helicopter landing decks
- Fluorinated greenhouse gases
- Diesel generators
- Scour / cable protection
- Grouting

Corrosion protection systems are assumed to be one of the major sources of chemical inputs during the operational phase of wind farms. The 'site development plan' gives guidance on how to reduce emissions, especially by cathodic protection systems in the underwater zone, while maintaining the required corrosion protection during the lifetime of the offshore structures. This includes the preference for ICCP as they are made of solid materials such as metal oxide-coated titanium (PowerTech, 2018). Galvanic anodes should be avoided or, if unavoidable, should only be used in combination with coating of the foundations. Offshore wind projects shall further reduce the content of impurities of galvanic anodes such as heavy metals. The use of zinc anodes is not allowed in the German EEZ. Regarding coatings for corrosion protection, the 'site development plan' prohibits biocides and all other anti-fouling agents to avoid potentially negative effects on the marine environment.

3.4.2. Legal framework case study: the UK

In the UK, OWFs with a capacity of >100 MW (all wind farms except small demonstration projects) are regarded as "Nationally Significant Infrastructure Projects" (NSIPs) in the Planning Act 2008, Section 15 (UK Government, 2008). NSIPs are regulated under the Planning Act 2008 and licensed by the Planning Inspectorate at the UK level. National Regulators, the Marine Management Organisation (MMO), Marine Scotland, and Planning and Environment Decisions Wales (PEDW) support the Planning Inspectorate in the decision-making process.

The Offshore Chemical Regulations (UK Government, 2002) in place were formed under the Petroleum Act (UK Government, 1998) but do not cover OWFs. Also, they do not cover paints and coatings nor chemicals used within closed systems where release into the environment is not deemed to occur. Even though the OSPAR guidance (OSPAR Commission, 2008) advises that all chemicals being used in OWFs should be approved for use in the marine environment and have their ecotoxicological properties known, there is no formal mechanism for doing so in the UK. Essentially, the UK has no bespoke regulations governing the use of chemicals in the offshore renewable energy sector, although the UK MMO does require developers to provide information on chemicals used and discharged as part of an OWFs deemed marine licence and supported by their power/remit under the Marine and Coastal Access Act 2009 (UK Government, 2009).

Therefore, in most, if not all cases, a wind farm licence will include conditions relating to the use of chemicals which the developer must abide by. Blake et al. (2022) conducted a review of the licence conditions of all UK wind farms up to December 2020. They found that, in general, the licence conditions followed the spirit of the Offshore Chemical Regulations (which are specific to the oil and gas industry). There was, however, notable variation in the application of licence conditions and in the wording of conditions between wind farms and regulatory bodies, which probably reflects the semi-formal efforts to compensate for specific regulations.

The most common licence condition found was that chemicals used must be on the UK Offshore Chemical Notification Scheme (OCNS) definitive ranked list of registered chemicals. The OCNS list is derived from modelling chemical emissions based on generic parameters of oil and gas platforms. If chemicals were not on the OCNS list, then prior approval would be needed. In contrast to oil and gas applications, a site-specific risk assessment of chemical use is not routinely required for OWFs. Other conditions on licences stated that all chemicals with a pathway to the marine environment should be notified to the regulator, which determines if more information is required. In contrast to oil and gas applications, a site-specific risk assessment of chemical use is not required routinely for OWFs and is only undertaken when specifically requested by the regulator. This may be as little as a request for an updated MSDS to the provision of all the PBT test reports at substance level for approval prior to use. Blake et al. (2022) found approximately 300 different substances being used across the UK offshore wind sector. The greatest quantities of chemicals found to be used were grout/cement, hydraulic and transmission oil, and cooling and drilling fluids.

