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Analysis of the reduced wake effect for available wind power calculation during curtailment

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Abstract. With the increase of installed wind power capacity, the contribution of wind power curtailment to power balancing becomes more relevant. Determining the available power during curtailment at the wind farm level is not trivial, as curtailment changes the wake effects in a wind farm. Current best practice to estimate the available power is to sum the available power calculated by every wind turbine. However, during curtailment the changed local wind conditions at the wind turbines lead to inaccurate results at the wind farm level. This paper presents an algorithm to determine the available power of a wind farm during curtailment. Moreover, results of curtailment experiments are discussed that were performed on nearshore wind farm Westermeerwind to validate the algorithm. For the case where a single turbine is being curtailed, it is shown that the algorithm reduces the estimation error for the first downstream turbine significantly. Further development of the algorithm is required for accurate estimation of the second turbine. All further downstream turbines did not experience a change in wake conditions.

1. Introduction

The electricity market is currently experiencing a paradigm shift from a market dominated by generators running on fossil fuels, towards a more varied market with multiple renewable power sources. Wind power plays an important role in this transition. Notwithstanding the benefits of wind power, the transition also poses new challenges concerning the power balance in the electrical system. These challenges are mostly related to the variability and partial unpredictability of wind power. [1] This makes it difficult for the power supply to follow the demand, both on the short-term and long-term. From the two cases of power imbalances that can be identified — either the supply being higher than the demand, or vice versa — this research considers a surplus of power production. A method of mitigating this surplus is to (temporarily) reduce the power production.

It is important to continuously determine how much power is being curtailed, to allow settlement of the curtailed energy afterwards and to optimise the amount of curtailed power that provides a buffer for peaks in the demand. In order to calculate the curtailed energy ($E_{curtailed}$) during a certain period (T), equation 1 can be used.

$$E_{curtailed} = \int_T (P_{available}(t) - P_{produced}(t)) dt \quad (1)$$



The actual power produced ($P_{produced}$) is measured directly. For conventional power systems the maximum available power ($P_{available}$) is equal to the nominal capacity. However, for wind farms determining the available power is not trivial.

The available power of a wind farm depends on the installed capacity, the availability of each wind turbine and the wind conditions. The latter determines the production of upstream turbines directly, but also influences the wake development behind those turbines. This in turn, influences the power production of downstream turbines in the wind farm. During curtailment, less power is extracted from the wind and thus the wake effects are reduced. This leads to a wind speed increase at the downstream turbine and therefore to an apparent increase of its available power. [2] [3] This phenomenon is referred to as the *reduced wake effect*. Summing the individual available power estimations of all turbines, will therefore lead to an overestimation of the total wind farm available power during curtailment. However, this is currently the industry's best practice.

This paper presents and validates an algorithm to determine the available wind power of a wind farm during curtailment. For the validation, wind turbines in the nearshore wind farm Westermeerwind have been curtailed to measure the reduced wake effect and determine the reduction of the error of the algorithm with respect to the error of the current best practice. Westermeerwind is located in the middle of The Netherlands and operated by Ventolines BV.

2. The algorithm

The algorithm has two requirements: 1) deliver more accurate results than the current best practice and 2) be fast, allowing direct estimation of available power and settlement shortly after curtailment. Due to the validation study of Westermeerwind, the implementation of the algorithm could only use data signals from the turbines, so no data from external meteorological instruments were included, besides an air density correction.

2.1. Selection of wake models

In order to quantify the difference in wake losses during the normal and curtailed operation modes, proven wake models are used. Models that require computational fluid dynamics are excluded, as they are too computationally expensive. For this research, only the kinematic Jensen [4] and Larsen [5] wake models are considered. These wake models are quick to evaluate, but also yield a less accurate physical representation of the wake. It is part of this research to find if these wake models are useful for the determination of the available power. For the Jensen wake model the wake decay parameter is defined as in equation 2 [2], where TI refers to the local turbulence intensity measured at each turbine. Using the local turbulence intensity resulted in better estimations than using a single value for the entire wind farm. These two wake models were selected for their robustness, widely available validation studies in literature, and simple implementation.

$$k = 0.4 \cdot TI \quad (2)$$

2.2. Modelling of wakes during curtailment

The mentioned wake models are designed for the evaluation of the wind speed deficit at a certain position behind a single turbine. The boundary conditions for the application of the wake models are determined by the turbine state. Under curtailment this state is different from normal operation. Therefore, the changed state needs to be modelled to obtain the correct inputs for the wake models. This will be called the *curtailment model* and together with the thrust curve, the wake model and a method of mixing multiple wakes, it forms the *wake – curtailment model*, see figure 1. This model allows the calculation of the wind speed deficit at each turbine taking into account the curtailment of each turbine.

