Review Article
Turkish Journal of Maritime and Marine Sciences

DOI: 10.52998/trjmms.1415808
Volume: XX Issue: XX (20XX) XX-XX

Chemical Approach to Offshore Wind Turbines: Coating Systems, Environmental Impacts, And Sustainable Development

Açık Deniz Rüzgar Türbinlerine Kimyasal Bakış: Kaplama Sistemleri, Çevresel Etkiler Ve Sürdürülebilir Kalkınma

Türk Denizcilik ve Deniz Bilimleri Dergisi

Cilt: XX Sayı: XX (20XX) XX-XX

Gülşah Çelik GÜL[1,*], Metin GÜL[2]

[1] *Balikesir University, Chemistry Department, Çağış Yerleşkesi, 10145 Altıeylül/Balıkesir, Türkiye*
[2] *Balikesir University, Sci&Art Institute, Mech. Eng. Department, Çağış Yerleşkesi, 10145 Altıeylül/Balıkesir, Türkiye*

ABSTRACT

The deployment of offshore wind turbines (WTs) is gaining momentum worldwide, offering significant potential for clean energy generation. However, the maintenance and longevity of offshore WT structures present complex challenges, particularly concerning corrosion protection coatings and their environmental impacts. This paper discusses the key design criteria, protective mechanisms, and application methods of coating systems for offshore WTs, emphasizing the need for durable solutions to withstand harsh marine conditions. Additionally, the study examines the chemical emissions originating from offshore wind farms, including corrosion products and plastics, and their potential ecological impacts. While there is a lack of comprehensive scientific studies on the environmental effects of deepwater, floating offshore wind farms, this paper aims to shed light on these issues and their implications for marine ecosystems and human health. By synthesizing existing literature on analogous situations, the discussion provides insights into the environmental footprints of offshore wind power and underscores the importance of prudent decision-making in advancing future offshore wind projects.

Keywords: Offshore wind turbines, Chemical pollutants, Chemical emissions.

Article Info
Received: 22 January 2024
Revised: 01 March 2024
Accepted: 16 March 2024

* (corresponding author)
E-mail: gulsahcelik@balikesir.edu.tr

To cite this article: Çelik Gül, G., Gül, M. (2024). Chemical Approach to Offshore Wind Turbines: Coating Systems, Environmental Impacts, and Sustainable Development, *Turkish Journal of Maritime and Marine Sciences* XX (XX): XX-XX. doi: 10.52998/trjmms.1415808.

ÖZET

Açık deniz rüzgar türbinlerinin (RT'ler) konuşlandırılması dünya çapında ivme kazanırken, temiz enerji üretimi için önemli bir potansiyel sunmaktadır. Bununla birlikte, açık denizdeki rüzgar türbini yapılarının bakımı ve uzun ömürlülüğü, özellikle korozyona karşı koruma kaplamaları ve bunların çevresel etkileriyle ilgili olarak karmaşık zorluklar ortaya çıkarmaktadır. Bu çalışma, zorlu deniz koşullarına dayanacak dayanıklı çözümlere olan ihtiyacı vurgulayarak, açık deniz RT'leri için kaplama sistemlerinin temel tasarım kriterlerini, koruyucu mekanizmalarını ve uygulama yöntemlerini hakkında gerçekleştirilen bir derlemedir. Ayrıca çalışma, açık deniz rüzgar santrallerinden kaynaklanan, korozyon ürünleri ve plastikler de dahil olmak üzere kimyasal emisyonları ve bunların potansiyel ekolojik etkilerini incelemektedir. Derin sularda yüzen açık deniz rüzgar santrallerinin çevresel etkilerine ilişkin kapsamlı bilimsel çalışmalar bulunmamakla birlikte, bu makale bu konulara ve bunların deniz ekosistemleri ve insan sağlığına olan etkilerine ışık tutmayı amaçlamaktadır. Çalışma, benzer durumlara ilişkin mevcut literatürü sentezleyerek, açık deniz rüzgar enerjisinin çevresel ayak izleri hakkında fikir oluşturarak ve gelecekteki açık deniz rüzgar projelerini ilerletmede yerinde ve doğru karar vermenin öneminin altını çizmektedir.

Anahtar sözcükler: Açık deniz rüzgar türbinleri, Kimyasal kirleticiler, Kimyasal emisyonlar.

1. OFFSHORE WIND FARMS

1.1. Offshore wind energy turbines and Türkiye's policy

The main offshore wind energy facilities are a significant component of the renewable energy sector on a broad scale. Renewable energy is defined as the energy derived from the ongoing natural processes, and it is sourced from existing energy flows. While currently, 80% of global energy is generated from fossil fuels (IEA, 2023), in December 2022, this ratio decreased to 54% in Türkiye (Fig.1). Renewable energy sources play a crucial role in reducing dependence on fossil fuels such as coal, oil, and natural gas (Zou *et al*., 2016). Solar, wind, biomass, geothermal, hydro, hydrogen, and ocean energy (wave and tidal) are considered within the scope of renewable energy (TEİAŞ, 2022).

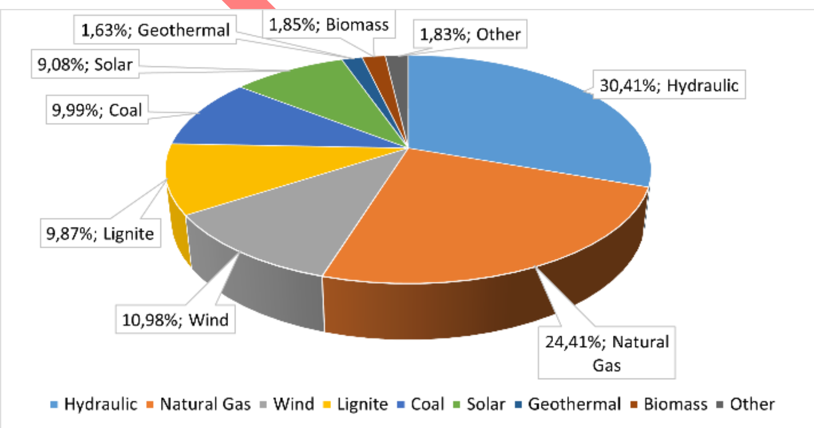

Figure 1. Installed electricity capacity in Türkiye for the year 2022 (TEİAŞ, 2022)

The characteristics of wind vary temporally and spatially due to local geographical differences and the non-uniform heating of the Earth's surface. Wind is expressed through two parameters: speed and direction. Wind speed increases with height, and its theoretical power changes proportionally to the cube of its speed. Despite the initial high investment costs, low-capacity factors, and disadvantages such as variable energy production associated with wind energy-based electricity generation applications, the advantages can generally be listed as follows:

- It is a renewable and clean energy source, environmentally friendly.
- There is no risk of depletion and increasing prices over time.
- Its cost has become competitive with contemporary power plants.
- Maintenance and operating costs are low.
- The technology for installation and operation is relatively simple.
- Commissioning can be achieved in a short period of time.

