energies

MDPI

Article

Microplastics Emission from Eroding Wind Turbine Blades: Preliminary Estimations of Volume

Leon Mishnaevsky, Jr. *, Antonios Tempelis, Yauheni Belahurau and Nicolai Frost-Jensen Johansen

Department of Wind and Energy Systems, Technical University of Denmark, 4000 Roskilde, Denmark; atem@dtu.dk (A.T.); yaube@dtu.dk (Y.B.); nijoh@dtu.dk (N.F.-J.J.)
* Correspondence: lemi@dtu.dk

Abstract: The erosion of wind turbine blades is one of the most frequently observed mechanisms of wind turbine blade damage. In recent months and years, concerns about high volumes of eroded plastics and associated pollution risks have surfaced on social networks and in newspapers. In this scientific paper, we estimate the mass of plastic removed from blade surface erosion, using both a phenomenological model of blade erosion and the observed frequency of necessary repairs of blades. Our findings indicate that the mass of eroded plastic ranges from 30 to 540 g per year per blade. The mass loss is higher for wind turbines offshore (80–1000 g/year per blade) compared to onshore (8–50 g/year per blade). The estimations are compared with scientific literature data and other gray literature sources. Using the entire Danish wind farms portfolio, we quantify the yearly mass of plastic from blade erosion to be about 1.6 tons per year, which is an order of magnitude less than that from footwear and road marking and three orders of magnitude less than that from tires. While the contribution of wind blade erosion is small compared to other sources, the results of this work underline the importance of the (A) effective leading-edge protection of wind turbines, (B) regular and efficient maintenance, and (C) the optimal selection of materials used.

Keywords: wind energy; wind turbines; microplastics; surface erosion; leading edge erosion

check for updates

Citation: Mishnaevsky, L., Jr.; Tempelis, A.; Belahurau, Y.; Johansen, N.F.-J. Microplastics Emission from Eroding Wind Turbine Blades: Preliminary Estimations of Volume. *Energies* **2024**, *17*, 6260. https://doi.org/10.3390/en17246260

Academic Editor: Davide Astolfi

Received: 13 November 2024
Revised: 27 November 2024
Accepted: 2 December 2024
Published: 11 December 2024

1. Introduction

Wind energy is a green, secure way of energy production, but it is a young industry. The first offshore wind park was installed in 1991 (as compared to the first cars, in the 1880s, and the first airplane, in 1903). Therefore, not all the elements of the technology were “born sustainable”. This apparent fact becomes, however, hot news, when this or that element of the technology requires additional upgrade. The side effects of the sustainability transition are widely reported, become viral on social networks, and influence public opinion, with negative views toward renewable energy expansion. A famous example is the initial difficulties of recycling composite wind turbine blades [1]. While a lot of efficient blade recycling technologies now exist [2], corresponding regulations are also introduced to ensure the environmentally friendly end of life management of blades [3]; the story about the problem with the recyclability of wind blades has attracted the attention of the wider public. Another topic is the possibility of plastic particle detachment due to the erosion of wind turbine blades [4,5].

Surfaces of wind turbine blades are subject to erosion due to rain and hail impacts [6–8]. This problem has attracted the industry’s attention, and many projects have been initiated (e.g., [9]). In [6,7], some recent investigations on the mechanisms, modeling, and impact of the leading-edge erosion of wind turbine blades are discussed. Solutions for the mitigation of blade erosion are summarized in [7], including thermoplastic and hybrid thermoplastic coatings, highly viscoelastic coatings, structured interfaces to enhance the coating attachments, electroforming metallic leading-edge erosion shields, and structured nanoreinforced coatings. One of the side effects of blade erosion is that particles, detached from the blade surface due to erosion, might fall into the water (for the case of offshore wind turbines). The surface erosion of wind turbine blades has high maintenance costs and worsened aerodynamic properties [6,10], but it can also lead to small plastic particles detaching from the blade surface and falling down. The drastic expansion of offshore wind energy requires a detailed analysis of all the possible environmental effects.

In a new project called PREMISE "Preventing MIcroplastics pollution in SEa water from offshore wind" [11], supported by Velux Fonden, the process of the surface erosion of wind turbine blades is investigated with a view to the possibilities of plastic particle emission.

In this paper, a preliminary evaluation of the volume of eroded plastic is presented and compared with some literature data. The contribution of plastic particles from eroded wind blades is also compared to the overall plastic emissions in seas.

2. Data Extrapolation Challenges in Estimation of the Mass Loss

Many public and social network posts about the risks of microplastic pollution from wind blade erosion refer to the report by Solberg and colleagues [5], which was put online in 2021, without any peer review or validation. In this section, the logic and reasoning in this report are analyzed in order to evaluate the correctness of this report and provide correct estimations of microplastic emission.

In the report by Solberg and colleagues [5], a series of experiments carried out at the University of Strathclyde [12] are used as a starting point of their analysis. The observations are extrapolated for wind turbine parks, and from that, conclusions about a large volume of eroded plastics of wind energy are drawn.

Extrapolation of results from [12] to real wind turbine parks. In the publication in [12], epoxy/glass composite samples were subject to rain erosion tests and showed some loss of weight. While these results of the University of Strathclyde team were interesting from a scientific viewpoint, the experiments in no way reflect a realistic situation. Epoxy/glass composites are materials used for the structural parts of wind turbine blades. Before they are used, the composites are always covered by soft, damping coatings (typically polyurethane-based) and are never exploited as pure epoxy/glass structures. The reason is that epoxy is relatively brittle material, which can indeed show quick surface degradation and damage under high impact loading, which is why such epoxy glass composites are covered by soft coatings. The transfer of observations from pure epoxy composites to polyurethane-covered composites is in principle wrong.

Extrapolation of mass loss results from [12] on larger wind turbine blades. In the paper by Pugh and Stack [12], the authors carried out experiments on the surface degradation of epoxy glass composites under rain loading conditions. The degree of erosion was characterized by "mass loss". This means that a sample was weighted before and after the tests, and the difference was calculated. It was a relatively reasonable way of estimating surface degradation for the authors. However, such estimation cannot be extrapolated in a way of how the authors of [5] do it. Figure 1 illustrates the schema. In other words, if a sample 10 × 10 × 10 mm is subject to surface degradation (rain erosion, corrosion, or grinding) and loses 3 mm of upper layer, its mass loss is 30%. However, if a sample of 10 m × 10 m × 10 m is subject to the same surface load and loses 3 mm from the upper layer due to surface degradation (the rain is not going to become 1000 times stronger only because the sample became 1000 times bigger), its mass loss is in no way 30% but rather 0.003%. A simple transfer of the 30% rule to a larger sample (like "if a 3 year old boy grew up from 1 m to 110 cm, 10% in one year, then he will reach 10,000 m at the age of 50") is plainly wrong.

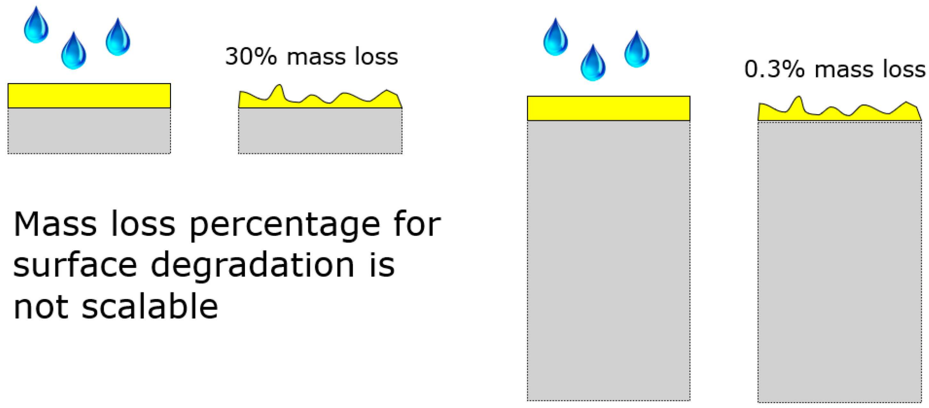


Figure 1. Why weight loss percentage cannot be extrapolated for surface degradation.

