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ASSESSING THE FEASIBILITY OF OFFSHORE HYDROGEN BUNKERING: A STATISTICAL ANALYSIS BASED ON HISTORIC SEA STATE DATA

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ABSTRACT

The shipping industry needs to adopt more sustainable fuels. Hydrogen is regarded as an environmentally sustainable option, particularly for vessels of a smaller scale. Recent studies have proposed a novel approach to the production of hydrogen, namely, its generation in offshore wind parks and subsequent bunkering to ships at these platforms. However, the viability of this approach is contingent upon various factors, including environmental conditions. A literature review indicates that this solution can be economically viable under certain conditions. However, a significant number of studies have overlooked the impact of sea state on these operations. This study analyzes historic meteorological data from the Copernicus Climate Change Service for offshore wind parks in German waters. The findings indicate that the offshore bunkering of hydrogen in the Baltic Sea is more feasible than in the North Sea due to less challenging environmental conditions. In the North Sea, the viability of this approach is contingent upon on the operational limit for significant wave height. This study highlights the challenging environmental conditions for offshore bunkering and provides assistance to those tasked with the planning of such operations.

Keywords: Sea State, Bunkering, Hydrogen, Offshore, Shipping

NOMENCLATURE

μ	mean value
A_i	i-th sample value
H_S	significant wave height [m]
N	Number of data points
S	Standard deviation
i	index variable

1. INTRODUCTION

The shipping industry is in need to utilize more sustainable fuels. The International Maritime Organization (IMO) has put different measures in place with the objective of achieving climate neutral shipping by or around 2050. Hydrogen is regarded as a climate-friendly fuel, particularly for smaller units [1]. In recent studies, the utilization of offshore power for the production of hydrogen has been proposed. The generation of hydrogen can be leveraged to circumvent the necessity of deactivating wind turbines during periods of high wind speeds and low electricity demand. Consequently, the surplus energy can be stored for extended periods. The hydrogen produced can then be utilized in various applications. In order to achieve further increases in efficiency for ships remaining on sea for long periods of time, such as fishing vessels, it is also proposed that the hydrogen be produced directly in the offshore wind park and subsequently bunkered to the ship at this platform [2]. For land-based utilization of the produced hydrogen, transport to shore via pipeline or ship can be suitable [3]. Li et al. [4] proposed to charge battery powered ships offshore. Seo et al. [5] conducted an analysis of six design concepts for supply chains utilized in the offshore production of hydrogen. Four of the aforementioned supply chains rely on ship-based transport to shore. One of these supply chains transports hydrogen to shore via pipeline, while the last transfers the generated electricity to shore via subsea cable. Notably, the hydrogen is produced onshore.

In the case of more extensive transport distances, the viability of a connection from the offshore wind park to the shore via cable or pipeline may be questionable. Consequently, ship-based transport could emerge as a viable solution. Literature review has indicated that the proposed solution is economically viable under certain conditions [6]. Varotto et al. [7] performed an optimization of different offshore energy production and transport configurations. They found that the offshore production of hydrogen and subsequent transport of hydrogen via ship to shore can be economical viable, if the installation of additional submarine transmission facilities is not possible .

However, a significant number of these studies do not take into account the sea state as a limiting factor in these hazardous operations, such as bunkering. Wave-induced motions of floating