Wind turbines, the main structural elements of wind energy plants, are machines that primarily convert the kinetic energy of moving air into mechanical energy and subsequently into electrical energy. According to the December 2022 report data from the Turkish Electricity Transmission Corporation (TEİAŞ), wind turbines constitute approximately 11% of the installed capacity in Türkiye (Fig.2). Considering these data, it can be stated that wind energy is a significant resource for Türkiye (Fig.3) (GMKA report, 2023).

According to World Bank data, Türkiye's technical potential for offshore wind turbines (WTs) is identified as 75 GW (World Bank, 2019). Within this capacity, 12 GW is expected to come from fixed-base WTs, and 63 GW is projected to be provided by floating WTs. It is noted that within this capacity, 50-55 GW can be defined as technically feasible and more efficiently reachable capacity (Leybourne, 2022).

Figure 2. Wind energy installed capacity development in Türkiye

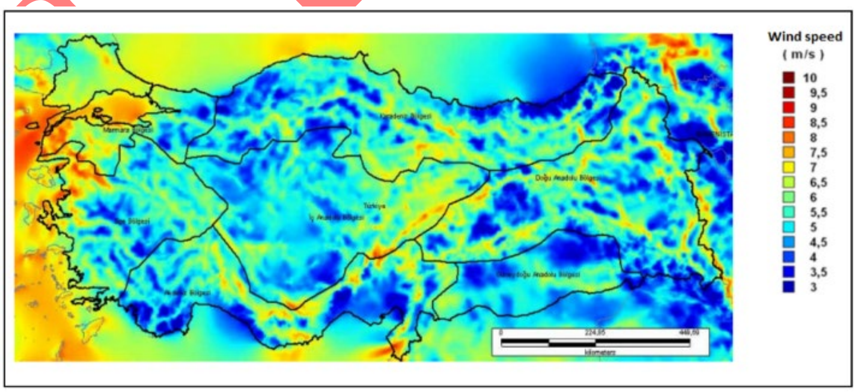

Figure 3. Wind map of Türkiye

1.2. Global perspectives on offshore wind farms

Growing demand for electrical energy and concerns about the consequences of climate change have led governments worldwide to establish ambitious targets for reducing greenhouse gas emissions and increasing the share of renewable energy sources, such as solar and wind, in their energy portfolios (Graabak *et al.*, 2016).

The wind industry is an emerging sector that experienced significant growth, boasting 1.1 million jobs globally in 2016 (Irena, 2016). Notably, China, Germany, and the USA stand out as the primary employers in this field (Irena, 2016). While onshore WTs constitute a significant portion of the installed capacity, it is observed that the share of offshore WTs in installed capacity has been steadily increasing since 2009 (Leybourne, 2022). In the first quarter of the 2000s, the offshore wind energy industry has evolved from turbines on foundations in shallow waters to floating turbines in deeper waters, and there are even considerations for floating turbines in very deep waters (BOEM wind energy Call Areas and the Castle Winds proposal in California, USA; BOEM, 2018, Trident Winds, 2016) (BOEM, 2021). As an example, China, hold first place, reached 2.8 GW of offshore wind energy capacity in 2017 and aims to reach 30 GW by 2020 (GWEC, 2018).

If we delve into the details of these advancements; the most substantial capacity increase in offshore WTs occurred in 2020, reaching 21 GW (Leybourne, 2022). According to the "2021 Global Wind Energy Report" prepared by the Global Wind Energy Council (GWEC), the installed wind power capacity worldwide has reached approximately 837 GW levels. As of the year 2021, 780 GW of the installed capacity comes from onshore wind energy plants, while the remaining 57 GW is from offshore WTs. Since 2001, onshore WTs has shown significant development in terms of installed capacity, while this progress has been slower in offshore WTs. However, in recent years, significant strides have been made in offshore WTs due to advancements in technology (GWR, 2021). At this point, it can be stated that offshore plants have gained global significance. As of 2021, offshore WTs represents 6.8% of the total installed capacity worldwide, while onshore WTs constitutes 93.2% (Leybourne, 2022).

In the last two decades, there has been a significant increase in new investments in offshore wind energy, particularly in Europe (Fig.4). The total installed capacity in European waters was less than 50 MW in the year 2000, but by the end of 2008, it had risen to approximately 1500 MW (EWEA, 2019). As a result of these investments, there is an annual average growth rate of around 50%. Although most operational offshore systems are concentrated in a limited number of Northern European countries, global interest in offshore wind farms is on the rise (EWEA, 2019). Both onshore and offshore wind turbines share similar components, such as the tower, nacelle, rotor assembly, and rotor blades. However, distinctions emerge concerning factors like costs, size, transportation of components, working environment, novelty, wind conditions, and more (EU-OSHA; 2013). Therefore, the current share of offshore wind farms remains lower compared to onshore activities (EWEA, 2019).

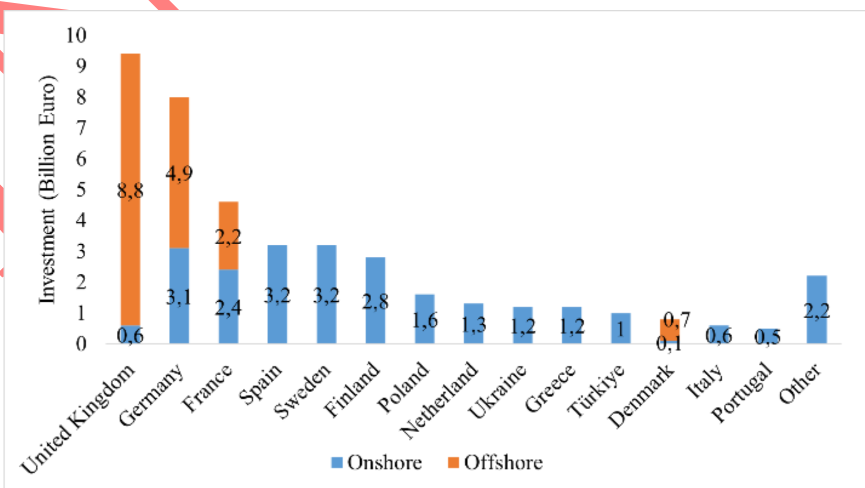

Figure 4. 2021 European wind energy investments

As seen in the Table 1, as of 2021, the global installed capacity of offshore WTs has reached 57,176 MW. Approximately half of this capacity was added in the year 2022 (GWEC, 2022).