Different polymers are used in different parts of wind turbine blades. The report [5] starts with a statement about the dangers of bisphenol A (which, according to the authors, lands in the sea due to erosion). Bisphenol A is an organic synthetic compound used in formulating epoxy resin. As said, the leading-edge erosion of wind turbine blades means the degradation of protective coatings, which are polyurethane-based. Unless the degradation reaches extreme stage, and all the protective coating is worn out, the erosion does not involve the degradation of epoxy. No bisphenol A is used when producing polyurethane coatings according to all the coating manufacturers. A case when erosion continues for so long that the damage reaches even laminate is indeed possible theoretically, but this would be an extreme case, when proper maintenance of the blade is neglected. Since the surface erosion of a blade leads to a reduction in aerodynamic efficiency, reduction in energy generation, and an increase in the risk of full blade failure, this situation, when a wind park owner neglects such growing erosion and just waits until the blade fails (for which they would expect a bill of several hundred thousands of dollars for a replacement), is a rare and extreme case.

Formula for lifetime is transferred to mass loss. In the classical Springer model, the linkage between the lifetime (number of rain droplet impacts until failure) and blade velocity is described by a power function with a power coefficient of 5.7 [13,14]. Springer observed that time to first failure relates to the impact pressure as $N_I^*(P) = C * \left(\frac{S}{P}\right)^{-5.7}$, where P is the water hammer pressure, S is a material strength parameter, and C is an arbitrary constant. In most cases, we can assume that S is constant and then obtain $N_i^*(P) = C * \left(\frac{1}{P}\right)^{-5.7} = C * P^{5.7}$. Since the water hammer pressure is a linear function of velocity, Springer's model can be rewritten as $N_i^*(v) = C * v^{5.7}$. This now relates to how the number of impacts to failure follows the velocity. The authors in [5] transfer this power function of 5.7 to the volume loss of the blade due to erosion. The justification of using this exponent value is that "One report stated a potency of 5.7 for pressure change, but 5.7 is used often". Apparently, the amount of impacts until failure is in no way directly proportional to the volume of eroded material. The formula for the number of impacts until failure (i.e., fatigue strength of given material) versus velocity cannot be transferred to the volume of spalled material (one can easily imagine a situation, when a plastic sample reaches fatigue limit, without losing even a single unit of material). The temporal characteristic of the damage process (number of impacts until failure) is not connected and does not correlate with the volume of removed material. For surface degradation, the damage is localized in a small surface layer [8,15]. Even if the material is brittle, or has a low fatigue lifetime, the damaged zone will not expand into a large volume. Such an easy calculation (assuming that lifetime is inversely proportional to the volume of removed material) is plainly wrong. The correct way to calculate the volume of removed material, taking into account its properties, is presented in [15], for instance.

Confusion with power degrees: Adding kinetic energy on top of kinetic energy. According to [5], this formula (with power degree 11) is a combination of Springer's model for homogeneous materials (amount of hits to failure versus velocity) and kinetic energy correction (additional power 2). In the Springer model, however, kinetic energy is already accounted for, in the 5.7 exponent. Thus, even when assuming that all the elements are correct (while they are not), the power coefficient should not be multiplied additionally by 2.

To summarize, one should state that when extrapolating experimental observations from laboratory tests to field situations, it is important to check the comparability of the data (is the material tested the same which is used?), the transferability of the observations, and also the correctness of the mathematical transformations.

3. Qualitative Estimations of Volume of Eroded Plastics

In this section, two methods of the estimation of plastic splitting from the wind turbine blade surface due to erosion are presented; one method is based on the impact modeling and the other is based on the repair statistics. The results are compared with the literature data.

3.1. Estimation via Liquid Impact Mechanics and Probabilistic Model of Erosion

The roughening of and plastic material removal from the surface take place as follows [6,8]. A rain droplet hitting a wind turbine surface causes a local stress increase, the formation of stress waves, and the deformation of polymers. Rain droplets, hail, and sand hit wind turbine surfaces day after day, year after year. This repeated surface deformation leads to fatigue damage, microcracking, and the splitting of small polymer parts. Wind turbine blades are coated by polymer layers which protect their load bearing parts, but they still degrade due to rain and hail erosion.

An exact finite element-based model of the roughening of wind turbine blade surfaces is given in [8,15]. However, this model is relatively complex and requires many input data. In order to give a quick estimation of the eroded volume, Tempelis and colleagues presented a probabilistic, phenomenological model of the erosion of wind turbine blades [15]. This model is used here to estimate the volume of the removed material.

In the model [15], a simplified geometry of the blade's surface is discretized as a number of material elements. Surface erosion by multiple droplet impacts is modeled through the removal of these material elements. The impact positions of the droplets were generated as random values based on a uniform random distribution, and a probability of failure is used to determine failure and material removal. For each impact, the probability of failure p_{fail} is calculated as a Weibull probability function:

$$p_{fail} = 1 - e^{-\left(\frac{t}{t_c}\right)^k} \quad (1)$$

where t is the time under rain, t_c is the characteristic life of the coating material for the current rain conditions, and t_c can be calculated from the rain erosion data (V-N curve) or analytically. Parameter k determines the shape of the volume loss curve. The methods of the evaluation of these parameters were given in a previous paper by the authors [8,15]. The parameters are determined using the data from rain erosion testing (RET) experiments by fitting them into the RET data.

The mean size of the removed fragments must also be defined as a parameter or estimated from the measurements and literature data. The position where failure occurs is chosen randomly based on the impact location. It is assumed that an impacting droplet that causes failure affects an area with a radius equal to the droplet radius. If an impact occurs near a damaged area, the failure position is chosen randomly but in a way that increases the size of the damaged area. This is to resemble the failure observations from RET. When failure occurs, the heights of the affected material points are reduced by the removed fragment size. Figure 2 shows the schema of how the height of a given point is reduced as a result of droplet impact and the resulting damage. The model parameters were calibrated by RET (rain erosion tester) datasets of viscoelastic polyurethane coatings.

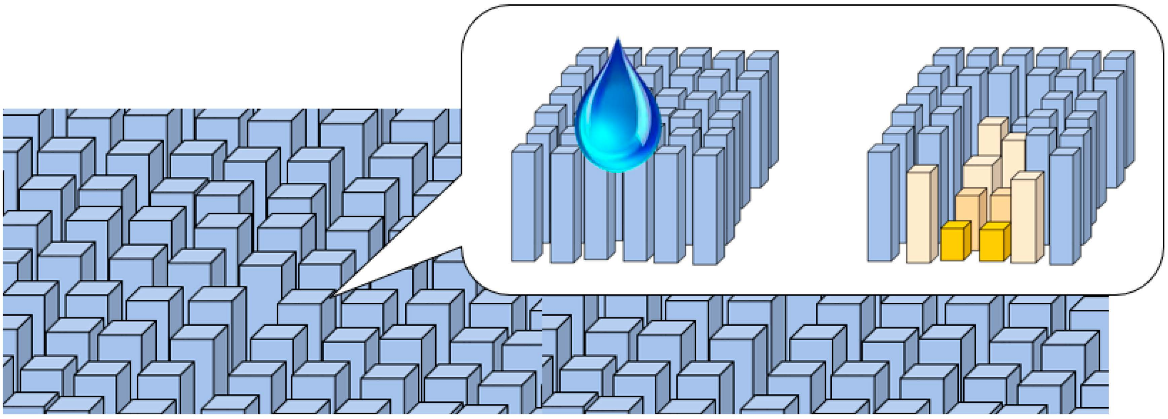


Figure 2. Schema of the discretized model of surface roughening due to droplet impact used in [15].

