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Study of Wake Effects for Offshore Wind Farm Planning

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Abstract—**The main task of a wind farm is to get as much energy as possible from the minimal number of wind turbines and with a minimal space between the turbines due to the economy of land in onshore and connections costs in offshore. However, minimization of the distance between single wind turbines within a wind farm causes an increase of the so called wake effect, which is introduced by the shadowing of some wind turbines by the other units within the farm and as a consequence causes a turbulent flow. This leads to the reduction of energy yield in the shadowed units. For the offshore wind farms which consist of 100 and more wind turbines is this effect especially significant.**

In this paper the aspects of wake effects will be discussed. In the first step the wake phenomena will be characterized and the analysis and comparison of the existing mathematical models for wake effects will be performed. Then, the planning tasks for wind farms with an incorporation of the wake model in order to maximize the energy yield, such as optimal farm configuration, will be discussed. The modeling of an exemplary wind farm for wake effect simulation will be described and some exemplary simulations will be performed in order to show the influence of wake effect on energy yield.

Keywords- wind energy; offshore wind farm; energy yield; wake effect.

I. INTRODUCTION

A lot of countries throughout the world are using their experience and scientific potential in order to develop renewable energy sources. The Kyoto Protocol (1997) on the reduction of green-house gas emissions favors clean and sustainable energy production.

Wind energy is becoming one of the most common and preferred renewable energy sources. It is a very perspective method of energy generation. All around the world new wind power supplies are being built, more powerful wind turbines are being developed, and a large number of wind turbines are being erected in wind farms for more energy production. In Germany alone there were more than 21.000 installed wind turbines with an overall capacity of more than 25 GW [6] at the end of 2009, while in Europe the overall installed wind capacity exceeded 74 GW at that time point with more than 2 GW of offshore wind farms [7].

Generally, wind is a phenomenon that is present everywhere. However, there are regions where wind potential is especially high, as for example the seashore. As known, the wind on the sea is stronger than on the land [12]. This is due to the fact that the water creates less friction to the air masses flowing over the sea-surface than the land. Sometimes the wind over a large water area is twice as strong as the wind at the same time on the nearest coast. In order to use this advantage there are excessive plans in the EU to utilize the offshore wind potentials and many new offshore wind farms are planned in the time horizon till 2020, the capacity of which may amount to 40 GW [1]. Europe has a perfect geographical position for a good offshore wind energy potential, especially in the North Sea, and there are already some offshore wind farms with a large capacity in Denmark and the UK, such as Horns Rev I with 160 MW and Horns Rev II with 209 MW of installed capacity [2], [3]. Moreover, some vendors have recently developed large wind turbines with a rated power of 5 MW for offshore wind farms in order to make the wind energy more highly acceptable and economic [4], [5].

Generally, in order to obtain higher energy production and optimize the investment costs regarding installation and interconnection efforts as well as in order to make maintenance more efficient many single wind turbines are organized into groups – the so called wind farms. During the wind farm planning process an important task is to minimize the area utilized by the planned wind farm. However, minimizing the area used for the wind farm for the specified number of wind turbines leads to decreasing the distances between individual wind turbines, which can influence the overall energy yield from the farm. This is caused by the so called wake effect, which is evoked in a wind farm due to the mutual shadowing phenomena and causes a decrease of the incoming wind speed to the wind turbines that are placed in the “wind shadow” of some other units. Therefore, assessment of this effect and incorporation into the planning process of the wind farm plays a crucial role in the first-phase evaluation of the expected energy yield. Especially from the economical point of view, neglecting the wake effect can lead to an overestimation of the energy production.

In this paper modeling of the wake effect for offshore wind farm planning will be discussed. The available models will be introduced and compared to each other. The influence of the wake effect on the energy yield will be shown on an exemplary simulation using a defined test system that is based on a real offshore wind farm.

II. WIND FARM PLANNING

Generally, wind farms can be directly planned in an optimal way taking into account the defined number of wind turbines as well as their rated power and then built up, whereas additional wind turbines can be added later to enlarge the farm, if necessary. Another possibility is a wind farm that originates from the proximity of different wind turbines that were built up separately one after the other in some time span without a super-ordinate planning process. In the first case the big advantage lies in the possibility of increasing the efficiency of power utilization by an appropriate planning procedure.

The efficiency of wind power utilization depends on many parameters, such as finite number of blades and due to this fact tip losses, non-zero aerodynamic resistance, positioning of wind turbines near another wind turbine (or a wind farm structure) because of turbulence rotation behind the wind turbine rotor. Therefore, during the wind farm planning various aspects have to be taken into account, e.g.:

- The optimal layout of the wind farm for maximization of energy yield and minimization of the area utilization;

- Characteristics of the wind turbines to be erected in the farm regarding their aerodynamic properties, e.g. thrust coefficient that is also responsible for interaction between wind turbines;

- Optimal integration into the environment in order to provide minimal influence on the nature and landscape;

- Optimal integration into the electrical power system (compliance with the Grid Code).

To support the first aspect consideration of the wake effect is necessary. For all types of wind farms the distance between the turbines have been carefully taken into consideration, while the main task of a wind farm is to get as much energy as possible from the minimal number of wind turbines and with a minimal space between the turbines due to the economy of land (and for providing the infrastructure requirements). However, minimization of the distance between single wind turbines within a wind farm causes an increase of the wake effect, which is introduced by the shadowing of some wind turbines by the other units in the wind farm and as a consequence causes a turbulent flow. This leads to the reduction of energy yield in the shadowed units.