Table 1. The installed capacity of offshore WTs and capacity increases worldwide as of 2022.

Country	Installed capacity (MW) 2022	Total capacity (MW) 2022
World	8941	63200
Asia	**4678**	**32496**
China	4070	30460
Chinese Taipei	508	745
Japan	0	61
Korea Rep	0	136
Vietnam	100	1094
Europe	**4264**	**30663**
Belgium	0	2262
Denmark	0	2306
Finland	0	73
France	480	482
Germany	342	8129
Ireland	0	25
Italy	30	30
Netherlands	760	3220
Norway	60	66
Portugal	0	25
Spain	0	5
Sweden	0	193
UK	**2592**	**13848**
European Union	1612	16749
N America	0	41
USA	**0**	**41**

1.3. Types of offshore wind turbines

A general categorization for wind turbines installed offshore into the sea beyond the coast is commonly referred to as offshore wind turbines. Installations comprising multiple turbines arranged in groups or arrays are also recognized as offshore wind farms. The primary reasons for preferring installations at sea over onshore wind turbines include their minimal impact on residential areas and the ability to harness higher average wind speeds with less disruption from turbulence, as the wind flows unimpeded. However, offshore wind farms, compared to their onshore counterparts, are notably disadvantaged in terms of cost. Therefore, when deciding on the installation of any offshore wind farm, profitability calculations must consider installation, maintenance, and operation costs as crucial factors.

Furthermore, various aspects such as the region's wind climate, habitats of marine and airborne species, maritime routes, and other relevant considerations must be thoroughly assessed. Depending on the depth of installation, offshore wind turbines are broadly classified into two main types (Fig.4): those fixed to the seabed and those designed to float (Çokyaşar *et al.*, 2019).

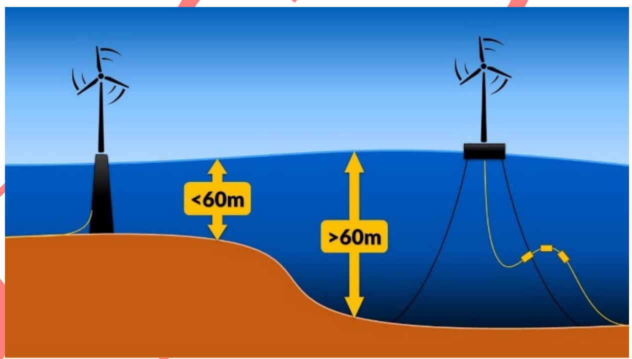

Figure 4. Fixed and floated offshore turbines (TEKMAR, 2023).

2. CHEMICAL EMISSIONS OF OFFSHORE WIND FARMS

2.1. Corrosive products

The generation of electric power through offshore WTs is gaining prominence globally. The offshore WTs can be broadly categorized into tower constructions and transmission platforms, both of which involve intricate engineering steel structures. The costs associated with repairing protective coating systems for offshore WTs are estimated to be approximately 50 times higher than the costs incurred for the initial application of corrosion protection systems during the tower manufacturing process. Consequently, protection systems for offshore WTs need to be designed with high reliability, and their expected durability can exceed 25 years (Momber *et al.*, 2018).

Key design criteria for coating systems on steel encompass binder type, dry film thickness, and layer system (ISO 12944-5, 2007; NACE SP0108-2008). Due to the absence of specific offshore WTs standards, the industry often relies on existing offshore coating standards, despite differing stress conditions between offshore WTs and oil and gas platforms (Norsok M-501, 2012; ISO 20340, 2009). For instance, offshore WTs support structures face high dynamic stresses from wind, waves, and operation, requiring resilience to an exceptionally high number of stress cycles throughout their design life (Anderson *et al.*, 2011). These unmanned structures lack systematic inspection and maintenance capabilities (Schaumann *et al.*, 2011). Additionally, internal areas such as monopiles and transition pieces within foundations have been identified as susceptible to corrosion (Hilbert *et al.*, 2011).

A coating system comprises multiple layers, each serving distinct purposes (Soerensen *et al.*, 2009). In the context of corrosion protection, a coating system generally includes the following layers:

Priming coat: the initial coat in the system.

Intermediate coat: any coat positioned between the priming and topcoat.

Topcoat: the final coat in the coating system.

Corrosion protection coatings (Fig.5) (Boga *et al.*, 2021) operate through different protective mechanisms, which can be categorized as follows:

Barrier effect: Priming and intermediate coats with inert pigmentation like titanium oxide, micaceous iron oxide, or glass flakes.

Inhibitive effect: Priming coats commonly use inhibitive pigments, relying on substrate passivation and protective layer buildup, often involving inorganic salts.

Galvanic effect: Achieved with sacrificial coatings, protecting the substrate through galvanic corrosion principles. Common protective metals include zinc and aluminium or their alloys, with zinc-rich organic coats being widely used (Soerensen *et al.*, 2009; Boga *et al.*, 2021).

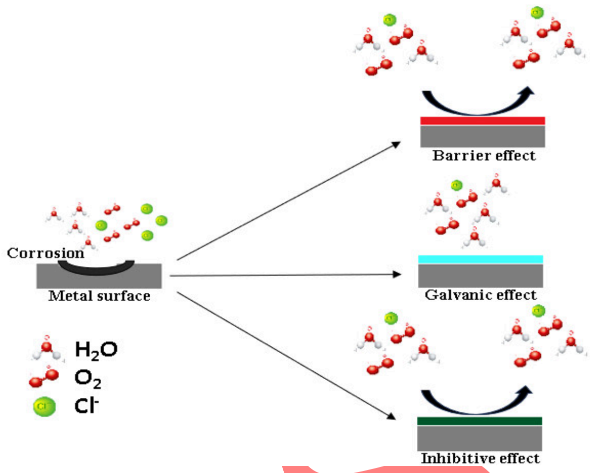

Figure 5. Schematic illustration of barrier; galvanic; and inhibitive effects

Most coatings for offshore WTs are chemically curing systems with two packs: a base component (binder/resin) and a curing agent component (hardener). Common binder types include alkyd, chlorinated rubber, acrylic, polyvinylchloride, epoxy, ethyl silicate, and polyurethane. Common hardeners include polyamines, polyamides, and polyisocyanates, with polyamines being more suitable for priming coats (ISO 12944-5, 2007).