Figure 3 shows the calculated roughness evolution of the blade surface. The results of this simulation are shown in Figure 4, with coating volume loss increasing with time. Assuming an average tip speed of 90 m/s, 1000 mm of rain annually, and a mean rain intensity of 1 mm/h, one can obtain 15 mm^3/cm^2 volume loss per year.

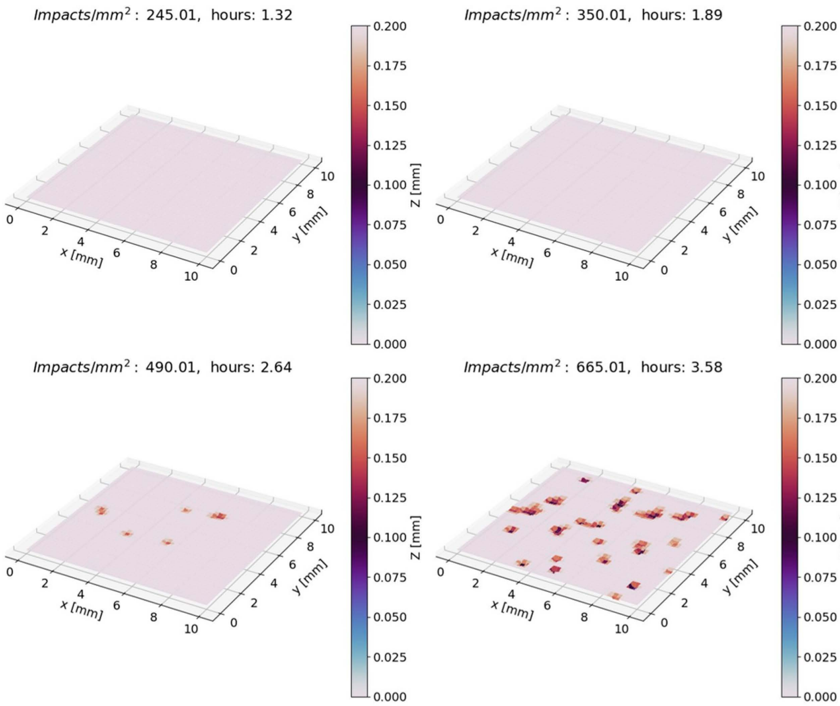


Figure 3. Predicted evolution of surface damage by using 3D surface roughness plots of the coating's surface. Reprinted from [15].

For the area 10 m × 50 mm (full leading-edge surface), this leads to 75 cm^3. This value is comparable and in the range of the values given in Section 3.2. So, it gives 75 g per blade per year. Apparently, by using a more detailed modeling of wind velocity and rain intensity, this model can be made very exact.

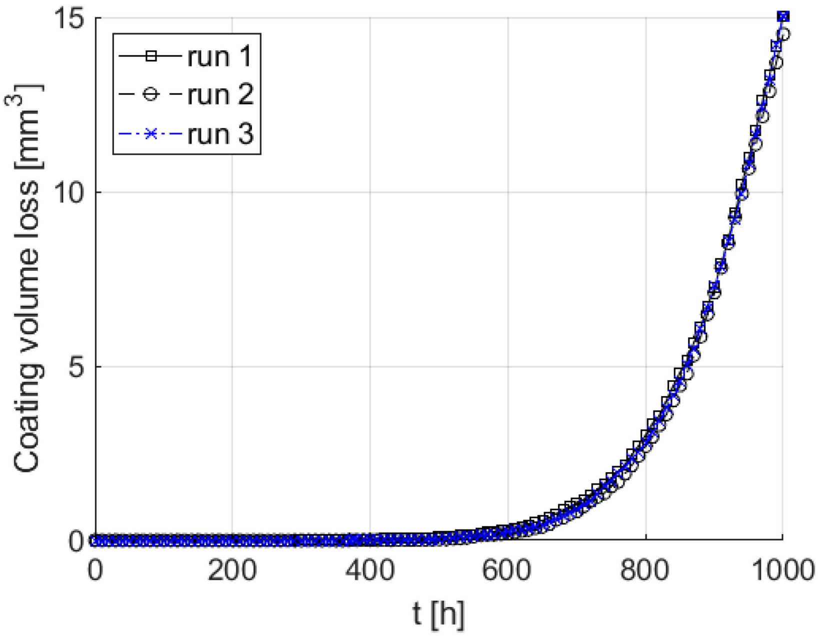


Figure 4. Estimated volume loss per area as a function of time under rain for a tip speed of 90 m/s and a mean rain intensity of 1 mm/h. Reprinted from [15].

The model is further validated by comparing it with the erosion depth measurements from the RET data. The RET data are available from the project DURALEDGE [9] and contain measurements for the end of incubation and breakthrough times from three samples tested in an R & D-style test machine. Four polyurethane-based coatings were tested, which are named 269-1, 269-3, 269-4, and 269-5. For the tests, the maximum tip speed was around 125 m/s, and the mean droplet size was 2.4 mm with a flow rate of 65 L/h. The predictions of the model for the maximum depth of erosion are performed by using the calibrated parameters from [15], and the required input is the number of impacts per mm^2 or the total rain impingement from the V-N or V-H curve of each coating. Since the end of incubation and breakthrough measurements are extracted from an area of the samples with approximately a tip speed of 120 m/s, the number of impacts per mm^2 or the total rain impingement is extracted for this tip speed. The number of impacts per mm^2 for a tip speed of 120 m/s, as extracted from the V-N curves, was 146.56, 300.347, 251.319, and 1111.52 for coatings 269-1, 269-3, 269-4, and 269-5, respectively. The number of impacts per mm^2 can be directly related to testing time by using equations to calculate the impact rate for the applied testing conditions for the R & D-style RET. The comparison graphs are presented in Figure 5. The depth for the breakthrough of the coatings is considered at 0.2 mm, which is the thickness of the coating layers in the RET samples. Three runs are used to account for the randomness in the impact positions and failure probability.

The predictions are in the range of the experimental measurements for both the end of incubation and breakthrough times. Coating 269-4 reaches breakthrough almost immediately after the end of the incubation, and the predictions are not able to capture this. However, the end of incubation time is predicted well. The predictions for the other coatings are reasonable and validate that the model can provide reasonable predictions.