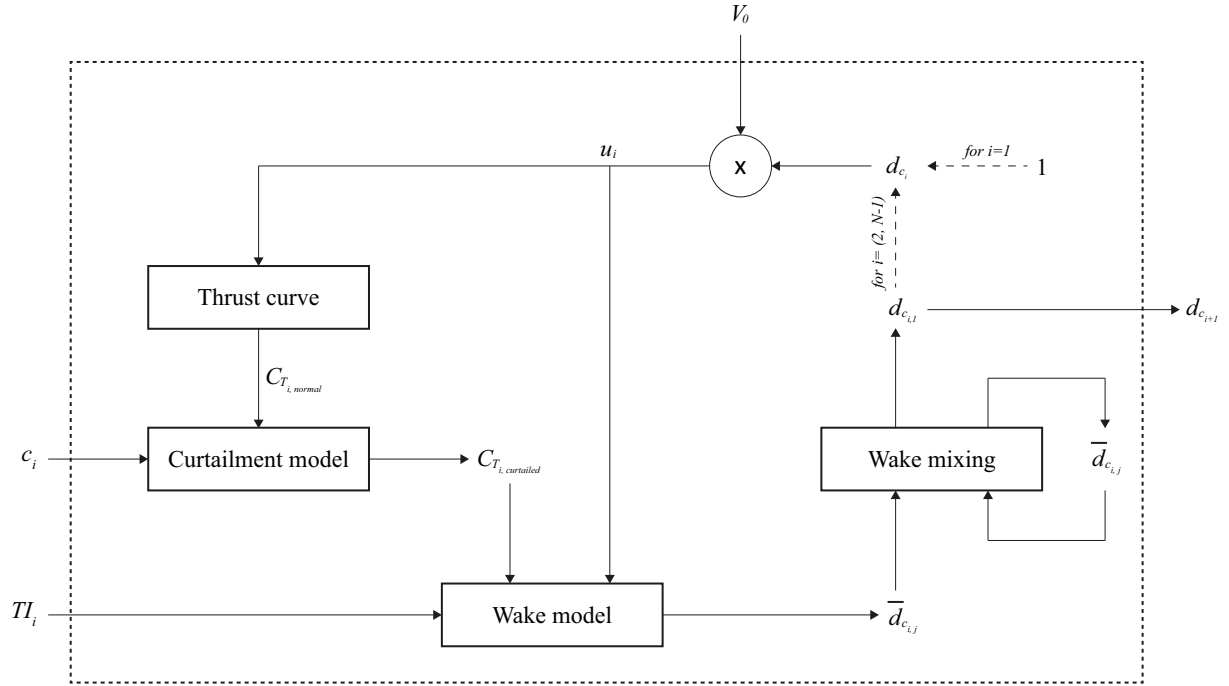


Figure 1. Flowchart of the wake – curtailment model, which calculates the wind speed deficit at each wind turbine taking into account the curtailment of each turbine, see table 1 for the description of each symbol.

Symbol	Description
$C_{T_{i,normal}}$	The thrust coefficient of turbine i if the turbine would not curtail its power
$C_{T_{i,curtailed}}$	The thrust coefficient of turbine i including curtailment
c_i	Curtailment factor of turbine i
$d_{c,i}$	Wind speed deficit at turbine i during curtailment
$\bar{d}_{c,i,j}$	Vector of wind speed deficits at downstream turbines j due to turbine i only
$d_{c,i,1}$	The wind speed deficit at the turbine directly downstream of turbine i
j	A turbine downstream of turbine i , i.e. $j \in (i + 1, N)$
N	Number of turbines
TI_i	Turbulence intensity at turbine i
u_i	Wind speed at turbine i
V_0	Free stream wind speed

Table 1. Symbol descriptions of figure 1

2.2.1. Curtailment model. Both wake models require the thrust coefficient of the turbine as an input parameter. The implementation of the curtailment model depends on the selected turbine and available data. For this research curtailed thrust coefficient curves were available for different curtailment factors $c_i = 0.1, 0.2, \dots, 0.9$. For the applicable wind speed, the thrust coefficient as a function of curtailment factor is linearly interpolated with the actual curtailment factor (equation 3), which is the ratio between the measured power production and the estimated available power.

