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Power output of offshore wind farms in relation to atmospheric stability

Laurens Alblas,^{1,3} Wim Bierbooms¹ and Dick Veldkamp^{1,2}

¹ Wind Energy Research Group (DUWIND), Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands

² Vestas Central Europe, P.O. Box 208, 6800 AE Arnhem, The Netherlands

E-mail: laurens.alblas@dnvgl.com, w.a.a.m.bierbooms@tudelft.nl, hfvd@vestas.com

Abstract. Atmospheric stability is known to influence wind farm power output, by affecting power losses due to wakes. This research tries to answer what atmospheric stability does to the power production and how conventional simulations using the Jensen wake model compare and can be improved. Data is used from two offshore wind farms, Egmond aan Zee (OWEZ) and North Hoyle. Stability distributions are determined using metmast data. By combining this data with the production data, the influence of stability on the power output is studied. It is found that very unstable conditions result in higher power output (i.e. smaller wake losses) than near-neutral conditions, and these again show higher power output than during very stable conditions. Differences in normalized power output of 10-20% exist between the very unstable and very stable conditions. Simulations can be improved by adapting the wake decay constant (WDC). Observed WDC values are $k \geq TI$, as opposed to the conventional $k \approx 0.5TI$. A hypothesis for further research is proposed regarding the influence of vertical turbulence.

1. Introduction

Atmospheric stability is known to influence wind farm power output, by affecting power losses due to wakes. A stable atmosphere has a lower turbulence intensity and therefore wakes will exist longer. The opposite is true for an unstable atmosphere. Previous investigations indicate that wake losses for a wind farm can range from 5 to 15% [1]. The large variation in power produced by a wind farm indicates the need for more research in this field, aimed at finding the causes of the variation and to improve predictions with this knowledge. The goal of this project is to answer the following three research questions regarding the influence of atmospheric stability on the power production of offshore wind farms:

- (i) What does atmospheric stability do to the power production?
- (ii) How do conventional simulations compare with the measurements?
- (iii) How to improve the conventional simulations?

2. Theory

Wakes and atmospheric stability are two vital subjects of this research. They are therefore shortly explained before going further into the data and results.

³ Present address: DNV GL, Veritasveien 1, 1322 Høvik, Norway.



Table 1: Monin-Obukhov length L [m] boundaries for stability classes as used in the analysis.

Stability class	Very stable	Stable	Neutral	Unstable	Very unstable
Boundaries	$0 < L < 200$	$200 < L < 1000$	$ L > 1000$	$-1000 < L < -200$	$-200 < L < 0$

2.1. Wake of a wind turbine

When a turbine extracts energy from the wind, an area of lower wind speeds and increased turbulence results downstream of the turbine: the wake [2, 3, 4, 5]. There will be a loss in power production for turbines further downstream when they are in the wake of the first turbine. Recovery of the wake is possible and occurs when the air in the wake mixes with the higher energy flow surrounding the wake. Mixing is improved during turbulent conditions.

2.2. Atmospheric stability

Stability in the atmosphere can be defined as the tendency of air to resist vertical motion [6, 7]. Roughly, the atmosphere can be classified into three stability classes: stable, neutral and unstable. When air parcels are displaced, they will respectively move back to their starting altitude, stay at their new altitude or move away from their starting altitude.

In wind power research, atmospheric stability is usually based on the Monin-Obukhov length L . It can be interpreted as the height above the surface at which turbulence produced by heat conduction first starts to dominate over turbulence produced by shear [7, 8, 9].

Grachev & Fairall [10], Lange et al. [11] and Sathe [12] describe different methods to determine the Monin-Obukhov length scale from measurements. The method used in this study is the bulk method, which uses the air temperature and wind speed at hub height and the sea surface temperature (SST) (the wind speed at sea surface is zero).

Under neutral conditions the air and sea surface temperatures are close together, which increases the uncertainty of the method. This drawback should be taken into account when using the method. During stable and unstable conditions the uncertainty in L reduces [11, 12].

Sathe [12] states that the bulk method is considered to be the most accurate method to determine atmospheric stability, and this is confirmed by Nielsen Nissen [13, 14]. The method has a higher accuracy because it uses the SST, which varies more slowly than the ambient temperature. This adds a certain damping to the stability determination, which makes the bulk method more robust than other methods.