(**A**)

(**B**)

(**C**)

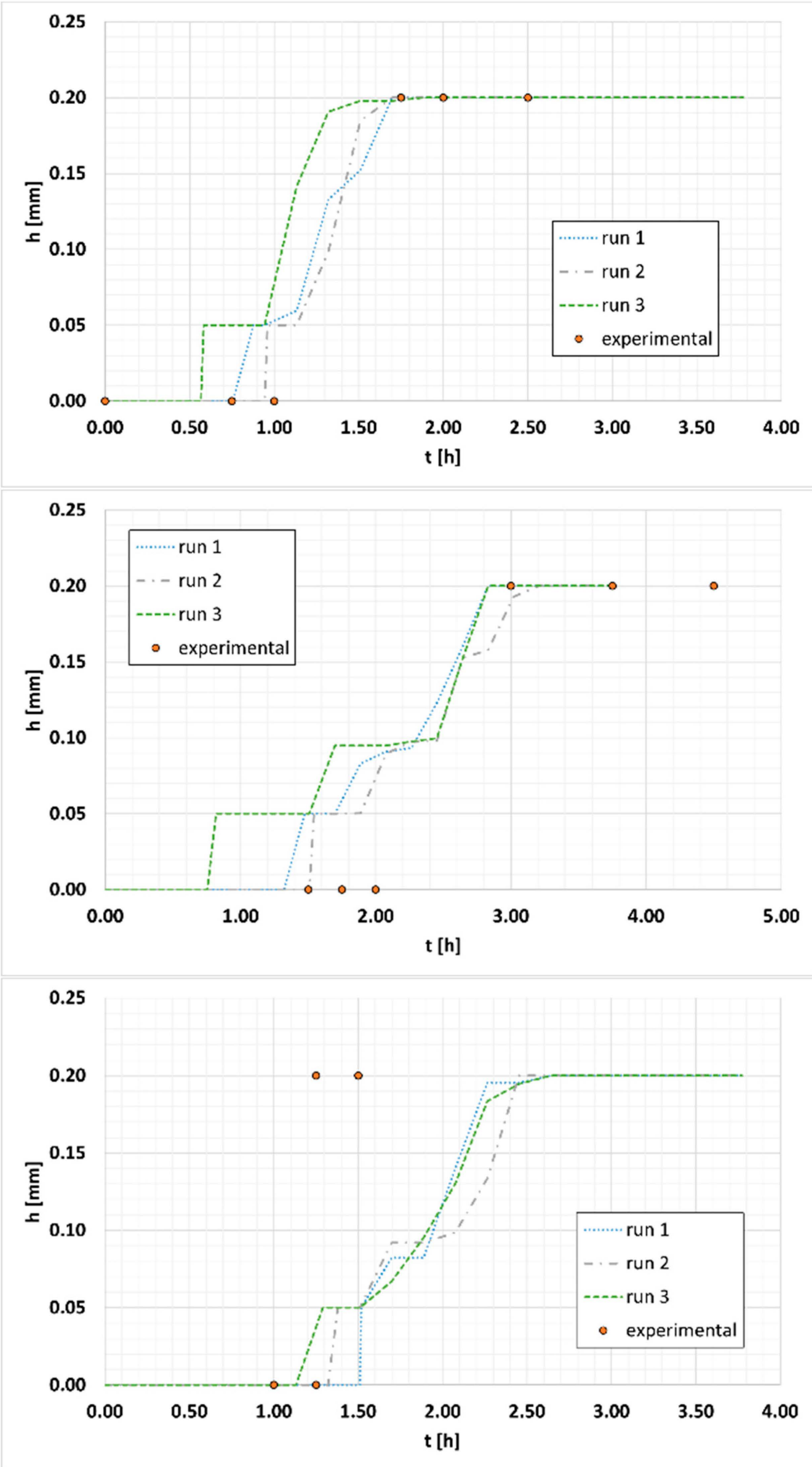


Figure 5. *Cont*.

(D)

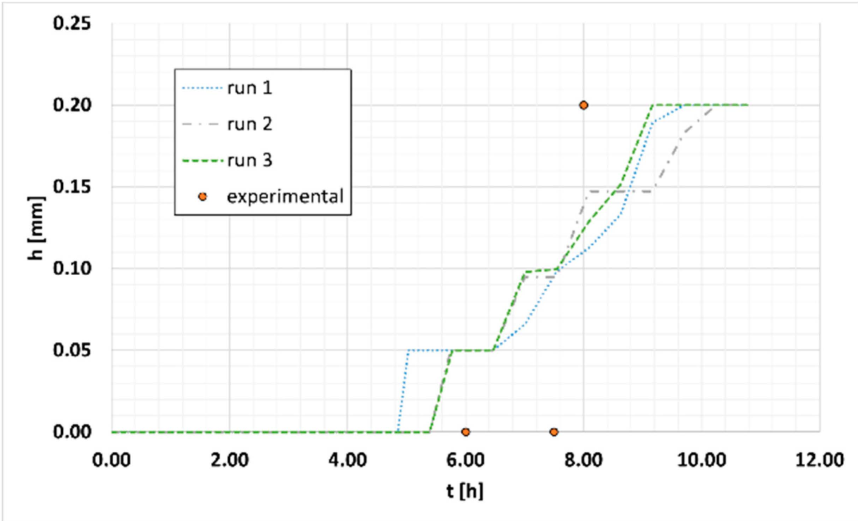


Figure 5. Comparison of erosion depth predictions with experimental RET data for coatings 269-1 (**A**), 269-3 (**B**), 269-4 (**C**), and 269-5 (**D**).

3.2. Estimation via Repair Statistics

Another way to estimate the volume of removed plastic is to use the repair and maintenance statistics. The average frequency of blade repairs, distributed over various damage mechanisms, is known and available from various databases and surveys [10,16,17]. Wind turbine blade repair is very expensive, so the repair teams are only called when they are necessary and the blade's degradation/erosion is visible, detectable, and could start influencing the energy generation of the wind turbine. The frequency of repair (F times per year) multiplied by the average volume of the removed blade material each time the repair team arrives is equal to the volume of eroded plastic per year.

According to the estimations in [10,16,17], the minor repair of wind blades is required on average 0.456 times per year per blade. This is the value taken from the 2010 to 2015 data. Probably, the new LEPs provide better protection, but the wind turbine blades are often much larger, and wind turbines are installed in more challenging regions, so the number should still be used as a conservative estimation. The team of the project PREMISE [11] contacted several service companies and asked them to share their experience, i.e., how large an eroded region is, how deep the eroded area is, and when they arrive to the repair site.

The estimations are as follows:

- Onshore: length of eroded region is of the order of 1.5. . .2 m; depth is 1–2 mm and width is 20–50 mm. Repair every 2 years.
- Offshore: length of eroded region is of the order of 4 up to 10 m; depth and width are the same. The scatter depends on sites, WTG models, blades, and coatings.

The volume of the removed coating material, per year, can be estimated by the following formula:

$$v = klwh\text{F} \quad (2)$$

where l, w, h—length, width, depth of eroded region, k—coefficient of shape of eroded hole, and F—frequency of repairs per year (i.e., frequency of finding such eroded areas). The estimation of the coefficient of shape is shown in Figure 6. The blade coating is not removed fully but rather in craters, and the distribution of these craters is quite irregular: there is high crater density or almost full removal on the leading-edge line and low crater density, and almost fully intact coatings, on the sides. To take into account the low density of the craters on the sides, and also the craters instead of full removal, we multiply k by 0.5. This is a first estimation, and more exact estimations are required.