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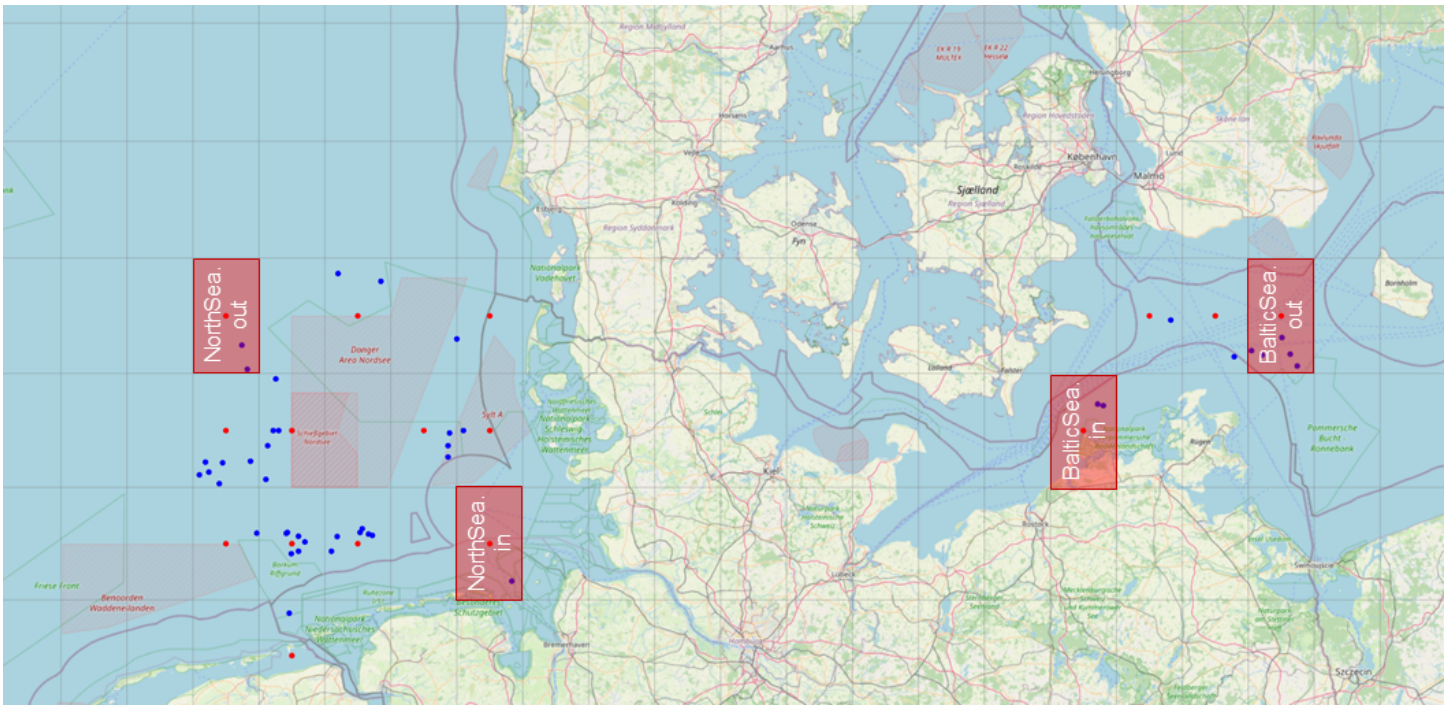


FIGURE 1: Map of offshore wind parks in German waters. Background map: ©OpenStreetMap contributors

structures — such as ships — can create hazardous situations in two distinct ways. First, the ship's motion is transmitted to the transfer equipment (e.g., hoses, cables), generating bending stresses in the material. Second, handling equipment on a moving platform requires personnel to work on a dynamic deck, which raises the likelihood of injuries. Both effects contribute significantly to the overall risk of offshore bunkering. In addition to the hazards, ship motion exerts an influence on the process itself. The motion of a ship can induce sloshing within the tank, a phenomenon with the capacity to exert multifaceted effects on the boiling process. The process of sloshing has been shown to increase the energy levels in the liquid phase, thereby enhancing the rate of boil-off. Conversely, sloshing can function analogously to a spraying system, thereby facilitating the re-condensation of the gaseous phase within the tank [8].

Orysiak et al. [9] analyzed the hydrological and meteorological conditions in seven Polish ports to assess the feasibility of bunkering liquefied natural gas (LNG) in these ports.

The duration of the bunkering process is contingent on various factors, including the storage form of hydrogen (compressed, liquefied or as a derivate) and the bunkering method employed. The transfer of hydrogen to the ship can be accomplished in one of two ways. The hydrogen can be transferred via hose or loading arm, or it can be filled into the tanks on the platform. Subsequently, the filled tanks can be loaded to the ship. The storage form and the bunkering method substantially influence the bunker duration and thus no universal assumption can be made. Previous work by the authors [10] found a bunker duration of 6 hours necessary to transfer 135 t of liquid hydrogen to a cruise ship in port.