There is currently no firm criterion to define the limits of L of the stability classes. They are only based on previous research experience [15]. As a result, different stability classifications exist in literature. The classification used in the present study is shown in table 1. (Near-)neutral conditions are more common during high wind speeds and correspond to high absolute values of L [12, 16]. Lower wind speeds correspond to lower absolute values, and can either be stable ($L > 0$) or unstable ($L < 0$), depending on the temperature gradient.

3. Data

Two offshore wind farms have been investigated in this project, see figure 1. The first is Egmond aan Zee (OWEZ, The Netherlands) consisting of 36 Vestas V90-3.0MW turbines. The second is North Hoyle (UK) which consists of 30 Vestas V80-2.0MW turbines. The hub height is 70m at both sites. Meteorological measurements are available at both sites from a meteorological measurement tower (metmast). Metmast data at OWEZ is available from 1 July 2005 to 30 November 2008 and production data from 1 September 2006. Metmast data at North Hoyle is available from 14 September 2007 to 31 December 2011 and production data from 11 June 2008. The measurements are stored as 10-minute average values.

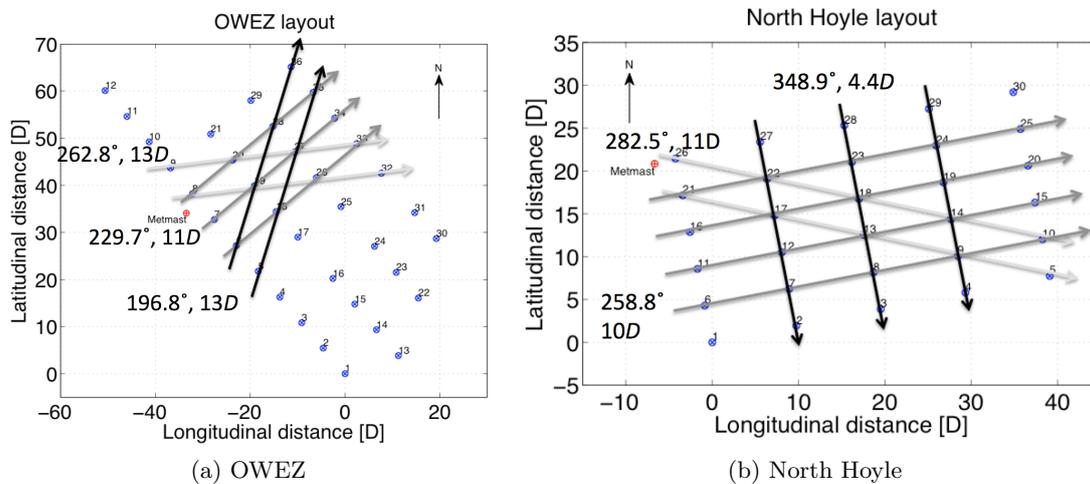


Figure 1: Layout of the two wind farms and rows of turbines used for wake loss investigation, including wind direction and downstream distance between turbines (in rotor diameters, D).

Filters are applied to the data to exclude erroneous and disturbed data. Incorrect or missing values are indicated in the metmast and turbine data by an error code, and hence can be discarded. The values are checked to be in certain validity ranges regarding wind speed and direction, temperature, pressure and power output. Other filters make sure that the turbine and generator were running for the complete 10-minute measurement period, that there was no alarm, no servicing going on and that the turbine was not de-rated. Wind directions for which the metmast is disturbed by the wind farm wake are excluded. For OWEZ this is the wind direction sector from 310° to 150° , for North Hoyle this is 40° to 170° . A small percentage of measurements cannot be used, as they fall outside the validity range of the stability equation. Finally, a 10-minute period should have both turbine and metmast data available, which further reduces the amount of usable data. The amount of filtered data remaining for the wake loss investigation is 26865 10-minute measurement periods for OWEZ and 62206 for North Hoyle.

All wind speed measurements have been normalized according to the IEC-61400-12-1 regulations for power performance of electricity producing wind turbines [17].

4. Results

The atmospheric stability distributions, wake losses and wind farm efficiencies are shown and discussed in this section.