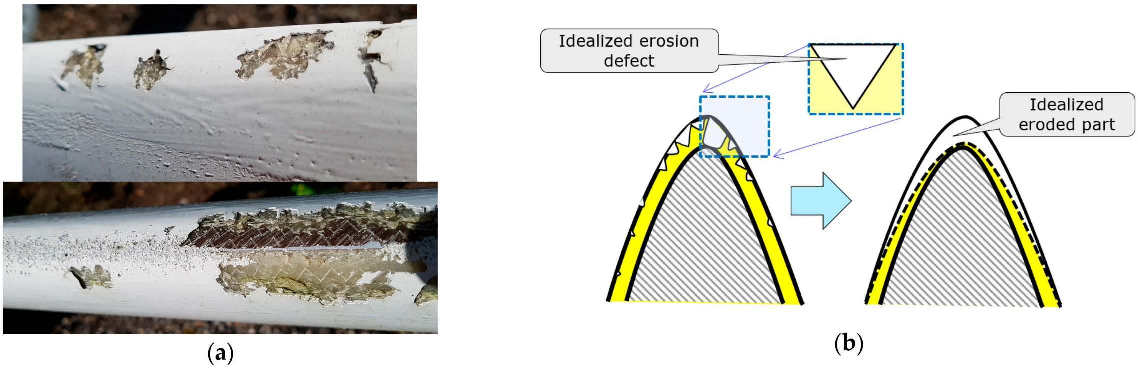


Figure 6. Examples of eroded blades (**a**), from Vindeby farm, left, photo by Jakob Bech) and schema of coefficients of shape of eroded surfaces (**b**).

Using the formula above, one can determine the volume of the removed coating material, per year, as shown in Table 1.

Table 1. Estimated volume of removed coating material based on repair statistics.

Onshore		
	Volume, cm^3	Weight, g
○ Lowest estimation, per year	8	8
○ Highest estimation, per year	50	50
○ Average	29	29
Offshore		
○ Lowest estimation, per year	80	80
○ Highest estimation, per year	1000	1000
○ Average	540	540

For the lowest estimation (if the wind park owner invests in the quick and regular repair of blades and if the wind turbine is located onshore), the small erosion of a blade, it is 8 cm^3 per year. This corresponds to the analytical estimation above.

For upper bound (extremely high erosion; the situation when the wind park owner almost neglects regular repair), it is 540 cm^3 per year. If the polyurethane density is 1000 kg/m^3, then it means 30 g to 540 g per year. In 2023, there were 6326 wind turbines in Denmark onshore and 648 offshore [18]. In order to determine the overall microplastic volume due to wind energy, we multiply these numbers (6326 onshore and 648 offshore) by the average detached volumes from the blades, presented in Table 1.

The estimated result is that all the onshore wind turbines in Denmark produce between 100 and 900 kg of polyurethane per year, on average 500 kg per year. All the offshore wind turbines emit between 200 and 1900 kg of plastic per year, with an expected average of 1000 kg per year. This means that the volume of eroded polyurethane is 1.6 tons per year.

3.3. Discussion and Comparison with Other Data

Several investigations have been carried out, with the purpose of investigating the likelihood and effects of possible microplastic emissions.

In [19], the microplastic content in sediment samples collected under and in the vicinity of an offshore wind farm (OWF, Hywind Scotland, Peterhead, UK) was assessed, with a specific focus on the occurrence and quantification of larger MPs (>300 µm), in particular those derived from the OWF infrastructure (e.g., coatings from rotor blades and leading-edge protection materials), as well as the background levels of other MPs from other sources. The authors sought to test the physicochemical effects of the established MP extraction procedure on laboratory-generated particles from coatings and quantify and characterize the extracted MPs using a combined approach of microscopy and FTIR analyses. They used reference microparticles (RMP) > 300 µm from three examples of coating materials provided by Equinor, including leading-edge protection material, top (surface) layer of rotor coating, and subsurface layer of rotor material. No detectable presence of MP contamination from coating materials used for the rotor blades or from the leading-edge protection materials was found in the analyzed fraction of the sediment samples. However, background MP contamination was detected from other sources, as thermoplastics supposedly released from other anthropogenic products.

In [20], it is written that the estimated amount released each year per blade is less than 50 g for a large onshore turbine and less than 100 g for a large wind turbine blade. This estimation is similar to the above calculation.

In [21], the following estimates are presented. The estimate by the company Key Wind Energy GmbH, Berlin, Germany, gives the erosion-related material loss to be around 67.5 kg per wind turbine over its entire twenty-year service life in the worst-case scenario (heavily stressed locations and without regular repairs of small damage). This would correspond to an annual material loss of around 3.38 kg per wind turbine.

The estimate of the company Deutsche Windtechnik, Bremen, Germany (also presented in [21]) gives similar results. They state that the blade is eroded approximately six to ten meters along the leading edge, which corresponds to around 500 g of polyurethane (PU) coating per blade, plus an additional 200 g per blade in additional layers. With three rotor blades per year, this would result in a material loss of 2.1 kg per wind turbine. Both estimations are also relatively close to the numbers presented in Section 3.

In [22], a team from the Norwegian Water Resources and Energy Directorate (NVE) sought to quantify the mass (volume) of erosion from turbine blades in Norway and came to an estimate of 200 g/blade per year. The methodology was that one windfarm which had experienced leading-edge erosion took exact measurement of all the repair material they used when they repaired their blades. Since the density of the repair material was about the same as the leading-edge erosion material, they could give a reasonable measured result of the amount of erosion the blade had experienced over seven years of operation. This was carried out for all the turbines in the wind farm.

3.4. New Observations of Wind Turbine Blade Erosion Mechanism: Spot Erosion

The estimations presented above rely on the recommendations obtained on the basis of experiences. The repair frequency presented in [17] was published in 2016 and apparently reflects observations from the late 2000s to early 2010s. Similarly, the recommendations of wind turbine service companies (service and repair every 2 years) are based on experiences from the 2000s to 2010s. Many research projects have been carried out over the last decade to improve blade protection [6,9], and new excellent coatings have been developed. On the other hand, new and bigger blades have been developed and installed. How has this changed the situation with erosion and the volume of eroded plastic?

The project team carried out interviews and discussions with wind turbine owners (WTOs) and energy companies to collect recent observations. The observations are as follows:

- Rarer repair operations. According to the WTO, practical repair occurs not every 2 years (as estimated in [17], and recommended to repair technicians, and also used in the above simulations) but rather once per 5. . .8 years. Apparently, this is related to better, newly developed LEPs.
- Changing erosion mechanisms: the introduction of new LEPs leads to changing mechanisms of their degradation. Namely, the detachment of coatings or coating parts occurs sufficiently more often than real erosion.

- Changing mechanisms of erosion: "spot" or "tiger tail" erosion. In the recent observations, eroded blades look to be not randomly eroded (with some gradient from high erosion closer to the blade tip) but rather eroded in random spots along the leading edge. Figure 7 shows what such an erosion looks like. Apparently, erosion in this case is not a random process but starts probably from some defect. It can be seen that the pits can reach laminate but still remain very localized.

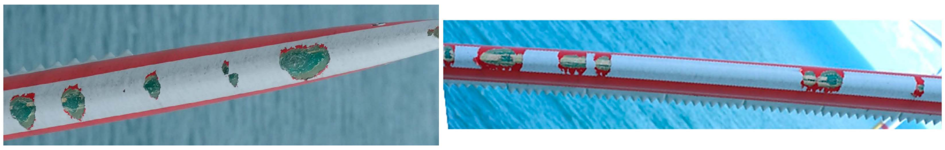


Figure 7. Erosion observations in 2023.

Apparently, the changed erosion mechanisms and much more seldom repairs mean that the amount of separated plastic is reduced by three or more times, as compared to the values estimated in Section 3.2.