Coating systems, comprising both organic and metallic coatings, can be applied either in a factory setting or on-site. Factory application of coatings provides numerous benefits, including precise control over application conditions to ensure optimal performance, ease of damage repair, and effective waste and pollution management. However, drawbacks should be taken into account, such as limitations on component size and the potential for damage during handling, transportation, and installation. Maintenance activities are typically conducted on-site. The most prevalent methods for applying coatings to structural steelwork in construction involve organic coatings, primarily through manual application or spraying. Additionally, metallic coatings are applied using techniques such as hot-dipping, electroplating, thermal spraying, and diffusion. Both types of coatings contain hazardous components, including poly(vinylchloride) copolymer, chlorinated rubber, zinc silicate, alkyd, epoxy, polyurethane, zinc-iron alloys, silicon, and phosphorous (Price *et al.*, 2017).

In offshore environments, structures are subjected to prolonged exposure to high humidity, elevated salinity levels, intense UV radiation, wave action, and bird droppings. Research indicates that bird droppings can degrade coating systems through chemical processes (Rafiei *et al*., 2016; Ramezanzadeh *et al*., 2011; Ramezanzadeh *et al*., 2009). Ramezanza-deh *et al.* (2009) found that biological materials, such as bird droppings, can chemically impact coating performance through hydrolytic reactions catalyzed by enzymatic structures (Ramezanzadeh *et al*., 2009). The corrosion rate of steel towers on wind platforms varies depending on factors such as oxygen and humidity levels, water depth around the structure, salt concentration, mechanical stresses (e.g., ice drifts or floating debris), current velocities, biological factors, temperature fluctuations, irregular inspection schedules, maintenance and repair expenses, and the intended design lifespan. All these factors should be considered when selecting a corrosion protection system (Price *et al*., 2017).

Recent developments include high-solid coats, with a solids volume ranging from 70% to 100%, providing an alternative for offshore WTs applications (Momber *et al*., 2018).

The exposure to the rigorous marine environment poses a significant challenge for the construction and longevity of offshore structures, predominantly composed of steel. Offshore WTs, offshore substation platforms, and converter platforms are engineered with a minimum operational lifespan of 25 years. The chemical characteristics of the immersion medium, be it seawater or brackish water, exert a pronounced influence on the corrosion mechanisms of metals. Seawater, with its heightened salinity, is notably corrosive in comparison to freshwater. Corrosion rates escalate with the increasing salinity of seawater, while additional factors such as oxygen concentration, pH levels (seawater typically ranging from 7.8 to 8.3), and temperature also contribute to the modulation of corrosion processes (Adedipe *et al*., 2016; Sato, 2011).

In contrast to the previous studies and reviews addressing various ecological aspects and pressures on the marine environment, there exists limited knowledge concerning the chemical emissions originating from Offshore Wind Farms throughout their construction, operation, and decommissioning phases, along with their potential impacts on the environmental status of the sea and seafood quality. Potential chemical emissions from the offshore wind industry may arise from various sources, including increased maritime traffic and associated risks of accidental spills, the disturbance of seabed sediment due to subsea cable and foundation construction, discharges from wastewater treatment plants and cooling water from platforms, use of artificial scour protection materials, atmospheric emissions from diesel generators, and direct chemical releases and spills during accidents (e.g., platform fires and the use of firefighting foams, or unintentional spills of oil, lubricants, or coolants). Nevertheless, the risk of emissions or accidental release of these chemicals can be significantly mitigated through the implementation of constructive preventive measures, such as backup systems, secondary containment, closed-loop systems, and recovery tanks (Kirchgeorg *et al*., 2018).

Due to the emissions generated, it is essential to handle paints and coatings with care. Adhering to all health and safety guidelines provided by the manufacturer during work procedures is crucial to mitigate potential health hazards. Prolonged contact with epoxies may lead to dermatitis, while hardeners found in polyurethane (PU) coatings can impact the respiratory system. Furthermore, many solvents are flammable and pose risks to human skin. When mixing paints and coatings, protective measures should be taken to minimize the inhalation of paint particles and solvents (Price *et al*., 2017). The painting and coating processes, commonly conducted to mitigate corrosion, particularly on steel components, including composite or ceramic parts within the turbine structure, encompass a range of substances such as chlorinated rubber, acrylic, polyvinyl chloride, epoxy, ethyl silicate, polyurethane, polyamines, polyamides, polyisocyanates, zinc silicate, alkyd, zinc-iron alloys, silicon, and phosphorous. Following degradation under offshore turbine conditions (pH, temperature, salinity, etc.) and exposure to

UV radiation, the emissions resulting from these components will initially integrate into the marine ecosystem and eventually permeate throughout the entire ecosystem over the medium to long term.

2.2. Plastics and derivatives

Across the globe, people extensively utilize plastics, which are organic synthetic polymers, due to their distinctive characteristics such as a high strength-to-weight ratio, bio-inertia, and affordability. The global production of plastic is reported to exceed 300 million tons annually (Plastics Europe), with an estimated 10% of this amount entering the ocean (Thompson, 2007). Studies suggest that 4.8–12.7 million tons of plastic debris find their way into the marine environment each year, and this figure is projected to increase significantly by 2025 (Jambeck *et al*., 2015). Plastic, known for its persistent nature lasting hundreds to thousands of years (Collignon *et al*., 2012), poses a potential threat to marine environments and ecosystems. Environmental debris of this nature can be categorized by size into macroplastics, mega plastics, and microplastics (Barnes *et al*., 2009). Microplastics typically refer to plastic fragments smaller than 5 mm, including those at millimeter and micron levels.

Microplastic sources can be categorized into primary and secondary types. Primary microplastics directly enter the oceans in micro-sized forms, encompassing synthetic fibers, cosmetics, medicine, and raw materials used in plastic production (Ashton *et al*., 2010; Browne *et al*., 2011; Fendall *et al*., 2009; Lechner *et al*., 2015). Secondary microplastics primarily result from the degradation of larger plastic items through mechanical action, biodegradation, photodegradation, photooxidative degradation, and other processes (Rochman *et al*., 2013; Zbyszewski *et al*., 2014).