2. MATERIAL AND METHODS

The present study analyzes historic ERA5 (fifth generation European Centre for Medium-Range Weather Forecasts reanalysis for the global climate and weather for the past 8 decades) hourly data provided by the Copernicus Climate Change Service [11] for offshore wind parks in German waters. The wind parks are grouped on a 0.5° latitude and longitude grid, and the wave data is analyzed for each grid. The primary parameter that must be assessed in order to ascertain the feasibility of bunkering offshore is the significant wave height H_S; this is due to the fact that it exerts a significant influence on the amplitude of the ship's motion.

The significant wave height is obtained from the Copernicus Climate Change Service for the years 1940 to 2023. The data is provided on a 0.5°x0.5° grid as well. For the linear interpolation of the precise location we used the RegularGridInterpolator from SciPy [12]. In the context of the six points that are in close proximity to the shore, conventional grid interpolation was found to be ineffective. Consequently, it was necessary to exclude the points located on land and instead employ a linear interpolation between the two non-NaN points.

For different wave height operational limits, as defined below, the time above these limits is examined on a monthly basis. Given the hourly nature of the data and the absence of any missing values, the analysis focused exclusively on the number of data points that exceeded the established limit within the monthly data set that has been systematically sorted. The percentage is derived by comparing it to the total number of data points.

It has to be noted, that in the case of the Baltic Sea, there were also periods of ice coverage in the regions under consideration. These periods were excluded from the investigation. Depending on the ice thickness and the ship type, ice will further influence

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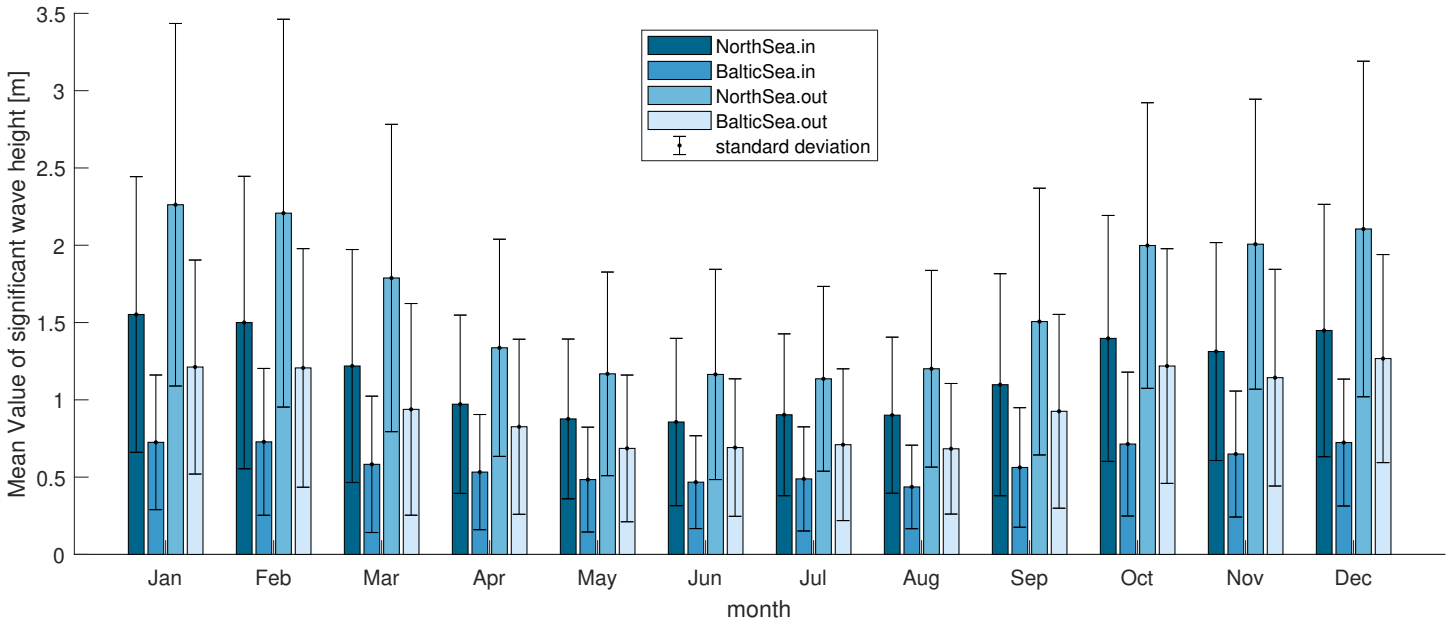