Further developments of LEP/protective coatings are underway now. For instance, nanoengineered coatings developed in [23] allow for the incubation time to be extended up to 13 times. Further, new, bio-based coatings are under development now; for instance, cellulose particle-reinforced LEPs [24]. The advantage of these coatings is that they can degrade in nature without causing any negative effects or pollution (as normal, tree cellulose). Thus, with the extension of wind energy in future decades, new coatings could potentially allow for the mitigation of both blade erosion and the negative effects from the erosion.

4. Comparative Assessment of Contribution of Wind Energy to General Pollution

In order to rank the level of microplastic pollution from wind turbines, a number of reports and other publications about microplastic pollution were reviewed. According to [25], the annul emission of microplastics is up to 5.6 million metric tons, and up to 1.5 million tons appear in the world's oceans [26]. The main sources of microplastic pollution are textiles, car tires, and ship painting [27]. The data are summarized in Figure 8. The figure shows that there are three main sources of microplastic pollution: car tires, road markings, and pre-product plastics. The data provide the maximum possible amount of microplastics.

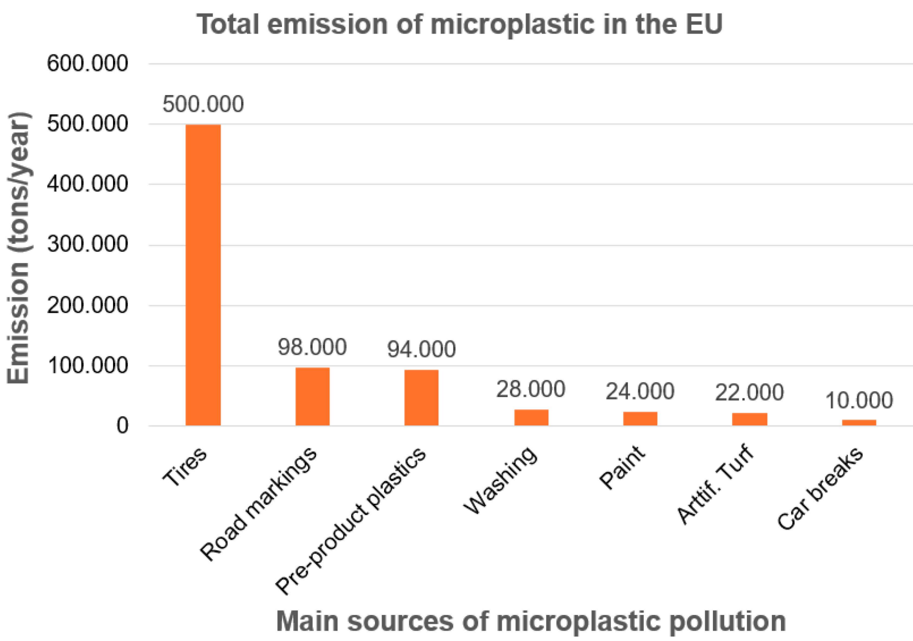


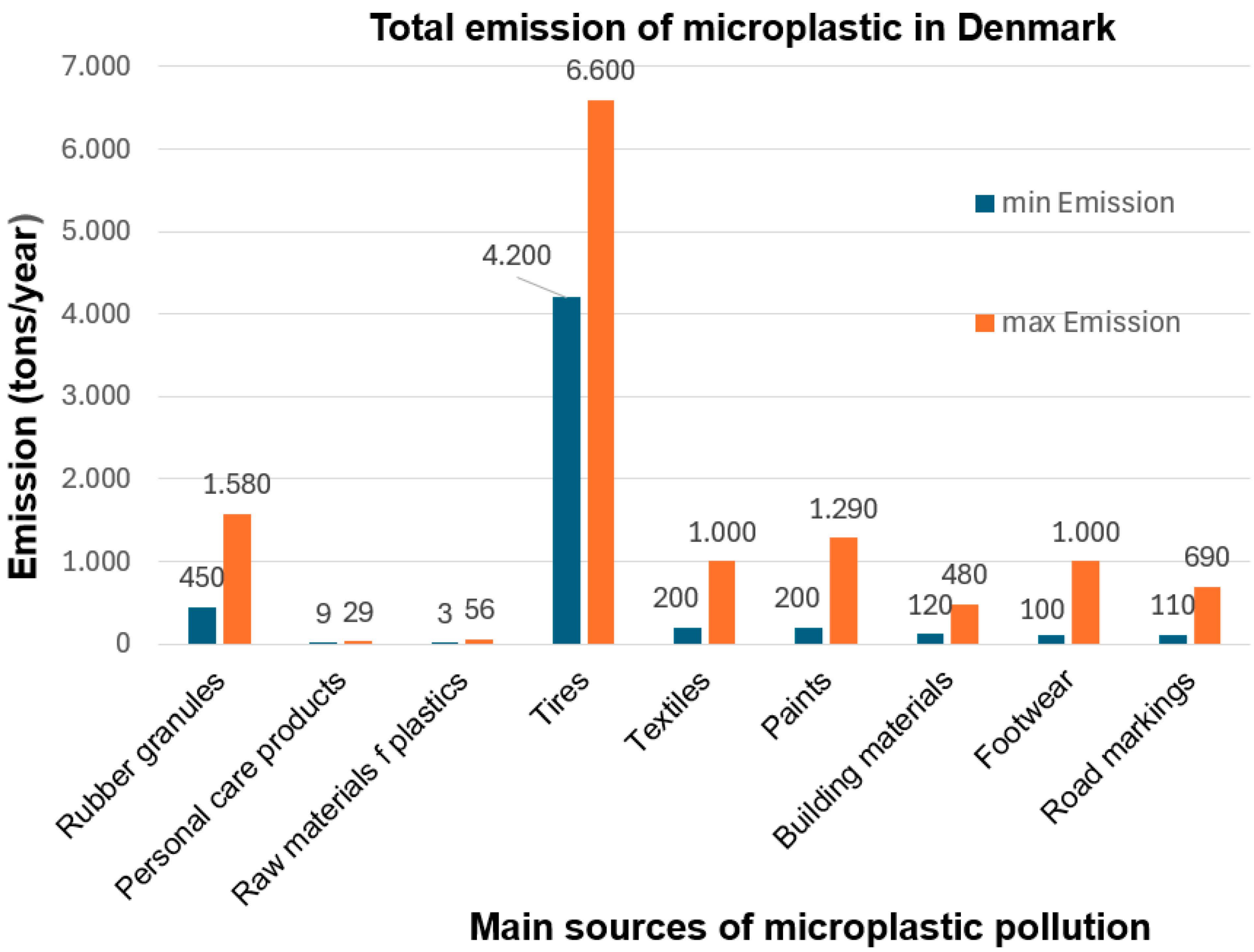
Figure 8. Data on the emission of microplastic in the EU in 2016.

In Figure 9, we illustrate the data on microplastic emission in Denmark [28–30]. As in Figure 8, we observe that car tires, paints, and textiles are the primary sources of microplastic pollution. Therefore, the total emission of microplastic to the Baltic and North Seas can be estimated to be up to 3100 tons/year.

Table 2 summarizes the numbers for various emission sources to make a better comparison.