$$c_i = 1 - \frac{\hat{P}_{c_i}}{P_{APE_i}} \quad (3)$$

2.2.2. Wake mixing. Some turbines are positioned inside the wakes of multiple turbines. In order to determine the total wind speed deficit at those turbines, the total effective wake deficit is calculated using the root mean square method, see equation 4 where d_j refers to the wake deficit due to the operation of upstream turbine j .

$$d_{total} = 1 - \sqrt{\left(\sum_j (1 - d_j)^2\right)} \quad (4)$$

2.2.3. Partial wake incidence. Considering the layout of Westermeerwind, see figure 3, it was possible to consider straight rows of turbines. Validation was performed for the wind direction aligned with these rows. Implementation of rotor averaging for partial wakes was therefore not required. It is noted that in order to evaluate the Larsen wake model, the equations were discretized over the rotor radius with 100 sections. This is necessary as in the Larsen wake model the wind speed deficit varies over the rotor area of the turbine.

2.3. Full algorithm

Besides the wake – curtailment model, there are more modules in the algorithm, as can be seen in figure 2. Part 1 of the algorithm is evaluated twice: once where the inputs of the wake models are set to the values in normal operation, and once with the curtailed equivalents.

2.3.1. Turbulence model. Both the Jensen and the Larsen model for wind speed deficit depend on turbulence intensity (see e.g. equation 2). During curtailment, the hypothetical turbulence intensity that would exist without curtailment is not known and needs to be modelled. In this research the turbulence intensity is measured just before and just after curtailment and these values are used as the hypothetical turbulence intensity that would need to be modelled during curtailment. Such measurements without curtailment are only representative for the hypothetical turbulence intensity during curtailment periods, if they are taken not too long before or after the curtailed operation. During continuous curtailment, such measurements would not be available.

2.3.2. Reduced wake effect. The reduced wake effect is the difference between the power of a turbine in the wake of a curtailed turbine and the power it would have if the upstream turbine was not curtailed. This effect is the result of the increased wind speed at the downstream turbines, due to the curtailment of upstream turbines, effectively reducing the wake loss. It is calculated as the difference between the modelled power for curtailed condition (P_{c_i}) and the power for the modelled normal condition (P_i).

2.3.3. Available power estimator. The available power estimator determines the available power at a single turbine during curtailment for the local wind conditions. The methodology generally uses a combination of the pitch-power curve and rotational speed - power curve. [6] For this research the turbines were provided with an available power estimator by the manufacturer.

2.3.4. Available wind farm power The total available power of the wind farm equals the sum of the individual available power signals minus the reduced wake effects of each turbine, see equation 5.