4.1. Atmospheric stability

Atmospheric stability at both sites is shown in figure 2. It can be seen that there is a large number of (very) unstable cases occurring at North Hoyle as compared to the number of (very) stable cases. The very unstable cases mostly occur at low and medium wind speeds (up to about 16 m/s). Compared with the results at OWEZ, a larger number of very stable cases exists at North Hoyle and these occur up to higher wind speeds. It is also observed that North Hoyle has a larger number of (very) unstable cases than OWEZ. The results at OWEZ are similar to those observed in [15]. Variation of atmospheric stability on an hourly and a monthly scale is observed, but the graphs are not shown here. The variation is related to the variation of the temperature difference between air and sea surface.

Figure 3 shows the variation of temperature gradient and turbulence intensity (TI) with

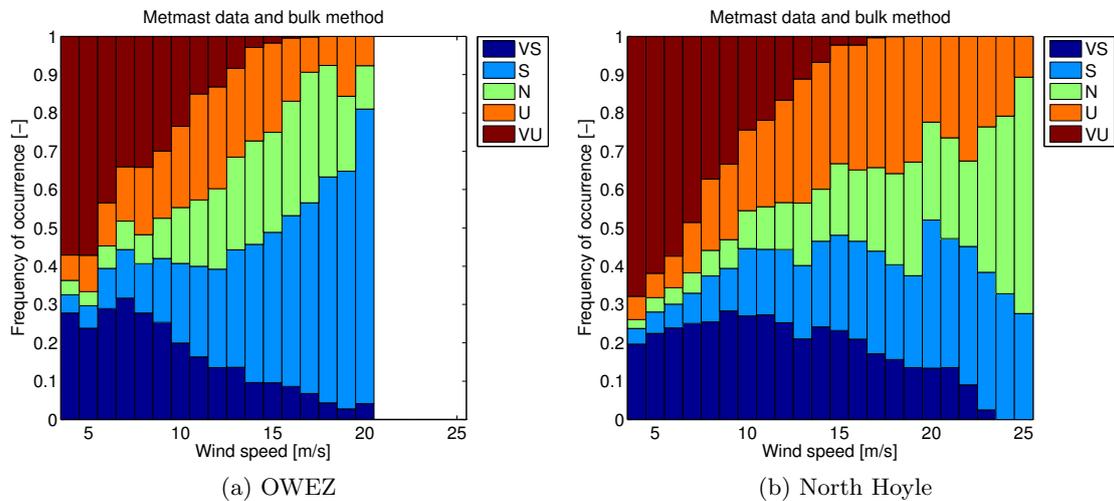


Figure 2: Distribution of stability classes versus wind speed at OWEZ and North Hoyle. Wind speeds above 20 m/s have been excluded at OWEZ due to low data availability (i.e. less than 0.1% of total amount of data per bin). VS = very stable, S = stable, N = neutral, U = unstable, VU = very unstable.

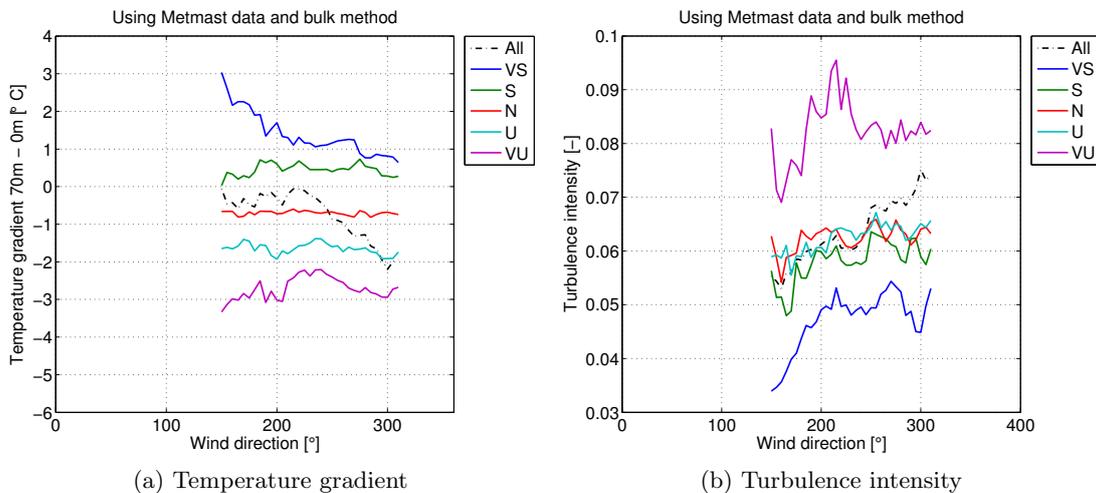


Figure 3: Variation with atmospheric stability for various input parameters at OWEZ over the investigated wind directions. VS = very stable, S = stable, N = neutral, U = unstable, VU = very unstable.