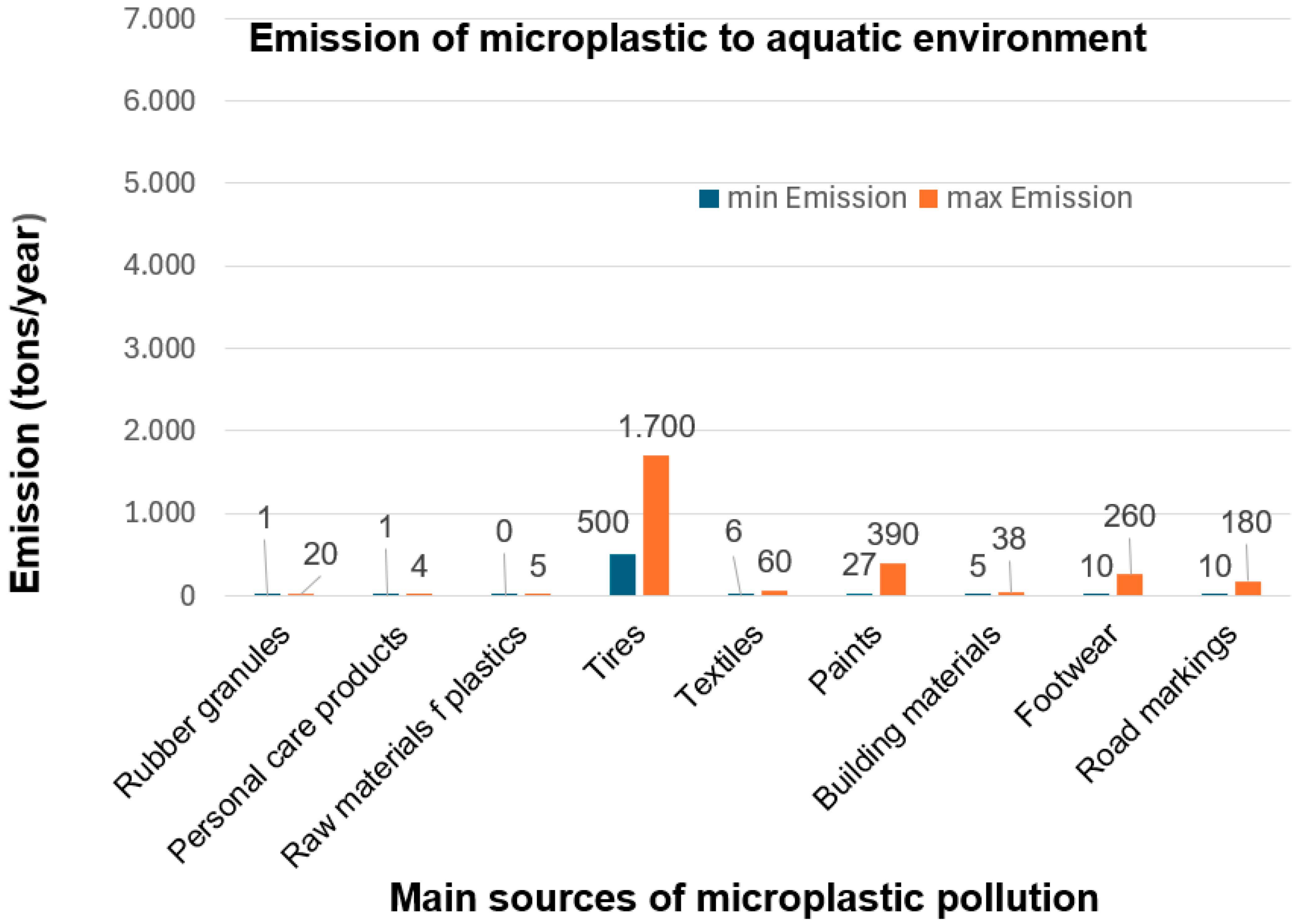
Table 2. Microplastic pollution from different sources in Denmark.

Source	Value
Car tires	Up to 1700 tons/year
Textiles	Up to 60 tons/year
Paints	Up to 390 tons/year
Wind turbines (our theoretical estimation)	1.7 tons/year



(**a**)

Figure 9. *Cont*.



(**b**)

Figure 9. Microplastic pollution in Denmark: (**a**) total emission of microplastics and (**b**) emissions to the sea.

5. Conclusions

In this article, the volume of removed plastic due to the leading-edge erosion of wind turbine blades is evaluated using different approaches. A probabilistic model of material removal due to successive rain droplet impacts was developed and applied to the determination of the volume loss of blades due to erosion. As a result, it was shown that for the case of an average tip speed of 90 m/s, 1000 mm of rain annually, and a mean rain intensity of 1 mm/h, the volume loss is at the level of 15 mm^3/cm^2 per year. For the area 10 m × 50 mm (full leading-edge surface), it leads to 75 cm^3 or 75 g per blade per year.

Another estimation is made on the basis of the blade repair statistics. Given that the blade repair frequency is known (from various surveys and databases [16,17]), and the repair is carried out at approximately the same degree of erosion (not too often, to reduce costs, but also not to seldomly, to exclude the surface defects reaching into the laminate), one can determine the volume of eroded plastic, per year, as the frequency of repairs, multiplied by the average volume of removed blade material each time the repair team arrives.

The estimated volume of eroded plastic is 30. . .540 g per year per blade. It is higher for offshore wind turbines (80. . .1000 g per year) and lower for onshore wind turbines (8. . .50 g per year). For the whole of Denmark, it is estimated to be about 1.6 tons per year, which is one order of magnitude less than footwear and road markings and three orders of magnitude less that tires. The estimations made with repair statistics correspond well to the estimations made with the probabilistic model, and also to the literature data. Additionally, the estimations made by Solberg and colleagues in [5] are analyzed, and it is demonstrated that these results are based on a wrong extrapolation and many wrong assumptions.

With a view to the wind energy development strategy, one should note the following. With increasing blade size, its erosion will become more intensive; thus, it is very important to develop new, improved leading-edge protection. While 100. . .400 g per year is not a large value, and is hundreds or thousand times less than the plastic coming from footwear and tires, there is still potential to develop better, more protective coatings [31,32]. Further, regular and efficient maintenance is also very important to avoid the situation when the surface erosion reaches the laminate. To achieve this, the blade repair costs should be reduced and the maintenance procedures optimized [32,33].

Author Contributions: L.M.J.—conceptualization, formal analysis; investigation; methodology; software; visualization; validation; writing—original draft; writing—review and editing; funding acquisition; resources; supervision; A.T.—investigation; software; visualization; N.F.-J.J. and Y.B.—data curation. All authors have read and agreed to the published version of the manuscript.