$$P_{AWF} = \sum_{i=1}^N (P_{APE_i} - \Delta P_{rw_i}) \quad (5)$$

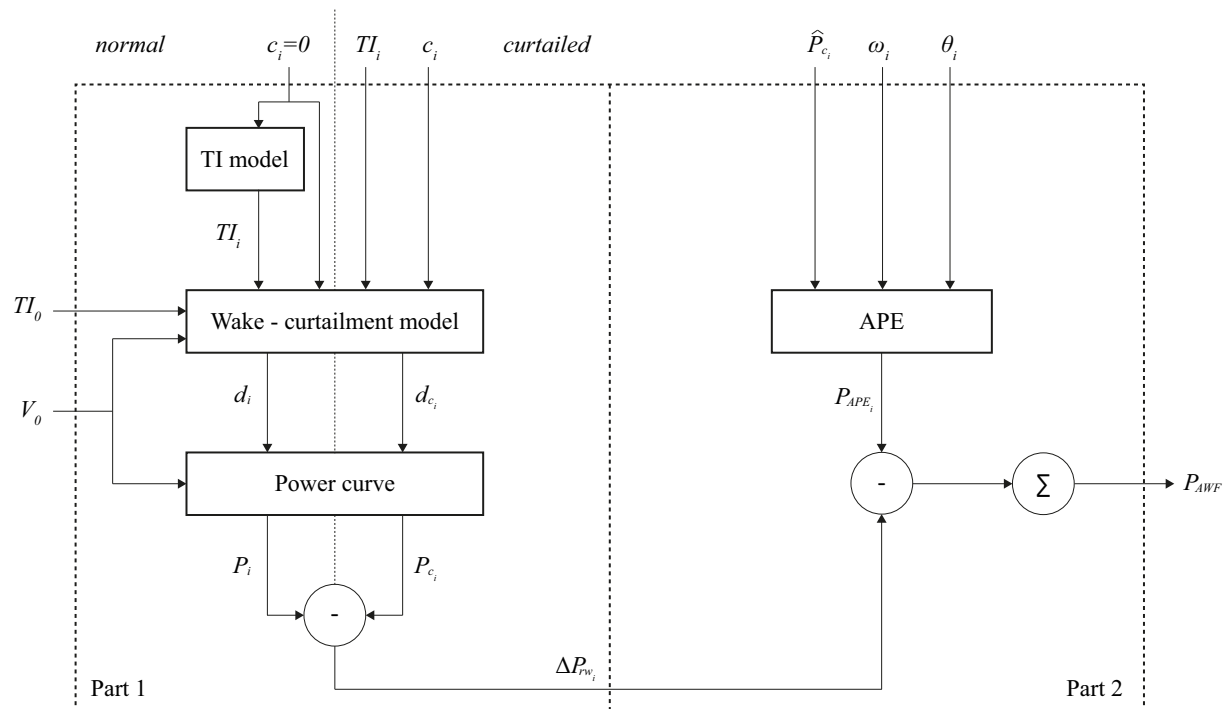


Figure 2. Flowchart of the algorithm, see table 2 for description of each symbol in addition to table 1.

Symbol	Description
θ_i	Blade pitch angle of turbine i
ω_i	Rotational speed of turbine i
APE	Available power estimator
d_i	Wind speed deficit at turbine i in normal operation mode
ΔP_{rwi}	Reduced power loss of turbine i due to wake reduction
P_{AWF}	Available wind farm power, including the reduced wake effect
P_{APE_i}	Estimated available power of turbine i , excluding the reduced wake effect
P_i	Modelled power production of turbine i in normal operation
P_{c_i}	Modelled power production of turbine i during curtailment
$\hat{P}_{c_i}$	Measured power production of turbine i during curtailment
TI_0	Free stream turbulence intensity

Table 2. Symbol descriptions of figure 2 in addition to table 1

2.4. Uncertainties of the algorithm

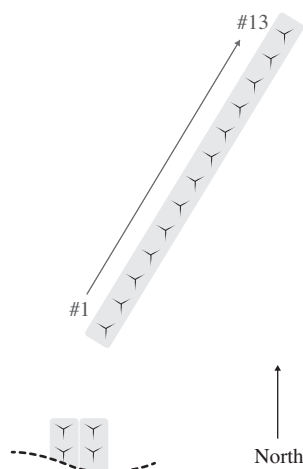
The main uncertainties of the algorithm are 1) the wake models; 2) using the wake models instantaneously; 3) applying the wake models during curtailment and 4) using the power curve instantaneously. Most validation studies available in literature test wake models for large time spans and on a 10-minute average basis. It is unknown if the wake models are able to produce valid results instantaneously during curtailment. The power curves provided by the turbine manufacturers are generally only guaranteed for 10-minute periods too. The preliminary validation of this study will indicate the combined effect of these uncertainties on the overall performance of the algorithm.

3. Experimental methodology

In order to validate the presented algorithm, curtailment experiments have been performed on wind farm Westermeerwind.

3.1. Wind farm Westermeerwind

The nearshore Westermeerwind project in the Netherlands consists of 48 3.0-108 MW wind turbines from Siemens Wind Power. The layout consists of three straight rows of turbines of which only the northern row is used in the experiment, see figure 3. This row contains thirteen turbines, and is 30 deg inclined with respect to North. Just south from the turbines of interest, the other rows of turbines are located. The relevant turbine specifications can be found in table 3. The turbines are spaced 520m apart, which equals 4.8 times the rotor diameter.



SWT 3.0 MW D3-10	
Rated power	3MW
Cut-in wind speed	$3 \frac{m}{s}$
Cut-out wind speed	$25 \frac{m}{s}$
Rated wind speed	$12 \frac{m}{s}$
Rotor diameter	108m
Hub height	95m

Figure 3. Layout wind farm Westermeerwind

Table 3. Wind turbine specifications [7]

3.2. Curtailment experiments

In the experiments turbine #1 from figure 3 is being curtailed by pitch control. In each experiment a different power production limit is set, resulting in different curtailment factors. Between each consecutive experiment, a reference period without curtailment is reserved, to reacquire the normal wind conditions at each turbine. Both the curtailment experiment and the reference period had a duration of four minutes.