atmospheric stability at OWEZ. The (very) unstable classes have a negative temperature gradient (SST is larger than ambient temperature), whereas the (very) stable classes correspond to a positive gradient. For TI, there is a clear difference between the very unstable class (larger TI) and very stable class (smaller TI). The near-neutral classes show a TI in between these two and are close together. The variation in TI suggests that there will be a difference in wake loss recovery in the wind farm between the very stable, near-neutral and very unstable classes.

Data from the Vestas mesoscale model is compared to the metmast data and it is found that the stability distributions are similar. The mesoscale data can be used as input to simulate

the turbine production, but the mesoscale wind speed and wind direction can not replace the measured data when investigating the measured wake losses.

4.2. Wake losses

The effect of the atmospheric stability on the wake losses can be investigated by combining the stability classification of each 10-minute period with the power production of the turbines. This is done for rows of downstream turbines. The data is filtered to find those 10-minute periods where all turbines of a row are operating at the same time. The investigation is performed for various row directions (and hence downstream distances between the turbines).

Wake losses in a wind farm are largest for wind directions parallel to the downstream direction of the row of turbines. Therefore a narrow wind direction sector of $\pm 2.5^\circ$ around each row direction is used. A wind speed bin of 8.0 ± 0.5 m/s is used, as this is close to the mean wind speed, but the turbines have not started pitching their blades yet. Only the inner rows are investigated for their wake losses as these losses are largest inside the wind farm.

Wake loss results are shown in figure 4 for two of the investigated cases. For these specific two cases, 109 10-minute measurement periods are used at OWEZ and 136 at North Hoyle. The small wind speed and wind direction bins in combination with the requirement to have all turbines in the row simultaneously operating leads to a strong reduction in the number of usable measurements, but the number is still considered to be large enough to give meaningful results.

From the five stability classes defined in table 1, the stable, neutral and unstable classes have been taken together as a near-neutral class, to have more measurements per class. During the analysis it was found that wake loss data can be obtained more accurately when using the wind speed and wind direction measurements of the turbines in the first column (i.e. in the free-stream), instead of those from the metmast. This is applied for North Hoyle. The turbine wind directions are not available at OWEZ, so the metmast is used instead.

Figure 4 shows the power output for each turbine in the row, normalized with respect to the first turbine in the row. The power decreases for turbines further downstream, although the largest wake loss occurs when going from the first to the second turbine in the row. At both sites, the difference between each stability class is clear. For all the investigated cases, the power production is higher in the very unstable class than in the near-neutral class, and higher in the near-neutral class than in the very stable class. Wake losses are thus smaller under more unstable conditions. This can be explained by noting that under more unstable conditions the wake recovery is larger, due to the increased turbulence intensity. The results of the wake losses are summarized in table 2. The differences between the very stable and very unstable conditions in terms of normalized power production are observed to be in the order of 10-20%. These results agree with those found at offshore wind farms Horns Rev [4, 18] and Nysted [3, 4].

A few things attract the attention. There is an increase in power for the fourth turbine in the rows at OWEZ, meaning that the turbines have a higher energy inflow. This may be because the wind direction for all turbines in the rows at OWEZ has been taken from the metmast, so the wind might not be exactly down the row of turbines. At North Hoyle this problem does not occur, as the wind direction is taken from the average of the first turbines in the row. A second observation is that the power output of the shown case from North Hoyle is lower than at OWEZ. This is due to the influence of the wind turbine spacing. At this particular wind direction at North Hoyle, the spacing is only $4.4D$, resulting in a high wake loss from the first to the second turbine, a small recovery towards the third turbine, after which the wake loss converges. Overall, it is hard to make a general statement about the standard deviation, which may be due to the limited amount of measurements used for each case.