Funding: The author acknowledges the financial support of the Velux Foundation via the project PREMISE "Preventing MIcroplastics pollution in SEa water from offshore wind" (https://premise.dtu.dk/), and of the Ministry of Foreign Affairs of Denmark via the Danida grant 19-M02-DTU "Maintenance and repair strategy for wind energy development" (https://www.maintainergy.dk/).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Martin, C. Wind Turbine Blades Can't Be Recycled, So They're Piling up in Landfills. Bloomberg. 5 February 2020. Available online: https://www.bloomberg.com/ (accessed on 1 December 2024).
2. Mishnaevsky, L., Jr. Recycling of wind turbine blades: Recent developments. *Curr. Opin. Green Sustain. Chem.* **2023**, *39*, 100746.
3. Kramer, K.J.; Beauson, J. Review existing strategies to improve circularity, sustainability and resilience of wind turbine blades—A comparison of research and industrial initiatives in Europe. In *IOP Conference Series: Materials Science and Engineering, Proceedings of the 43rd Risoe International Symposium on Materials Science, Roskilde, Denmark, 4–7 September 2023*; IOP Publishing: Bristol, UK, 2023; Volume 1293, p. 21.
4. Hill, S. Letters/Microplastics from Wind Turbines. *Shetland News*, 19 October 2021. Available online: https://www.shetnews.co.uk/2021/10/19/microplastics-from-wind-turbines (accessed on 1 December 2024).
5. Solberg, A.; Rimereit, B.E.; Weinbach, J.E. *Leading Edge Erosion and Pollution from Wind Turbine Blades*; The Turbine Group: Queensland, Australia, 2021.
6. Mishnaevsky, L., Jr.; Hasager, C.B.; Bak, C.; Tilg, A.-M.; Bech, J.I.; Rad, S.D.; Fæster, S. Leading edge erosion of wind turbine blades: Understanding, prevention and protection. *Renew. Energy* **2021**, *169*, 953–969. [CrossRef]
7. Mishnaevsky, L., Jr.; Tempelis, A.; Kuthe, N.; Mahajan, P. Recent developments in the protection of wind turbine blades against leading edge erosion: Materials solutions and predictive modelling. *Renew. Energy* **2023**, *215*, 118966. [CrossRef]
8. Tempelis, A.; Mishnaevsky, L., Jr. Surface roughness evolution of wind turbine blade subject to rain erosion. *Mater. Des.* **2023**, *231*, 112011. [CrossRef]
9. Innovation Foundation of Denmark (IFD). Project DURALEDGE "Durable Leading Edges for High Tip Speed Wind Turbine Blades", 2018–2022. Available online: https://www.duraledge.dk/ (accessed on 1 December 2024).
10. Mishnaevsky, L., Jr.; Thomsen, K. Costs of repair of wind turbine blades. *Wind Energy* **2020**, *23*, 2247–2255. [CrossRef]
11. Velux Foundation Project PREMISE. Preventing MIcroplastics Pollution in SEa Water from Offshore Wind. (2024–2027, 6.2 Mio kr.). Available online: www.premise.dtu.dk (accessed on 1 December 2024).
12. Pugh, K.; Stack, M.M. Rain Erosion Maps for Wind Turbines Based on Geographical Locations: A Case Study in Ireland and Britain. *J. Bio-Tribo-Corros.* **2021**, *7*, 34. [CrossRef]
13. Springer, G.S. *Erosion by Liquid Impact*; Scripta Publishing Company: Fort Worth, TX, USA, 1976.
14. Verma, A.S.; Jiang, Z.; Caboni, M.; Verhoef, H.; van der Mijle Meijer, H.; Castro, S.G.; Teuwen, J.J. A probabilistic rainfall model to estimate the leading-edge lifetime of wind turbine blade coating system. *Renew. Energy* **2021**, *178*, 1435–1455. [CrossRef]
15. Tempelis, A.; Mishnaevsky, L., Jr. Coating Material Loss and Surface Roughening Due to the Leading Edge Erosion of Wind Turbines: Probabilistic Analysis. Available online: https://ssrn.com/abstract=4989709 (accessed on 1 December 2024).

16. Boopathi, K.; Mishnaevsky, L.; Sumantraa, B.; Premkumar, S.A.; Thamodharan, K.; Balaraman, K. Failure mechanisms of wind turbine blades in India: Climatic, regional and seasonal variability. *Wind Energy* **2021**, *25*, 968–979. [CrossRef]
17. Carroll, J.; McDonald, A.; McMillan, D. Failure rate, repair time and unscheduled O & M cost analysis of offshore wind turbines. *Wind Energy* **2016**, *19*, 1107–1119.
18. Number of Active Wind Power Turbines in Denmark 2010–2023. Available online: https://www.statista.com/statistics/990723/number-of-active-wind-power-turbines-in-denmark/#:~:text=The%20number%20of%20active%20wind,6,326%20compared%20to%20648%20offshore (accessed on 1 December 2024).
19. Piarulli, S. Analysis of Microplastics in Sediments from Hywind Scotland. Available online: https://www.equinor.com/sustainability/impact-assessments (accessed on 1 December 2024).
20. Vindmøllevinger Og Mikroplast. 8 March 2023. Available online: https://videnomvind.dk/erosion-af-vingeforkanter/ (accessed on 1 December 2024).
21. Faktencheck: Erosion an Rotorblättern, BWE Bundesverband WindEnergie. August 2024. Available online: https://www.wind-energie.de/fileadmin/redaktion/dokumente/Aktuelles/Faktenchecks/20240801_BWE-Faktencheck_-_Erosion_an_Rotorblaettern.pdf (accessed on 1 December 2024).
22. Forurensning. 1 March 2022, Updated 12 July 2024. Available online: https://www.nve.no/energi/energisystem/vindkraft-paa-land/ (accessed on 1 December 2024).
23. Johansen, N.F.J.; Mishnaevsky, L., Jr.; Dashtkar, A.; Williams, N.A.; Silvello, A.; Cano, I.G.; Hadavinia, H. Nanoengineered graphene reinforced coating for leading edge protection of wind turbine blades. *Coatings* **2021**, *11*, 1104. [CrossRef]
24. Pathak, S.M.; Kumar, V.P.; Bona, V.; Mishnaevsky, L., Jr.; Lakshmi, R.V.; Bera, P.; Barshili, H.C. Development of cellulose-reinforced polyurethane coatings: A novel eco-friendly approach for wind turbine blade protection. *Energies* **2023**, *16*, 1730. [CrossRef]
25. First Sentier MUFG Sustainable Investment Institute. Microplastic Pollution: The Causes, Consequences and Issues for Investors. Report. Available online: https://www.firstsentier-mufg-sustainability.com/research/microplastics-05-2020.html (accessed on 1 December 2024).
26. Boucher, J.; Friot, D. *Primary Microplastics in the Oceans: Global Evaluation of Sources*; Report; International Union for Conservation of Nature: Gland, Switzerland, 2017.
27. Hann, S.; Kershaw, P.; Sherrington, C.; Bapasola, A.; Jamieson, O.; Cole, G.; Hickman, M. *Investigating Options for Reducing Releases in the Aquatic Environment of Microplastics Emitted by Products in EU*; Final Report; ICF: London, UK, 2016.
28. Lassen, C.; Hansen, S.F.; Magnusson, K.; Hartmann, N.B.; Jensen, P.R.; Nielsen, T.G.; Brinch, A. *Microplastics: Occurrence, Effects and Sources of Releases to the Environment in Denmark*; Environmental Project No. 1793; Danish Environmental Protection Agency: Copenhagen, Denmark, 2015.
29. Feld, L.; da Silva, V.H.; Murphy, F.; Hartmann, N.B.; Strand, J. A study of microplastic particles in Danish tap water. *Water* **2021**, *13*, 2097. [CrossRef]
30. Strand, J.; Feld, L.; Murphy, F.; Mackevica, A.; Hartmann, N.B. *Analysis of Microplastic Particles in Danish Drinking Water*; Danish Centre for Environment and Energy: Aarhus, Denmark, 2018.
31. Mishnaevsky, L., Jr. Toolbox for optimizing anti-erosion protective coatings of wind turbine blades: Overview of mechanisms and technical solutions. *Wind Energy* **2019**, *22*, 1636–1653. [CrossRef]
32. Paul, D.; Varshney, A.; Mahajan, P.; Mishnaevsky, L., Jr. Post-repair residual stresses and microstructural defects in wind turbine blades: Computational modelling. *Int. J. Adhes. Adhes.* **2023**, *123*, 103356. [CrossRef]
33. Mishnaevsky, L., Jr.; Johansen, N.F.-J.; Fraisse, A.; Fæster, S.; Jensen, T.; Bendixen, B. Technologies of wind turbine blade repair: Practical comparison. *Energies* **2022**, *15*, 1767. [CrossRef]