3.3. Using wind speed data

The accuracy of the sonic wind speed sensor, placed on top of the nacelle behind the rotor, proved to be too low for power calculations as the documentation states a maximum error of 5%. Therefore it was decided to use the power production measurements — with a maximum error of 0.2% — together with the power curve to determine wind speed. This resulted in much more consistent wind speed calculations between turbines. However, this does limit the maximum allowable wind speed for the validation to the rated wind speed.

However the sonic sensor is used to determine the turbulence intensity, as it does provide a good indication of the short-term fluctuation of wind speed. In order to determine the free stream wind conditions for the wake models the data signals of turbine #1 are used. A density correction is applied to adjust for temperature, pressure and humidity changes between the power curve specifications and the conditions during the experiments.

3.4. Time delay

In order to compare the wind speeds of different turbines, the time delay for wind conditions to travel over the wind farm needs to be accounted for. Gebraad et al. [8] achieved good results using the mean of the wind speed behind the first turbine based on the actuator disk theory and the wind speed at the direct downstream turbine (u_{i+1}), see equation 6. Note that the distance between turbines (Δx) is 520m for this research. It was found that this methodology yields good results in this research as well, using a fixed induction factor of $\frac{1}{3}$.

$$t_{delay} = \frac{\Delta x}{\frac{1}{2}(u_i(1 - 2a_i) + u_{i+1})} \quad (6)$$

3.5. Stability criteria experiments

The results from the curtailment experiments are only relevant when the environmental conditions do not change significantly during the experiment. The following criteria were set to ensure meaningful results:

- (i) The wind speed cannot reduce to a point where less than 200kW is being curtailed.
- (ii) The wind direction cannot change to the extend of modifying the wake profile of the turbines. Due to the absence of high quality wind direction data, this criterion was monitored manually by observing the nacelle directions and wind speed deficits.
- (iii) None of the turbines can operate above rated power.

4. Experimental results

Applying the stability criteria lead to five accepted experiments out of more than twenty performed experiments. This shows that the reduced wake effect is only measurable under specific stable wind conditions. See table 4 for an overview of the experiments, where $P_{1normal}$ and $P_{1curtailed}$ refer to the power of turbine #1 in the reference period and during the experiment.

Experiment	$V_0[\frac{m}{s}]$	$P_{1normal}[kW]$	$P_{1curtailed}[kW]$	<i>curtailment</i>
1	8.9	1,700	700	60%
2	8.8	1,700	500	70%
3	8.4	1,400	800	40%
4	7.8	1,100	600	45%
5	10.3	2,600	1,200	55%

Table 4. Overview accepted experiments

Figure 4 provides an overview of the experiments by showing the difference between mean power produced during the experiment and the reference period. When curtailing the leading turbine, the second turbine experiences an increase in power production due to the reduced wake effect; the third turbine has a decrease in power production smaller than that increase and all further downstream turbines have no significant change in power production. This confirms the premises of this research and the findings of Göçmen et al. [2], that it is important to estimate the changes in wake losses during curtailment. In general it was found that the accumulated effect of the curtailment of turbine #1 on the row of turbines, is a net decrease of power in the range of 0% to 60% of the power curtailed by the turbine #1.