FIGURE 2: Mean value and standard deviation of significant wave height per month

the bunkering possibility. However, this has to be investigated in further detail in future work and is out of scope of this paper.

This study will conduct an in-depth examination of four distinct groups, encompassing a total of 10 offshore wind parks. For both the North Sea and the Baltic Sea, the group closest to the shoreline and the most distant group has been selected.

Group NorthSea.in represents the position closest to the shoreline in the North Sea and consists of only one wind park. Group NorthSea.out on the other hand represents the most outward wind parks in the North Sea, however these two wind parks are still in a planing phase. For the Baltic Sea, group BalticSea.in represents two wind parks close to the shoreline and group BalticSea.out represents the four distant wind parks. The wind park under consideration and their groups are listed in Table 1. Figure 1 illustrates all German wind parks with a blue dot and the grid point for weather data is marked with a red dot. Even though wave data is available for each wind park, this study will focus on the four mentioned groups to increase clarity and focus.

TABLE 1: selected wind parks for analysis

name	latitude	longitude	group
Nordergründe	53,833	8,1667	NorthSea.in
EnBW Baltic 1	54,609	12,651	BalticSea.in
Gennaker	54,616	12,608	BalticSea.in
Fläche N-12.1	54,768	6,162	NorthSea.out
Fläche N-12.2	54,873	6,121	NorthSea.out
Wikinger	54,834	14,068	BalticSea.out
Arkona-Becken Südost	54,782	14,121	BalticSea.out
Baltic Eagle	54,83	13,855	BalticSea.out
Windanker	54,906	14,005	BalticSea.out
Fläche O-2.2	54,849	13,775	BalticSea.out

The analysis is conducted for each of the four groups. Initially, the data is sorted by month. Afterwards, the mean value, median value and standard deviation for each month are then calculated. The mean value is the sum of each data point, divided by the number of data points, see Eq. 1. For the median value, all data points are sorted by size and the median value is the middle element of this sorted sample. Thus, exactly half of the data points are larger than the median and half is smaller than the median. Equation 2 defines the standard deviation. It quantifies the typical distance of the data points to the mean value [13].

$$\mu = \frac{1}{N}\sum_{i=1}^{N} A_i \tag{1}$$

$$S = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N} |A_i - \mu|^2} \tag{2}$$

Different significant wave heights are proposed in literature as safe operation limits. Fischer et al. [14] assume 1.3 m wave height as limit for offshore wind park operations. It has to be noted, that these operations include transfer of personnel from a ship to the wind turbines or platforms. Miranda et al. [15] conducted a reliability assessment of LNG bunkering operations and assumed, that the bunkering operation would be stopped above 1 m significant wave height. Discussions with safety experts from the field of offshore wind yielded significant wave height of 2 - 3 m as operational limit for bunkering of hydrogen. Oil transfer at mooring boys is typically stopped at 2 m significant wave height. Hoog et al. [16] introduced a novel LNG transfer concept, that includes a novel tandem mooring configuration, and allows for transfer of LNG at significant wave height up to 5.5 m. Thus, this study considers wave height of 1, 2, 3 and 4 m as operational limit for bunkering. It is anticipated that systems such as