A standard wind turbine consists of a concrete foundation, a tower constructed from steel and/or concrete, a nacelle comprising steel and copper components, and typically three blades (Vestas 2006; Tremeac *et al*., 2009; Guezuraga *et al*., 2012). Wind turbine blades typically consist of either carbon fiber or glass fiber composite material, leveraging the combined properties of these materials to create lighter, longer blades with optimized aerodynamic shapes, thus enhancing blade performance while maintaining a lightweight profile (Lijin *et al*., 2018). The majority of blades are composed of a combination of fibers and polymers, constituting 60–70 wt% reinforcing fibers and 30–40 wt% polymer matrix (Liu *et al*., 2017; Albers 2009; Stewart 2012). For instance, one study estimates that in 2008, 260,000 tonnes of material were used for wind turbine blade production, increasing to 1.18 million tonnes by 2017 (Red 2006). and 43.4 million tonnes by 2050 (Liu *et al*., 2017). As of now, much of the waste generated from wind turbine blades, predominantly composed of carbon fiber and glass fiber materials, ends up in landfills due to the complexities associated with their recycling (Peter *et al*., 2022). Both the currently actively used wind turbine blades and the obsolete ones stored in landfills are directly involved in the life cycle by mixing with groundwater through primary or secondary pathways, depending on their size.

Due to their small size, microplastics can be ingested and transferred into the intestinal system, stomach, hepatopancreas, and other tissues of marine biota (Browne *et al*., 2010; Moos *et al*., 2012). Microplastic particles also absorb various persistent organic pollutants (POPs) and heavy metals (Bejgarn *et al*., 2015; Goldstein *et al*., 2012; Kaposi *et al*., 2016). These microplastics, along with their associated pollutants, pose toxicity to certain marine life, impacting growth, feeding, spawning, and other physiological activities of organisms (Bejgarn *et al*., 2015; Goldstein *et al*., 2012; Kaposi *et al*., 2016). Moreover, the potential hazards of microplastics extend to humans through the consumption of marine and terrestrial food products, as well as drinking water (Brennecke *et al*., 2015; Vethaak *et al*., 2016). Therefore, the investigation of microplastic pollution in the environment is a pressing concern.

Microplastics find their way into the marine environment through various pathways, including sewage river flow, discharge, currents, and wind (Auta *et al*., 2017; Ryan *et al*., 2009). They have been discovered in marine surface waters and sediments globally, especially in coastal and estuarine regions associated with human activities (Cole *et al*., 2013; Fossi *et al*., 2012; Lusher *et al*., 2013; Moos *et al*., 2012). Coastal areas face an elevated risk of microplastic contamination due to their proximity to microplastic sources, and the abundance of microplastics in coastal sediments surpasses that in the deep sea (Imhof *et al*., 2013). Additionally, coastal zones are rich in biological resources and serve as crucial ecosystems. The rise in human activities has heightened the threat of microplastic pollution in these coastal zones (Mathalon *et al*., 2014).

3. RESULTS AND DISCUSSIONS

The development of deepwater, floating offshore WTs offers advantages such as reduced impacts on human activities and marine ecosystems, leveraging existing infrastructure from the offshore oil and gas industry, and accessing larger and more consistent offshore wind speeds (Musial *et al*., 2010; James *et al*., 2015; Wang *et al*. 2019a, 2019b). However, the technology supporting deepwater, floating offshore WTs is still in its early stages, with few prototype turbines and mooring systems currently deployed. As a result, the potential environmental effects of these technologies remain speculative.

To date, there is no comprehensive scientific study on the potential environmental impacts of deepwater, floating offshore WTs.

This study aims to focus on examining the chemical emissions, such as corrosion products and types of plastics originating from offshore wind farms, for the first time in the literature. The objective is to investigate their impacts on the marine ecosystem and, consequently, on humans and the environment from a chemical perspective. This information can be valuable for evaluating and permitting processes for deepwater, floating offshore WT development sites and guiding coating products for operational facilities. While a comprehensive applicable study and testing of these effects are currently challenging due to the limited number of deepwater, floating offshore WTs in operation, plausible effects and their potential magnitudes can be estimated and reviewed by combining the scientific literature on analogous situations.

Boehlert and Gill (2010) conducted a synthesis focusing on the environmental and ecological impacts of ocean renewable energy development, identifying six key stressors: energy removal effects, electromagnetic field (EMF) effects, physical presence of devices, dynamic effects of devices, acoustic effects, and chemical effects. On the other hand, in a comprehensive report on the environmental effects of Marine Renewable Energy (MRE), Copping *et al*. (2016) delved into these stressors, examining associated risks and impacts. These included alterations in physical systems due to energy removal and changes in flow, EMF effects on marine animals stemming from cables, modifications in benthic habitat and reef fish communities due to energy devices, risks to animals from underwater sound, and the collision risk around turbines. In these two studies, by categorizing the direct or indirect impacts of chemical emissions on the marine ecosystem, we have transparently presented the facts and shed light on our compilation of such a review.

Offshore wind farms, harnessing clean technologies, hold the potential to enhance the supply of green energy. However, persistent challenges exist. Some research suggests potential risks to marine fisheries (Deveci *et al*., 2020), while others emphasize navigation hazards and possible drawbacks to tourism and marine ecology (Kulkarni *et al*., 2022). With the industry's expansion driven by its extensive supply chain, the environmental and economic impacts of offshore wind farms could escalate.

The intricate interplay between Offshore Wind Power (OWP), the marine economy, and the marine environment is crucial for the prudent advancement of future OWP projects, especially given the industry's rapid growth trajectory. A significant portion of existing literature revolves around OWP's environmental footprints, particularly its interactions with fisheries (Kulkarni *et al*., 2022). While economic analyses, though limited (Glasson *et al*., 2022), often concentrate on individual cases, emphasizing direct economic benefits. Notably, empirical studies evaluating OWP's influence on marine sectors like mining, salt production, and chemical production are conspicuously absent.

4. CONCLUSIONS

In conclusion, the development of offshore WTs represents a significant advancement in renewable energy production, offering numerous benefits such as reduced impacts on human activities and marine ecosystems, utilization of existing offshore infrastructure, and access to consistent offshore wind speeds. However, the technology supporting deepwater, floating offshore WT is still in its early stages, with limited deployment of prototype turbines and mooring systems. Consequently, the potential environmental impacts of these technologies remain speculative.