3.4.3. Legal framework case study: the US

In the US, the Department of the Interior, authorized through the Energy Policy Act (U.S. DOI, 2005), regulates renewable energy activities on the Outer Continental Shelf (OCS). The regulations provide a framework for the Bureau of Ocean Energy Management (BOEM) to issue leases, easements, and rights-of-way for renewable energy development on the OCS. Additionally, the Bureau of Safety and Environmental Enforcement (BSEE) evaluates facility design, fabrication, installation, safety management systems, and oil spill response plans; enforces operational safety through inspections, incident reporting, and investigations; enforces compliance, including safety and environmental compliance, with all applicable laws, regulations, leases, grants, and approved plans; and oversees decommissioning activities.

United States Federal Agencies must prepare environmental compliance documentation for proposed actions in accordance with the National Environmental Policy Act (NEPA, 40 CFR 1500–1508) (U.S. EPA, 1969) and other applicable laws. An EA or Environmental Impact Statement (EIS), all of which BOEM makes publicly available, is prepared to analyse the reasonably foreseeable effects of proposed activities. It includes a review of resource-specific baseline conditions and future offshore wind activities and assesses cumulative impacts that could result from the incremental impact of the proposed action and action alternatives when combined with past, present, or reasonably foreseeable activities. This assessment includes consideration of chemicals that may be released in the event of a spill or other occurrence, such as material degradation. In 2013, BOEM published a study evaluating the risks of chemical spills under various scenarios at offshore wind facilities using three locations along the US Atlantic coast as examples (Bejarano et al., 2013) and is currently contracting a study to provide an updated assessment of the chemicals used and stored at these facilities.

The US does not have chemical emissions standards specifically tailored to offshore wind facilities. Chemical emissions associated with offshore wind projects are regulated under broader frameworks:

- The National Pollutant Discharge Elimination System (NPDES) (U.S. EPA, 1983) permit program under Section 402 of the Clean Water Act regulates pollutants directly released into the waters of the US.
- The National Primary and Secondary Ambient Air Quality Standards (NAAQS; 40C.F.R. part 50) (U.S. EPA, 1971), required by the Clean Air Act, sets standards for six principal pollutants (CO, Pb, NO_2, O_3, particle pollution, and SO_2) which can be harmful to public health and the environment.
- The New Source Performance Standards (NSPS) (US EPA, 2013a) under Section 111 of the Clean Air Act (40C.F.R. part 60 subpart IIII) sets out standards for 18 non-metallic minerals.
- The National Emission Standards for Hazardous Air Pollutants (NESHAPs) (US EPA 2013b), under Section 112 of the Clean Air Act (40C.F.R. parts 61 and 63 subpart ZZZZ), are stationary source standards for hazardous air pollutants. Hazardous air pollutants (HAPs) are those pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive effects or birth defects, or adverse environmental effects.

3.5. Potential ways to minimise emissions

All offshore facilities are complex technical structures and consist of many different components and technical systems. Offshore facilities require a space-saving design, concurrently they have to be built in a solid way to ensure stable and secure operation conditions and to withstand the harsh marine environment (Díaz and Guedes Soares, 2020), with the possibility for immediate access in case of failure or accident. Additionally, they should be designed and conducted in a manner that they do not cause any avoidable emissions or entail the least possible impact to marine environment (UN General Assembly, 1982

Art. 145). With regard to chemical emissions, for all offshore facilities the corrosion protection system is important. For OWT the most relevant technical systems are machineries (e.g.generators, transformators) as well as cooling systems and for offshore platforms as substations (OSS) and converters transformators, seawater cooling systems, wastewater systems, drainage systems, and firefighting systems are crucial. For emission control, it is not easy to define state-of-the-art techniques explicit for offshore wind facilities. Only very few detailed recommendations or guidelines for technical measures for OWF are currently available (e.g. Pans and Plenker, 2024). However, technical measures from other (maritime) industrial fields could be applied (e.g. MARPOL, 2012), since the same or similar technical systems are used.

Overall, three categories of different measures can be applied or combined to avoid or reduce chemical emissions from OWFs: technical measures, material measures, and structural safety measures. Technical measures are used to reduce concentrations of contaminants in an

Table 2
Summary of potential measures to avoid or reduce chemical emissions. [1]material measures, [2]technical measures, [3]structural safety measures.