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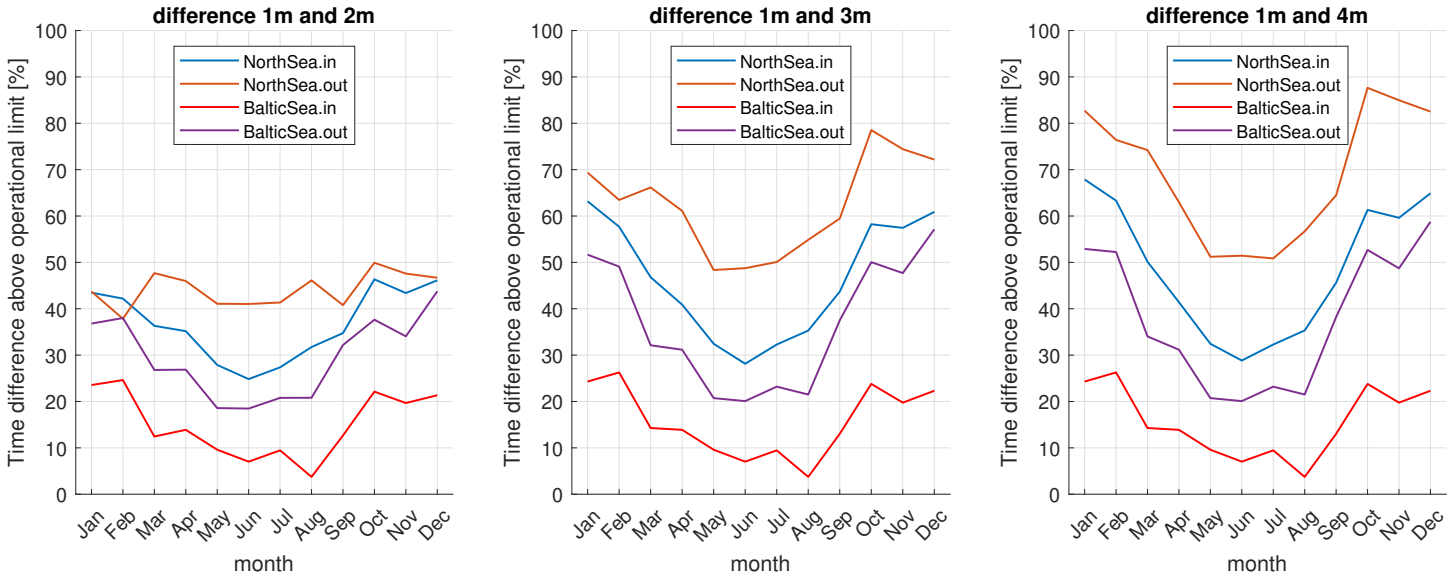


FIGURE 3: Change in downtime compare to operational limit of H_S=1 m in percentage points

a motion compensator will be essential for facilitating operations at the upper end of the designated wave heights.

3. RESULTS AND DISCUSSION

Figure 2 illustrates the the mean values and standard deviation per month of the four groups of wind parks. As is expected and evident from Fig. 2, the wave height is significantly higher during winter month, than during summer. The values in the winter are approximately two times larger than in summer, e.g. for group NorthSea.out, the outmost group in the North Sea, the mean significant wave height in June is 1.14 m and in January the mean significant wave height increases to 2.21 m. Group BalticSea.in, the innermost group of the Baltic Sea, the mean significant wave height is 0.45 m in May and June and 0.76 m in January. The standard deviation is around 1.5 times larger in winter, than during summer. For group BalticSea.in, it ranges from 0.33 m in May and June to 0.49 m in January.

As evident from Fig. 2, the mean wave height and standard deviation are also significant larger for the North Sea, than for the Baltic Sea. The mean significant wave height in January is 2.21 m for group NorthSea.out in the North Sea and 1.28 m for group BalticSea.out in the Baltic Sea. The standard deviation in January is 1.18 m for group NorthSea.out and 0.78 m for group BalticSea.out in January. These two groups are the outmost groups in the North Sea and Baltic Sea, respectively.

The median significant wave height is illustrated in Fig. 4. The median values exhibit similar behavior as the mean values, but are smaller than the mean values for all groups and month. For example, the mean significant wave height for group NorthSea.in in May is 0.87 m and the median is 0.74 m. Group NorthSea.in is the innermost group in the North Sea. Still, the same tendency between summer and winter month are observable. The median significant wave height in December is 1.32 m and 0.74 m in May for group NorthSea.in. The median significant wave height is as well smaller in the Baltic Sea than in the North Sea. Group NorthSea.in has a median significant wave height in May of 0.74 m and group BalticSea.in, the innermost group in the Baltic Sea, has a median significant wave height of 0.35 m.