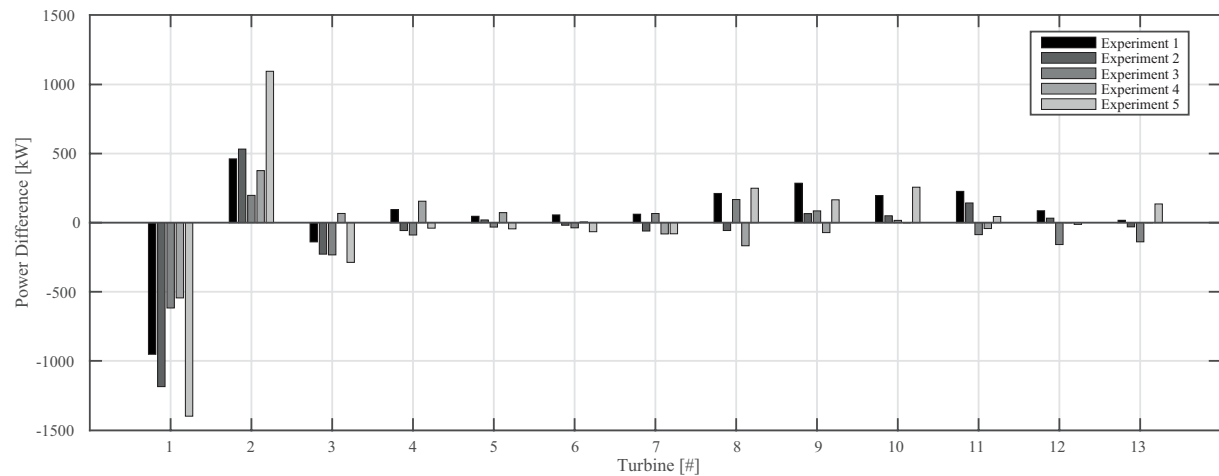


Figure 4. Mean power difference between normal and curtailed operation. The bars of turbine #1 indicate the curtailed power, whereas the bars for turbine #2 show the reduced wake effect.

4.1. Results algorithm validation turbine #2

Figure 5 shows the algorithm applied using the measurements of experiment 1, which is a typical result. First, a reference period can be seen without curtailment. Then, turbine #1 is curtailed to 700kW. Finally, turbine #1 returns to the normal operation state for a second reference period.

The second solid curve indicates the power estimation for turbine #2 during curtailment and allows validation of the wake model. The estimations of the two wake models have a maximum error of 300kW on average. The reduced wake effect during curtailment is modelled with a similar accuracy.

The dashed curves in figure 5 for the models indicate the power production estimations as it would be without curtailment, i.e. the hypothetical normal operation. These estimations look reasonable as well, as they stay between the situations in the reference periods. Together with the solid curves, they allow validation of the performance of the algorithm to estimate the reduced wake effect.

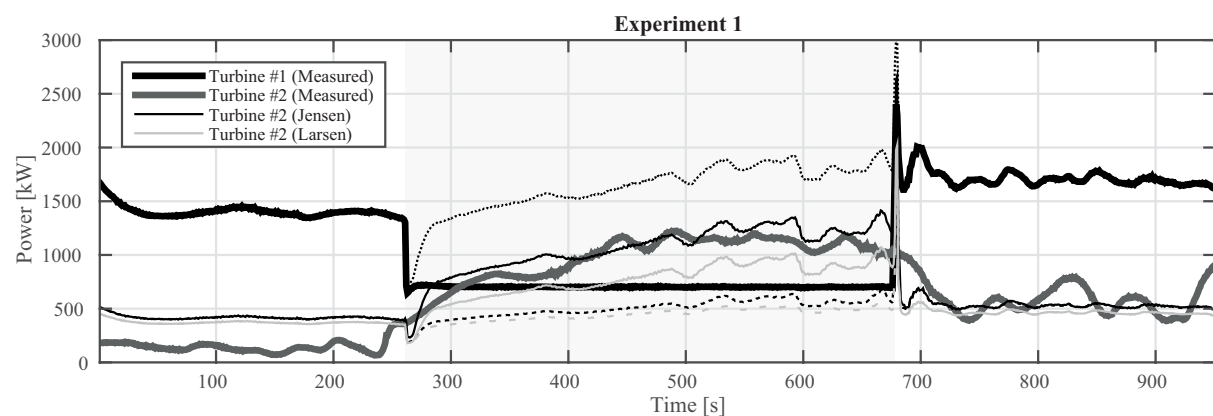


Figure 5. Power production signal of turbine #1 and #2. The dotted line of turbine #1 indicates the available power estimation. The dashed lines of the wake models indicate the estimated power production of turbine #2 if turbine #1 would not curtail its power.

In figure 6 the mean results of the algorithm with respect to the current best practice — summing the available power signals — and the measured available power during curtailment can be seen for turbine #2. The error of the approximation reduces from 60%–100% using the current best practice to 10%–40% for the algorithm with the Larsen wake model and to 1%–20% using the Jensen variant.