Source	Occurrence	Chemical emission	Measure	Reference
Equipment/ technology/ storage	Platform	Operation materials	Double-walled system[3]	BSH, 2025; Pans and Plenker, 2024
	OWT, platform		Bunded area[3]	OSPAR commission, 2008
	OWT, platform		Collection tank[3]	BSH, 2025
	Platform		Drainage system[3]	BSH, 2025
	OWT, platform		Enclosure[3]	BSH, 2025
	OWT, platform		Leakage sensor system (e.g. level sensor, pressure transmitter) [2]	BSH, 2025
	OWT, platform		Usage of biodegradable operation material[1]	RAL gGmbH, 2015; BSH, 2025
	OWT, platform		Periodic inspection of installation	BSH, 2021; Pans and Plenker, 2024
Corrosion protection	OWT, platform	Metals	Usage of Impressed current cathodic protection (ICCP) wherever possible[2]	BSH, 2025
			Usage of galvanic anodes in combination with coating[2,3]	BSH, 2025
			Reduction of content of secondary components of the anode alloys, in particular zinc, cadmium, lead, copper and mercury to a technical minimum[1]	BSH, 2025
			Avoidance of zinc anodes[1]	BSH, 2025
			Limitation of zinc content of aluminium-zinc-indium anodes to technically necessary minimum[1]	BSH, 2025
Waste water system	Platform	Waste water	Collection in sufficient dimensioned tanks and disposal on land[2]	BSH, 2025
			Sewage treatment plant to reduce emissions of N, P and bacteria [2]	BSH, 2025; MARPOL, 2012
			Avoidance/Minimization of chlorination[1]	BSH, 2025; RAL gGmbH, 2015; MARPOL, 2012
Seawater cooling system	Platform	Biocides (e.g. NaOCl, Cu)	Application of alternative (closed) cooling water treatment[2]	BSH, 2025
			Minimisation of biocides by e.g.	BSH, 2025; EC, 2001
			o seasonal use (depending on water temperature and fouling growth pressure, respectively) [2]	
			o reduction of the effective concentration[1]	
			o pulse chlorination[1]	
			o monitoring of outlet concentration to continuously adjust effective concentration[1]	
			o filtration of cooling stream[2]	
			o UV treatment[2]	
			o Ultra sonic treatment[2]	
Closed cooling system	OWT, platform	Coolant (e.g. glycol)	Reduction of corrosion of cooling equipment[1,2]	EC, 2001
		Refrigerants	Selection of less hazardous cooling water additives[1]	EC, 2001
		Cooling additive (e.g. corrosion inhibitor)	Usage of refrigerants with lowest possible greenhouse gas impact[1]	RAL gGmbH, 2015
			Optimised application of cooling water additives[2]	EC, 2001
Firefighting foam	Platform	PFAS	PFAS-free[1]	Nicol et al., 2022
			Firefighting exercises only with water[1,2]	BSH, 2025
			Collection of water and foams used for firefighting in drainage system[2]	BSH, 2025
Electrical switchgear	OWT, platform	F-Gas (especially SF_6)	Usage of insulation gas with lowest possible greenhouse gas impact[2]	BSH, 2025
			Usage of SF_6 should be avoided[1]	European Parliament, 2024
Drainage water	OWT, platform	Oil/Grease/Lubricant	Collection in tanks and disposal on land[2]	BSH, 2025
	Platform		Oily water separator with residual oil content <5 ppm[2]	BSH, 2025; DIN e.V., 2005; RAL gGmbH, 2015
Coating, paint	OWT, platform	Paint debris, chemical leachate	Should be approved for use in the marine environment and their ecotoxicological properties known[1]	OSPAR Commission, 2008
			Housing during paint removal/repair[2]	
			Collecting/vacuum of particles during removal/repair process[2]	
			Usage of biocide-free antifouling paint and coating[1]	RAL gGmbH, 2015
Scour protection	OWT, platform	Div. chemical components	Usage of natural stone[1]	BSH, 2025; OSPAR Commission, 2008
		Plastic debris	Free of chemical contaminants and plastic[1]	BSH, 2025
Fuel	OWT, platform	SOx	Usage of fuel with minimum sulphur content[1]	BSH, 2025
Bunkering	Platform	Petroleum products	Shut-off valves on both sides of the connection and pipelines above the water surface[2]	Pans and Plenker, 2024
			Emergency spill kits[2]	BSH, 2025