From the analysis it is found that the temperature difference between the sea surface and the air has the largest influence on the stability classification. Furthermore, it is found that narrow ranges of temperature difference exist for the near-neutral classes. A measurement offset might

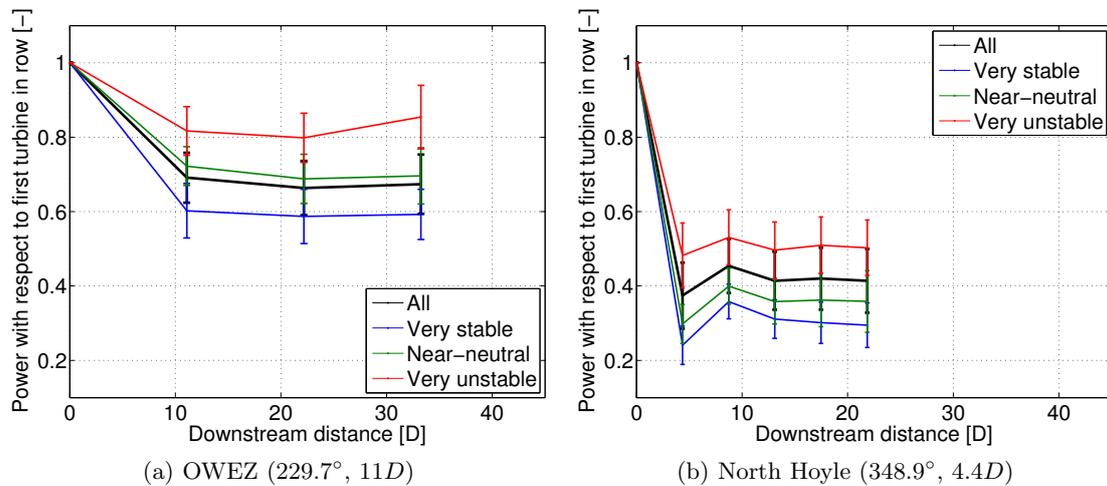


Figure 4: Wake losses at a) OWEZ and b) North Hoyle at wind speed 8.0 ± 0.5 m/s. The error bars represent one standard deviation (half above and half below the mean value).

Table 2: Relative production of the second turbine (i.e. first turbine in the wake) with respect to free-stream turbine as obtained from measurements.

	OWEZ	North Hoyle	North Hoyle
Distance	11-13D	4.4D	10-11D
Very unstable ($-200 < L < 0$)	80% ^a	50% ^a	75-80% ^c
Very stable ($0 < L < 200$)	60-70% ^a	25% ^b	70% ^c

^a Similar production for turbines further downstream.

^b The third turbine has 35% while the turbines further downstream all have around 30% relative production.

^c The turbines further downstream lose 5% normalized production compared to the previous turbine. The loss becomes less for turbines further downstream and is about 1-2% at the last turbine.

therefore result in cases being classified as another stability class than what actually occurred during the measurement. It is therefore important to measure the temperatures accurately. By taking the stable, neutral and unstable class together, part of this sensitivity is mitigated.

4.3. Wake losses simulated with WindPRO

The wind farms have been modelled in WindPRO and power output has been simulated using the Jensen wake model. The wake losses in the model are governed by the wake decay constant (WDC) k . At a downstream distance x , the width of the rectangular wake equals $D + 2kx$ and the wake speed is found by conservation of the velocity deficit. The recommended WDC value is $k \approx 0.5TI$, where TI is the turbulence intensity. For offshore, the recommended WDC is $k = 0.04$. It is found that the recommended WDC underpredicts the production.

The Jensen wake model does not take into account the effect of atmospheric stability on the production by default. Since turbulence in a wind farm is related to the atmospheric stability, and since the WDC is related to the amount of turbulence, the effect of the atmospheric stability on the predicted production can be taken into account by adapting the WDC. Comparing the

Table 3: Mean TI values [-] measured per wind direction and stability class, corresponding to the 10-minute periods used in the wake loss plots, and WDC [-] giving similar simulated wake losses. Note: Wind direction 196.8° at OWEZ has been excluded due to low data availability.