The statistical values of mean, median and standard deviation allow for a good representation of the average. However, to assess the feasibility of bunkering offshore, it is necessary to look at the time, in which bunkering is not possible in more detail. As discussed in chapter 2, four distinct wave heights - 1 m, 2 m, 3 m and 4 m - are investigated. As illustrated in Fig. 5, the percentage of time the significant wave height exceeds 1 meter varies among the four groups under consideration. Similar trends as for the mean and median values are observable. During the winter month, longer time periods are above the operational limit of 1 m than during summer month. The Baltic Sea also exhibits shorter time periods of waves above the limit in comparison to the North Sea.

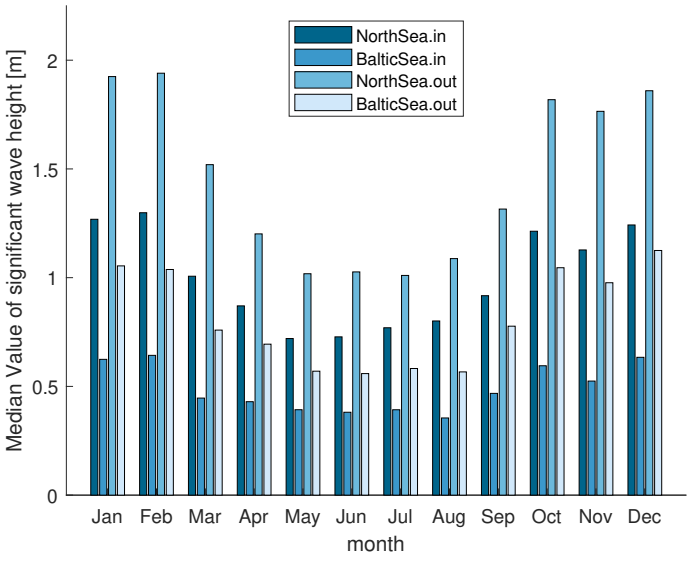


FIGURE 4: Median value of significant wave height per month

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The significant wave height for Group BalticSea.in, the innermost in the Baltic Sea, is between 7 % (in May) and 26 % (in January) of the time with $H_S < 1$ m. When the outermost position in the Baltic Sea is considered (group BalticSea.out), these values increase to 18 % in June and 56 % in January. For Group NorthSea.in however, these time frames increase even further to values between 31 % in May and 68 % in December. The longest time periods are evident for group NorthSea.out, the outmost group in the North Sea. Even in the summer month, 49 % (June) of the time, the significant wave height is above 1 m. This value increases to 88 % in January.

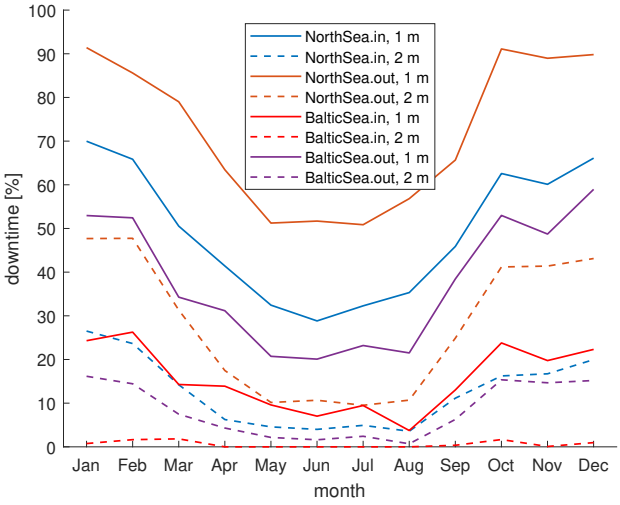


FIGURE 5: Percentage of time above a significant wave height of 1 m and 2 m per month

The general trends between the different locations and seasons, observable for the operational limit of 1 m wave height are also observable for the limit of 2 m, as illustrated in Fig. 5. However, the time frames above the operational limit has decreased. Group BalticSea.in is now between 0.1 % (May and July) and 2.4 % of the time above the established limit. For Group BalticSea.out, these values increase to 1.7 % in June and 16 % in January and for group NorthSea.in to 4 % in May and 23 % in January. Group NorthSea.out demonstrates the most significant value as well for the limit of 2 m. Group NorthSea.out exhibits waves larger than 2 m for 10 % of the time in May and for 50 % of the time in December.