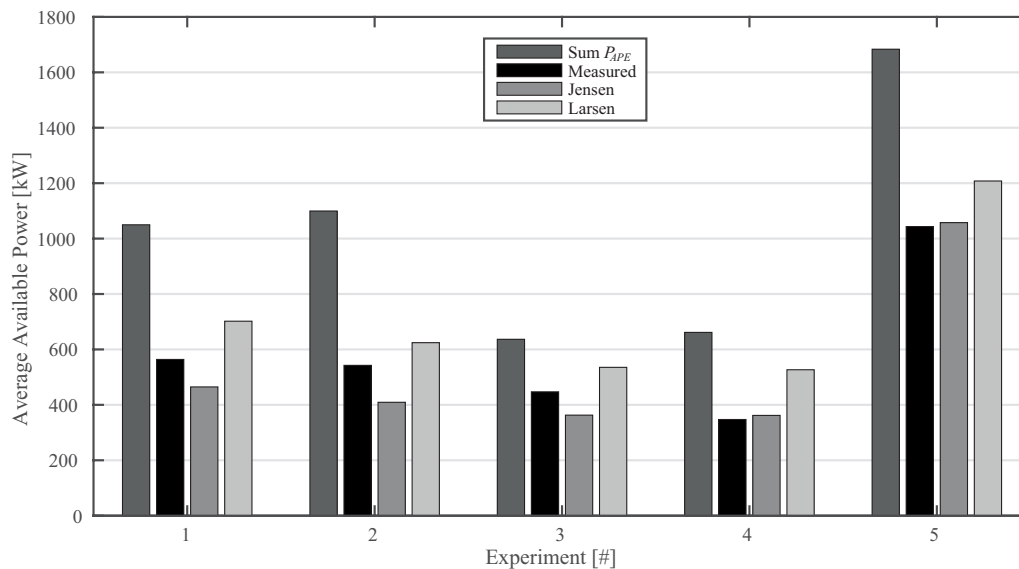


Figure 6. Average available power of turbine #2 for the current best practice; measured as the difference between normal and the reference period; using the algorithm with the two wake models.

4.2. Results algorithm validation turbine #3

For turbine #3 an increase of the wake loss is observed in figure 4. This can be explained by the fact that the wake development behind turbine #2 is increased, due to its increase in power production. The wake models were not able to accurately estimate the power at turbine #3 and further downstream for both normal and curtailed operation — the error was larger than 30% in most cases. The accuracy of the algorithm depends on the accuracy of wake model estimations for turbine #3 for both normal operation and during curtailment. Therefore, with the current implementation, it was not possible to accurately quantify the available power during curtailment for turbine #3.

5. Conclusion

Determining the available power of a wind farm during curtailed operation is complicated as the wake losses are different than during normal operation. In this paper an algorithm is presented and validated against measurement data of nearshore wind farm Westermeerwind.

It was found that using the Jensen and Larsen wake models instantaneously, instead of averaged over a longer period, still delivers accurate power predictions for turbine #2. The instantaneous use of the power curve in the algorithm was also found to be acceptable, despite the fact that it is defined for longer averaging periods. Finally, It was found that changing the thrust coefficient to model curtailment with the existing wake models proved accurate. This resulted in an improved estimation of the available power during curtailment for turbine #2, with an error reduction from 60%–100% using the current best practice to 10%–40% for the

algorithm with the Larsen wake model and to 1%–20% using the Jensen variant. For available power estimation of turbine #3 additional research is required.

There are still several steps to take to arrive at a full algorithm, but based on the findings it can be expected that the algorithm could be developed to correctly determine the available wind power for wind farms as a whole during curtailed operation of specific or all wind turbines.

6. Recommendations

In order to expand the validation of the algorithm as currently presented, the following recommendations are made:

- Perform curtailment experiments on wind farms with a layout different from a straight row.
- Perform curtailment experiments with multiple turbines under curtailment.
- Perform curtailment experiments above rated power. This will require a alternative method of determining the wind speed, as the power curve does not have a one-on-one relation above rated power.

In order to further develop the presented algorithm, the following recommendations are made:

- Validate the algorithm against simulations with computation fluid dynamics to reduce uncertainties regarding meteorological conditions, delay time, turbine characteristics, etc.
- Implement a turbulence model to model the turbulence intensity during the experiment as it would be without any curtailment.
- Add advanced wake phenomena like wake meandering and the wind shear.
- Test more wake models, like the wake models by Ainslie [9], Frandsen [10], Compagnolo et al. [11] and Bastankhah et al. [12].

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