	OWEZ				North Hoyle						
	229.7° (11D)	262.8° (13D)	348.9° (4.4D)	258.8° (10D)	282.5° (11D)	TI	WDC	TI	WDC	TI	WDC
Very unstable	0.075	0.14	0.077	0.11	0.085	0.11-0.12	0.083	0.08-0.09	0.070	0.07	
Very stable	0.048	0.05	0.049	0.05	0.062	0.07-0.08	0.067	0.06-0.07	0.056	0.05-0.07	

measurements with the model is therefore done by adapting the WDC and investigating for which WDC the measured and predicted wake losses agree best.

It is found that the WDC should be equal to or greater than the TI. The very stable cases require a WDC in the order of their TI. For the very unstable class the results vary between the two wind farms. The WDC value is about 1.5-1.9 times the mean TI value at OWEZ, whereas at North Hoyle the WDC and TI values are about equal for the larger turbine spacings. For the small spacing at North Hoyle (4.4D) the WDC values are higher. In all cases the WDC value should be higher for the very unstable class than for the very stable class. The results are summarized in table 3.

Simulating the wind farm efficiency at North Hoyle shows that similar WDC values can be used for the whole wind farm as those observed in the wake loss analysis in a row of turbines. The WDC is about 0.08 for the very stable class and 0.13 for the very unstable class. The results are less clear for OWEZ, which is thought to result from the small amount of data available.

4.4. Wind farm power output

A method to obtain the total wind farm efficiency could be to multiply the simulated wind farm efficiencies of the very stable and very unstable class with their frequency of occurrence. Summing these weighted efficiencies should give an approximate wind farm efficiency close to that of the complete wind farm for all stability classes. It is expected that the approximation improves upon including the near-neutral class. However, the most important factor is getting the WDC right, as it will influence the wind farm efficiency obtained from WindPRO.

5. Conclusions

The research questions posed in the introduction can now be answered.

Atmospheric stability influences the power production by influencing the amount of wake loss recovery through the turbulence intensity. The production of the wind farm is higher under very unstable conditions (i.e. smaller wake losses exist) than under near-neutral conditions, and higher under near-neutral conditions than under very stable conditions. The difference between very unstable and very stable conditions is in the order of 10-20% of normalized power production. A second order effect due to atmospheric stability exists, which is likely attributed to the change in vertical turbulence or turbulent length scale.

The conventional WindPRO simulations using an offshore WDC of 0.04 underpredict the power production, since the Jensen wake model does not take the atmospheric stability into account. A simple improvement is to adapt the WDC to account for the effect of atmospheric stability. The WDC should be higher for the very unstable class than for the very stable class. Observed WDC values are $k \geq TI$, as opposed to the conventional $k \approx 0.5TI$.

Note that results are for offshore wind farms. Onshore there will be a higher level of ambient turbulence in the wind farm and hence the effect of atmospheric stability is less pronounced.

6. Recommendations

It is important to measure temperature accurately, as narrow temperature ranges exist for the near-neutral stability classes (i.e. for neutral stability this range is only $0.2K$ wide).

The influence of vertical turbulence on total turbulence intensity should be investigated. The TI and WDC are observed to be closely related, but where they are approximately the same for the very stable classes, the TI is smaller than the WDC for very unstable classes. TI is measured horizontally (i.e. two-dimensional), but under unstable conditions vertical turbulence is most probably present as well, due to the temperature gradient. It would be interesting to see how the WDC and TI compare when the vertical turbulence is also included in the TI. Not much difference in TI is expected for the very stable class, as turbulent movements are suppressed. For the very unstable class the TI is expected to increase. The TI and WDC values may therefore become more similar for the very unstable class. This would mean that the WDC value to be chosen for a certain stability class should be close to the (three-dimensional) TI corresponding to that class. Further research is necessary to look into this hypothesis. In case a relationship between WDC and TI is found (and since TI varies with atmospheric stability), the WDC can be based on (three-dimensional) TI, and the atmospheric stability classification is not necessary anymore (Wharton & Lundquist [9, 19] already found that three-dimensional turbulent kinetic energy compares well with the Monin-Obukhov length). Next to vertical turbulence, the turbulent length scale may be another secondary influence on wake loss recovery, as the length scale (and hence wake meandering) is larger for more unstable conditions.

Similar research should be performed at other wind speeds and other wind farms to confirm the results found in this project.

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