effluent. For example, the oil content in drainage water can be reduced by using an oily water separator or wastewater can be purified using a sewage treatment system. Material measures refer to the usage of the most environmentally friendly materials, such as biodegradable materials (e.g. lubricating and hydraulic oils) or the selection of less toxic materials (e.g. composition of galvanic anodes or ICCP). Structural safety measures are construction measures to avoid accidental contaminant emissions in case of failure. Table 2 gives an overview of potentially applicable measures to avoid and reduce chemical emissions. This overview may serve as a guideline to planners, wind farm operators, and administrations. Two examples of measures for different relevant emission sources are discussed below in more detail.

3.5.1. Cathodic corrosion protection

The currently most applied corrosion protection system is GACP, which results in the continuous emission of metals. To reduce metal emissions, or at least the emission of certain metals that are considered pollutants, technical and material measures can be applied or combined. For example, GACP may be combined with (organic) coatings. Coatings can act as a barrier to separate the steel of the foundation from the environment (Lyon et al., 2017). When combining these two systems, the necessary amount of galvanic anode material can be reduced significantly, e.g. for monopile foundations by up to 54 % (Kirchgeorg et al., 2018), and costs can also be saved (Sarhadi et al., 2018). As a material measure, planners and operators can install galvanic anodes in which the content of secondary, toxicologically relevant components, in particular, zinc, cadmium, lead, copper, and mercury (Reese et al., 2020), are reduced to a technical minimum. In contrast to galvanic anodes, ICCP represents a system with very low or nearly no metal emission to the marine environment (Syrek-Gerstenkorn and Paul, 2024), though halogenated by-products may be generated due to the ongoing electrolytical processes (Michelet et al., 2020; Miquerol et al., 2023). The installation of ICCP is technically complex, and the effort for maintenance is high, especially repair work in the underwater zone, which can be demanding (PowerTech, 2018).

3.5.2. Seawater cooling system

The main purpose of offshore platforms such as OSS or converters (high-voltage direct current stations) is the collection and conversion of electrical energy. During these processes, large amounts of waste heat are generated. To sustain the operability, effective cooling systems with large cooling capacities and, at the same time, lowest possible space demand are required. Seawater cooling systems combine these requirements because (sea)water has a very high heat capacity (European Commission, 2001).

For seawater cooling systems, the waste heat is transferred via heat exchangers to seawater that flows through, and which is subsequently discharged into the sea. A disadvantage is that seawater contains biofouling organisms, which readily settle on critical components and, therefore, may endanger the operability of the system and, consequently, the operability of the whole converter (Bruijs and Jenner, 2012). To avoid biofouling, the most common method is the use of biocides (European Commission, 2001; Umweltbundesamt (UBA), 2003) e.g. sodium hypochlorite (NaOCl) or copper (Plenker et al., 2024), which are generated in situ by electro-chlorination of seawater or by the Impressed Current Anti Fouling (ICAF) method, respectively and continuously released with the cooling water into the sea. However, it is well known that biocides can have an adverse effect (dose depending) on the marine environment (Venugopalan et al., 2012). To reduce the release of biocides into seawater and optimise its usage, several of the best available techniques for industrial cooling systems (European Commission, 2001) can also be transferred and applied in OWFs. Biocide-based strategies include the reduction of biocide concentrations to the lowest possible, e.g. by seasonal use of biocides only (depending on water temperature and fouling growth pressure) or the monitoring of the outlet concentrations to continuously adjust effective concentrations, as well as pulsed chlorination (BSH, 2025; European Commission, 2001). In contrast, physical and mechanical (non-biocidal) strategies can be applied including the filtration of cooling streams to reduce the load of biofouling organisms and ultrasonic or UV treatment technologies. European Commission, 2001).