Despite the lack of comprehensive scientific studies on the environmental impacts of deepwater, floating offshore WTs, our study sheds light on the examination of chemical emissions, including corrosion products and types of plastics originating from offshore wind farms. Understanding these emissions' impacts on the marine ecosystem and human health is crucial for evaluating and permitting deepwater, floating offshore WT development sites and guiding coating product selection for operational facilities.

While challenges persist, such as potential risks to marine fisheries, navigation hazards, and impacts on tourism and marine ecology, the expansion of the offshore wind industry presents opportunities for enhancing green energy supply and reducing carbon emissions. However, a thorough understanding of the intricate interplay between offshore wind power, the marine economy, and the marine environment is essential for the prudent advancement of future offshore WT projects. Future research should aim to address gaps in knowledge regarding the environmental and economic impacts of offshore WTs on various marine sectors, facilitating informed decision-making and sustainable offshore wind energy development.

In summary, while offshore wind farms hold the potential to enhance the supply of green energy, the environmental and economic impacts must be carefully considered, especially in the context of the chemical effects on the marine ecosystem. As the industry expands, a holistic understanding of these factors will be essential for sustainable and responsible offshore wind power development.

ACKNOWLEDGEMENTS

We want to thank to Prof. Dr. Dilek TÜRKER for encouraging us and laid the first stone in writing this review.

AUTHORSHIP CONTRIBUTION STATEMENT

Gülşah Çelik GÜL: Conceptualization, Methodology, Validation, Formal Analysis, Resources, Writing - Original Draft, Writing-Review and Editing, Funding acquisition.
Metin GÜL: Resources, Writing - Original Draft, Writing-Review and Editing, Data Curation, Software, Visualization, Supervision, Project administration.

CONFLICT OF INTERESTS

The author(s) declare that for this article they have no actual, potential or perceived conflict of interests.

ETHICS COMMITTEE PERMISSION

No ethics committee permissions is required for this study.

FUNDING

No funding was received from institutions or agencies for the execution of this research.

ORCID IDs
Gülşah Çelik GÜL
https://orcid.org/0000-0001-7213-1657
Metin GÜL
https://orcid.org/0000-0001-6168-1768

5. REFERENCES

Adedipe, O., Brennan, F., Kolios, A. (2016). Review of corrosion fatigue in offshore structures: present status and challenges in the offshore wind sector. *Renewable and Sustainable Energy Reviews* 6: 141–154. doi:10.1016/j.rser.2016.02.017.

Albers, H. (2009). Recycling of wind turbine rotor blades - fact or fiction? *DEWI Mag.* 34:32–41.

Anderson, T.L, Frigaard, P, Rasmussen, M.R, Martinelli, L. (2011). Loads on Wind Turbine Access Platforms with Gratings, In: Smith, JM, Lynett, P (eds.) Proc. 32nd International Conference on Coastal Engineering. Coastal Engineering Research Council.

Ashton, K., Holmes, L., Turner, A. (2010). Association of metals with plastic production pellets in the marine environment. *Mar. Pollut. Bull.* 60 (11): 2050–2055. https://doi.org/10.1016/j.marpolbul.2010.07.014.

Auta, H.S., Emenike, C.U., Fauziah, S.H. (2017). Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions. *Environ. Int.* 102: 16. https://doi.org/10.1016/j.envint.2017.02.013.

Barnes, D.K., Galgani, F., Thompson, R.C., Barlaz, M. (2009). Accumulation and fragmentation of plastic debris in global environments. *Philos. Trans. R. Soc. Lond.* 364 (1526): 1985. doi:10.1098/rstb.2008.0205.

Bejgarn, S., Macleod, M., Bogdal, C., Breitholtz, M. (2015). Toxicity of leachate from weathering plastics: an exploratory screening study with Nitocra Spinipes. *Chemosphere* 132: 114–119. https://doi.org/10.1016/j.chemosphere.2015.03.010.

Boehlert, G.W., Gill, A.B. (2015). Environmental and ecological effects of ocean renewable energy development: a current synthesis. *Oceanography* 23 (2): 68–81. https://doi.org/10.5670/oceanog.2010.46.

Brennecke, D., Ferreira, E.C., Costa, T.M.M., Appel, D., Gama, B.A.P.D., Lenz, M. (2015). Ingested microplastics (> 100 µm) are translocated to organs of the tropical fiddler crab Uca rapax. *Marine Pollution Bulletin* 96(1–2): 491–495. doi:10.1016/j.marpolbul.2015.05.001.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R. (2011). Accumulation of microplastic on shorelines worldwide: sources and sinks. *Environ. Sci. Technol.* 45(21): 9175–9179. https://doi.org/10.1021/es201811s.

Browne, M.A., Galloway, T.S., Thompson, R.C. (2010). Spatial patterns of plastic debris along estuarine shorelines. *Environ. Sci. Technol.* 44(9): 3404. https://doi.org/10.1021/es903784e.

Burea of Ocean Energy Management (BOEM), Central California Call Area (2021). Accessed Date: 12.11.2023, https://l24.im/aHI is retrieved.

Çokyaşar E., Beji S. (2013). Açık Deniz Rüzgâr Çiftliklerinin Malî Açıdan İncelenmesi, *Gemi ve Deniz Teknolojisi Dergisi* 216: 1300-1973.

Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., Galloway, T.S. (2013). Microplastic ingestion by zooplankton. *Environ. Sci. Technol.* 47(12): 6646. doi:10.1021/es400663f.

Collignon, A., Hecq, J.H., Glagani, F., Voisin, P., Collard, F., Goffart, A. (2012). Neustonic microplastic and zooplankton in the north western Mediterranean Sea. *Marine Pollution Bulletin* 64 (4):861. doi:10.1016/j.marpolbul.2012.01.011.

Copping, A., Sather, N., Hanna, L., Whiting, J., Zydlewsk, G., Staines, G., Gill, A., Hutchison, I., O'Hagan, A.M., Simas, T., Bald, J., Sparling, C., Wood, J., Masden, E. (2016). *Annex IV 2016 state of the science report: environmental effects of marine renewable energy development around the world. OES-Environmental* 1–224.

Deveci, M., Ozcan, E., John, R., Covrig, C.F., Pamucar, D. (2020). A study on offshore wind farm siting criteria using a novel interval-valued fuzzy-rough based Delphi method. *J. Environ. Manage.* 270: 110916 https://doi.org/10.1016/j. jenvman.2020.110916.