Figure 6 illustrates the percentage of time during which the significant wave height exceeds 3 and 4 meter. It has to be noted, that for group BalticSea.in - the innermost group in the Baltic Sea - no time periods with $H_S > 3$ m were observed. Consequently, group BalticSea.in was excluded from Fig. 6. For the remaining groups the general trends between the different locations and seasons observed in Fig. 5 remain valid in Fig. 6. However, the duration during which H_S exceeds the operational limit has undergone a substantial reduction. During summer month only group NorthSea.out experienced waves with $H_S > 4$ m. Furthermore, Group NorthSea.out experienced waves with $H_S > 3$ m during January and February, with an occurrence rate of 22 %.

The disparity in the time above the operational limit in per-

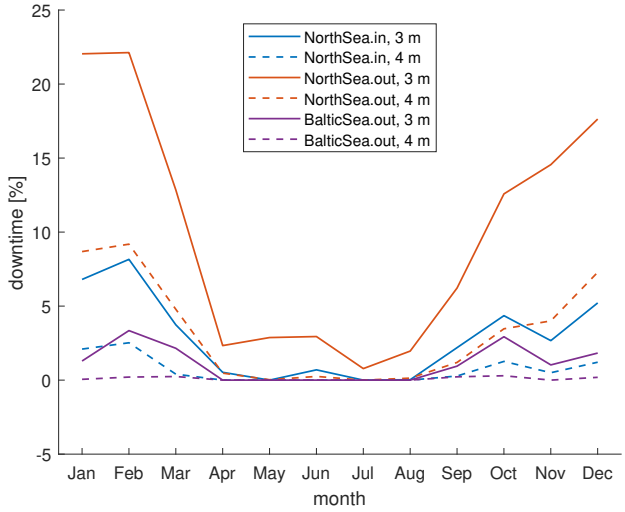


FIGURE 6: Percentage of time above a significant wave height of 3 m and 4 m per month

centage points is illustrated in Fig. 3. $H_S > 1$ m has been selected as a base value and compared to the other operational limits. As demonstrated in Fig 3, the most substantial reduction in downtime is attained when the operational limit is elevated from 1 m to 4 m. Nevertheless, given the impracticality of an operational limit of $H_S > 4$ m, a notable enhancement can be attained by increasing the operational limit from 1 m to 2 m significant wave height, thereby achieving a substantial increase of up to 50 % in the North Sea and 40 % in the Baltic Sea.

4. CONCLUSION

The present study demonstrated that sea states have the potential to impede the bunkering of hydrogen in offshore wind parks. The economic viability of such operations is contingent upon operational limits. In the context of operational limits of $H_S = 1$ m, the economic viability of bunkering in offshore wind parks, even in the Baltic Sea, is hindered by the significant downtime associated with waves. This downtime can reach up to 30 % for the innermost wind parks and 50 % for the outermost wind parks. Increasing the operational limit to 2 meters has been demonstrated to reduce downtime in the Baltic Sea to 2% or 15%, respectively. This adjustment renders the endeavor economically viable. In the North Sea, the viability of offshore hydrogen bunkering is further diminished. It has been determined that establishing an operational limit of $H_S = 1$ m would result in downtime ranging from 70 to 90 % during the winter months. In order to decrease the downtime to below 10 %, it is necessary to increase the operational limit to 4 meters of significant wave height. Despite the absence of defined operational limits for offshore bunkering, it is imperative to consider downtime resulting from sea state fluctuations when conducting investigations into the value chains of offshore-produced hydrogen.

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