Furthermore, environmentally friendly alternatives are closed cooling systems with no discharges which are already being applied on certain offshore platforms (BSH internal communication; Plenker et al., 2024).

4. Conclusions

A wide variety of chemical emissions from OWFs may enter the marine environment, including dissolved organic chemicals, inorganics, and particles. The relative share of OWF chemical emissions compared to other sources, as well as the impact of these chemicals on the marine environment, is unclear as current OWF monitoring is mainly focused on biological and ecological aspects. Standardized impact assessments or monitoring requirements for chemical contaminants seem not to be established on a regular basis so far, although, in some countries, specific regulations for chemical emissions are available. This review offers a comprehensive overview of potential OWF chemical emissions, which is an essential first step towards the implementation of impact assessment and sound regulations to optimally protect the marine environment. However, multiple gaps remain in reaching this goal. Whereas local data on OWF metal emissions, such as on the German part of the North Sea (Ebeling et al., 2023, 2025), are becoming publicly available, there is a strong need for systematic occurrence data at larger spatial and time scales for both organic and inorganic contaminants. Given the high diversity of chemicals and the cost to implement sound monitoring, this should be implemented using a risk-based approach, prioritising the OWF emissions of highest concern, developing a source-or distance-based spatial monitoring design and including numerical modelling to predict distribution and relative shares compared to other sources. Equally, there is a need for more detailed toxicity data for individual compounds and mixtures of OWF chemical emissions on early-life stages of marine species, as toxicity testing is mostly performed on freshwater species of a limited number of trophic levels, with limited relevance for the marine environment.

Additionally, we assume a general gap of knowledge concerning applied technologies and materials, that may potentially cause chemical emissions during operation of platforms and wind turbines. For example, information on compositions of coatings is often incomplete. Therefore, more transparency is required concerning applied technologies and materials as well as more effort towards the development of environmentally friendly materials. Furthermore, most operating materials are applied in closed systems (e.g. turbines, diesel storage tanks), and chemicals may be released only by leakages and/or accidents. Therefore, current assessments may rank offshore wind facilities as a “minor source” for chemicals compared to other input pathways into the marine environment (e.g. rivers). However, it is important to consider that while the global construction of OWFs at present is still reduced compared to other industrial facilities at sea (e.g. oil and gas), the foreseen future and fast expansion of this sector may change this dimension.

Despite the abovementioned gaps, there is a growing awareness on the topic of chemical emissions from OWFs at policy and industry level, including increasing efforts in the implementation of avoidance and reduction measures and the development of national regulations. Next steps include increasing our understanding of the overall impact of OWFs, apply and/or expand already existing regulations on a larger scale also for OWFs and to establish a cost-effective and integrated monitoring that involves impact assessment of chemical emissions as for other factors such as noise, electromagnetic fields, new habitat introduction. Enhancement of regulatory and mitigation strategies requires the need for interdisciplinary collaboration among policymakers,

engineers and environmental scientists. Ideally, this will lead to international agreed and harmonized guidelines, for example within the framework of regional sea conventions, and can benefit policy, industry as well as society in the construction of environmentally friendly OWFs.

CRediT authorship contribution statement

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Declaration of competing interest

None.

Acknowledgements

This review was the result of a collaboration between the Interreg North Sea Project Anemoi (Project number 41-2-13-22), which was co-funded by the European Union, the ICES marine chemistry working group and the ICES working group on offshore renewable energy. Special notifications go to coordinators and subgroup leads Elena Hengstmann, Pablo Zapata Corella, David Vanavermaete, Niklas Czerner, Katharina Alter, Torben Kirchgeorg, Jennifer Kenyon and Bavo De Witte. Thanks to Sylvia Blake (Cefas) who helped review the paper before submission.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.117915.

Data availability

The dataset (Zapata Corella et al., 2025) is publicly available: https://doi.org/10.5281/zenodo.14865443.

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