European Agency for Safety and Health at Work (EU-OSHA), Occupational safety and health in the wind sector (2013). Accessed Date: 10.11.2023, https://l24.im/Eac is retrieved.

Fendall, L.S., Sewell, M.A. (2009). Contributing to marine pollution by washing your face: microplastics in facial cleansers. *Marine Pollution Bulletin* 58(8): 1225–1228. https://doi.org/10.1016/j.marpolbul.2009.04.025.

Fossi, M.C., Panti, C., Guerranti, C., Coppola, D., Giannetti, M., Marsili, L., Minutoli, R. (2012). Are baleen whales exposed to the threat of microplastics? A case study of the Mediterranean fin whale (Balaenoptera Physalus). *Mar. Pollut. Bull.* 64(11): 2374–2379. https://doi.org/10.1016/j.marpolbul.2012.08.013.

Global Offshore Wind Report (GWR) (2021). Accessed Date: 11.11.2023, https://l24.im/mlHgQ is retrieved.

Global Wind Energy Council (GWEC), Global Wind Report 2022 (2022). Accessed Date: 12.10.2023, https://gwec.net/global-wind-report-2022/ is retrieved.

Global Wind Energy Council (GWEC), Global Wind Statistics 2017 (2018). Accessed Date: 18.11.2023, https://l24.im/kI9c1du is retrieved.

GMKA, TR22 Bölgesi Deniz Üstü Rüzgar Santrali ve Limanı Ön Fizibilite Raporu (2023). Accessed Date: 11.12.2023.https://www.gmka.gov.tr/dokumanlar/yayinlar/TR22-Bolgesi-Deniz-Ustu-Ruzgar-Santrali-Limani-On-Fizibilite-Raporu.pdf is retrieved.

Goldstein, M.C., Rosenberg, M., Cheng, L. (2012). Increased Oceanic Microplastic Debris Enhances Oviposition in an Endemic Pelagic Insect. *Biol Lett* 8(5): 817–820. doi:10.1098/rsbl.2012.0298.

Guezuraga B., Zauner, R., Pol, W. (2012). Life cycle assessment of two different 2 MW class wind turbines. *Renew Energy* 37(1):37–44. https://doi.org/10.1016/j.renene.2011.05.008.

Graabak, I., Korpås, M. (2016). Variability characteristics of European wind and solar power resources-a review. *Energies* 9 (6): 449. doi.org/10.3390/en9060449.

Hilbert, L.R, Black, A.R, Andersen, F., Mathiesen, T. (2011). Inspection and Monitoring of Corrosion Inside Monopile Foundations for Offshore Wind Turbines, Eurocorr 2011: European Corrosion Congress, Paper No. 4730, Stockholm, Sweden, 4–8.

IEA, World Energy Outlook 2023 (2023). Accessed Date: 16.12.2023 IEA, Paris https://www.iea.org/reports/world-energy-outlook-2023, Licence: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A) is retrieved.

Imhof, H.K., Ivleva, N.P., Schmid, J., Niessner, R., Laforsch, Christian, L. (2013). Contamination of beach sediments of a subalpine lake with microplastic particles. *Curr. Biol.* 23(19): R867. https://doi.org/10.1016/j.cub.2013.09.001.

International Renewable Energy Agency (IRENA), Renewable energy and jobs-Annual Review 2016 (2016). Accessed Date: 11.11.2023, https://l24.im/D1nl is retrieved.

ISO 12944-5-(2007). Paints and Varnishes—Corrosion Protection of Steel Structures by Protective Paint Systems—Part 5: Protective Paint Systems. *International Standard Organization*.

ISO 20340-(2009). Paints and Varnishes—Performance Requirements for Protective Paint Systems for Offshore and Related Structures. *International Standard Organization*.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L. (2015). Marine pollution. Plastic waste inputs from land into the ocean. *Science* 347(6223): 768. doi:10.1126/science.126035.

James, R., Costa Ros, M. (2015). Floating Offshore Wind: Market and Technology Review. *The Carbon Trust, United Kingdom* 168.

Kaposi, K.L., Mos, B., Kelaher, B.P., Dworjanyn, S.A. (2016). Ingestion of microplastic has limited impact on a marine larva. *Environ. Sci. Technol.* 48(3): 1638–1645. https://doi.org/10.1021/es404295e.

Karteek B., Ramyakrishna P., Ravi A., Rajender B., Sashivinay K.G. (2021). The role of anticorrosive polymer coatings for the protection of metallic surface. *Corros Rev* 2021.

Kirchgeorg, T., Weinberg, I., Hörnig, M., Baier, R., Schmid, M.J., Brockmeyer, B. (2018). Emissions from corrosion protection systems of offshore wind farms: Evaluation of the potential impact on the marine environment. *Marine Pollution Bulletin* 136:257–26. https://doi.org/10.1016/j.marpolbul.2018.08.058.

Kulkarni, S.S., Edwards, D.J. (2022). A bibliometric review on the implications of renewable offshore marine energy development on marine species. *Aquac. Fish.* 7: 211–222. https://doi.org/10.1016/j.aaf.2021.10.005.

Lechner, A., Ramler, D. (2015). The discharge of certain amounts of industrial microplastic from a production plant into the river Danube is permitted by the Austrian legislation. *Environ. Pollut.* 200: 159–160. https://doi.org/10.1016/j.envpol.2015.02.019.

Leybourne, M. (2022). Offshore Wind Technical Assistance for Türkiye. *Marentech Expo*, İzmir.

Life Vestas (2006). Cycle assessment of offshore and on shore sited wind power plants based on vestas V90-3.0 MW turbines. Accessed Date: 10.12.2023 https://www.vestas.com/~/media/vestas/about/sustainability/pdfs/lca_v90_june_2006.ashx is retrieved.

Lijin, T., Ramachandra, M. (2018). Advanced materials for wind turbine blade- A Review. *Mater Today Proc* 5:2635–40. https://doi.org/10.1016/j.matpr.2018.01.043.

Liu, P., Barlow, C.Y. (2017). Wind turbine blade waste in 2050. *Waste Manag*. 62: 229–40.

Lusher, A.L., Mchugh, M., Thompson, R.C. (2013). Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. *Marine Pollution Bulletin* 67(1–2): 94. https://doi.org/10.1016/j.marpolbul.2012.11.028.

Majewski, P., Florin, N., Jit, J., Rodney, A. (2022). Stewart.End-of-life policy considerations for wind turbine blades, *Renewable and Sustainable Energy Reviews.* 164:112538. https://doi.org/10.1016/j.rser.2022.112538.

Mathalon, A., Hill, P. (2014). Microplastic fibers in the intertidal ecosystem surrounding Halifax Harbor, Nova Scotia. *Mar. Pollut. Bull.* 81(1): 69–79. https://doi.org/10.1016/j.marpolbul.2014.02.018.

Momber, A.W., Marquardt, T. (2018). Protective coatings for offshore wind energy devices (OWEAs): a review. *J. Coat. Technol. Res.* 15 (1) 13–40. doi 10.1007/s11998-017-9979-5.

Moos, N.V., Burkhardtholm, P., Köhler, A. (2012). Uptake and effects of microplastics on cells and tissue of the blue mussel Mytilus Edulis L. after an experimental exposure. *Environ. Sci. Technol.* 46(20): 11327–11335. https://doi.org/10.1021/es302332w.

Musial, W., Ram, B. (2010). Large-Scale Offshore Wind Power in the United: Assessment of Opportunities and Barriers. *NREL* TP-500-40745. doi: 10.2172/990101.

NACE SP0108-(2008). ''Corrosion Control of Offshore Structures by Protective Coatings.'' Standard Practice SP0108-2008, *NACE*, Houston, TX.

Norsok M-501-(2012). ''Surface Preparation and Protective Coating. Norsok Standard M-501, Rev. 6, *Standards Norway*, Lysaker, Norway.

Price, S.J., Figueira, R.B. (2017). Corrosion Protection Systems and Fatigue Corrosionin Offshore Wind Structures: Current Status and Future Perspectives. *Coatings* 2017, 7(2): 25.

Rafiei, R., Mohseni, M., Yari, H., Mahdavi, M. (2016). Evaluation of degradability of two polyurethane refinish coatings against biological materials: A case study. *Prog. Org. Coat.* 93: 1–10.

Ramezanzadeh, B., Mohseni, M., Yari, H. (2011). On the electrochemical and structural behaviour of biologically degraded automotive coatings; Part 1: Effect of natural and simulated bird droppings. *Prog. Org. Coat.* 71: 19–31. https://doi.org/10.1016/j.porgcoat.2010.12.003.

Ramezanzadeh, B., Mohseni, M., Yari, H., Sabbaghian, S. (2009). An evaluation of an automotive clear coatperformance exposed to bird droppings under different testing approaches. *Prog. Org. Coat.* 66:149–160. https://doi.org/10.1016/j.porgcoat.2009.06.010.

Red, C. (2006). Wind turbine blades: big and getting bigger. Co posite Technology; 2006. Accessed Date: 17.12.2023, http://www.compositesworld.com/articles /wind-turbine-bladesbig-and-getting-bigger.

Rochman, C.M., Browne, M.A., Halpern, B.S., Hentschel, B.T., Hoh, E., Karapanagioti, H.K., Rios-Mendoza, L.M., Takada, H., Teh, S., Thompson, R.C. (2013). Policy: classify plastic waste as hazardous. *Nature* 494 (7436): 169–171. doi: 10.1038/494169a.

Ryan, P.G., Moore, C.J., Franeker, J.A.V., Moloney, C.L. (2009). Monitoring the abundance of plastic debris in the marine environment. *Philos. Trans. R. Soc. B* 364(1526): 1999–2012. doi:10.1098/rstb.2008.0207.

Sato, N. (2011). Basics of corrosion chemistry. In: Green Corrosion Chemistry and Engineering. *Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany* 1–32. https://doi.org/10.1002/9783527641789.ch1.

Schaumann, P., Lochte-Holtgreven, S., Steppler, S. (2011). Special Fatigue Aspects in Support Structures of Offshore Wind Turbines. *Materwiss. Werkstofftechn* 42 1075–1081. doi:10.1002/mawe.201100913.

Soerensen, P.A., Kiil, S., Dam-Johansen, K., Weinell, C.E. (2009). Anticorrosive Coatings: A Review. *Journal of Coatings Technology and Research* 6(2):135–176. doi:10.1007/s11998-008-9144-2.

Stewart, R. (2012). Wind turbine blade production - new products keep pace as scale increases. *Reinforc Plast.* 56(1):18–25. https://doi.org/10.1016/S0034-3617(12)70033-4.

TEİAŞ, Kurulu Güç Raporları (2022). Accessed Date: 17.12.2023, https://www.teias.gov.tr/kurulu-guc-raporlari is retrieved.

TEKMAR (2023). Accessed Date: 14.12.2023, https://deepwaterbuoyancy.com/comparing-fixed-and-floating-offshore-wind-turbines/ is retrieved.

The European Wind Energy Association (EWEA) (2019). Accessed Date: 10.11.2023, https://l24.im/iouvr is retrieved.

Thompson, R.C. (2007). Plastic debris in the marine environment: consequences and solutions. *In: Marine Nature Conservation in Europe.*

Tremeac B, Meunier F. (2009). Life cycle analysis of 4.5 MW and 250 W wind turbines. *Renew Sustain Energy Rev.* 13(8):2104–10.

Vethaak, A.D., Leslie, H.A. (2016). Plastic debris is a human health issue. *Environ. Sci. Technol.* 50(13): 6825. https://doi.org/10.1021/acs.est.6b02569.

Wang, Y., Walter, R.K., White, C., Farr, H.K., Ruttenberg, B.I. (2019a). Assessment of surface wind datasets for estimating offshore wind energy along the Central California Coast. Renew. *Energy* 133: 343–353. https://doi.org/10.1016/j.renene.2018.10.008.

Wang, Y.H., Walter, R.K., White, C., Kehrli, M.D., Hamilton, S.F., Soper, P.H., Ruttenberg, B.I. (2019b). Spatial and temporal variation of offshore wind power and its value along the Central California Coast. *Environmental Research Communications* 1: 121001. https://doi.org/10.1088/2515-7620/ab4ee1.

Zbyszewski, M., Corcoran, P.L., Hockin, A. (2014). Comparison of the distribution and degradation of plastic debris along shorelines of the Great Lakes, North America. *J. Great Lakes Res.* 40(2): 288–299. https://doi.org/10.1016/j.jglr.2014.02.012.

Zou, C., Zhao, Q., Zhang, G., Xiong, B. (2016). Energy revolution: From a fossil energy era to a new energy era. *Natural Gas Industry B.* 3(1): 1-11. https://doi.org/10.1016/j.ngib.2016.02.001.