III. WAKE EFFECT

A. *General Characteristics*

The wind turbines are becoming larger and larger. That is why it is very important to understand the aerodynamic nature and the properties of wake-effects, in order to calculate the optimal wind farm structure with new design models of wind turbines for providing the maximal energy yield. The correct study of the wake effect gives the possibility to control and adjust the shadowing of inner wind turbines, to decrease the wake and to increase the energy yield from the wind farm. Also it would be possible to find the optimal arrangement of wind turbines in the wind farm and to improve the financing cost reduction.

This effect is especially significant for the offshore wind farms which consist of 100 or more wind turbines. The lower ambient turbulence offshore is responsible for the wind speed in the wake recovering to the initial value more slowly than an onshore wind farm.

Wind turbines extract energy from wind and reduce the wind speed behind the rotor and swirl the air flow. If wind turbines worked in the same air flow direction, the second turbine would receive a reduced wind speed and would not optimally run because of the incoming wind turbulences caused by the first turbine. The spreading of the wake is also called wake effect and is one of the most important impacts of neighboring wind turbines that influences the electrical energy production. The maximal power output of the wind farm cannot be reached due to the described effects and should be considered for the design of the entire farm referring to the distances between the wind turbines.

The air flow that comes from one wind turbine to the next wind turbine is reduced and becomes turbulent. So the wind turbine positioned behind the first wind turbine gets the reduced and whirled air flow and, as a result, produces less energy. The phenomenon of shadowing is called wake-effect or array-effect. Such a factor is an extremely important parameter, while it could significantly influence the total energy yield, and it leads to the variable wind loads and vibration induced fatigue on the rotors and even the short circuit at the nearby power lines when they oscillate (swing) in opposite directions.

The structure of wake rotation is presented in Figure 1. As can be seen, the wake flow is an annular vortical motion of the air flow that has a conic form. This vortex widens and abates with distance. Figure 2 (a) shows the principle of wake spreading caused by the downstream of the first turbine. The related exemplary power curve in Figure 2 (b) indicates the drop in power output induced through the displacement of the operating point.

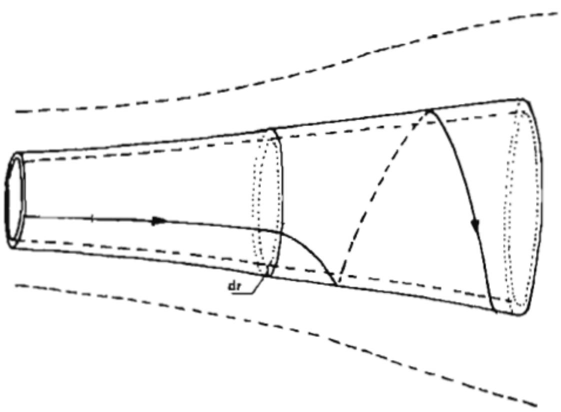

Figure 1. Model of wake rotation [9].

The power produced by the wind turbine can be estimated by Eq. (1):

$$P_{WT} = 0{,}5 \cdot \rho \cdot A \cdot V_{Wind}^{3} \cdot c_p \quad (1)$$

Thus, the small reduction of wind speed results in not proportionally high reduction of wind power (Figure 2).

The turbulence intensity can be described in relation to the distance between the neighboring wind turbines and is additionally dependent on the wind speed. Thus, the space has to be fixed generously to keep the turbulence impact negligible. Furthermore, sufficient spacing also increases the lifetime and energy output of the WT.

The wake's structure consists of several zones, such as: near wake, intermediate and far wake as presented in Figure 3. The length of each of these zones depends on the rotor diameter and has its own properties that are determined by the values of pressure *p* and wind speed *V*.

The near wake zone is characterized by the following properties [9]:

- The length is about 2 rotor diameters;
- The pressure in the front of the turbine increases, as the vortex flow expands to the blade's diameter, and then decreases suddenly at the other side of the turbine and after that constantly increases in the area of near wake to the free-stream value, p_a;
- The velocity inside of the vortex flow decreases as it comes to the turbine and stays constant at the other side of turbine, after that it reduces further in the near wake as the pressure rises to the value p_a;
- The radius of near wake increases up to some certain value when the pressure reaches p_a and the velocity decreases, which corresponds to the mass and momentum conservation law.

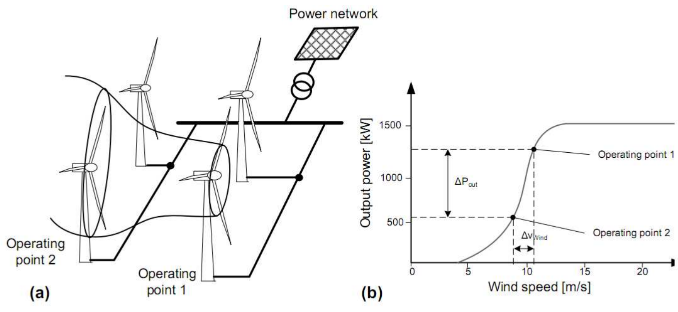

Figure 2. Principle of wake effect (a) and related power curve of wind turbines (b).

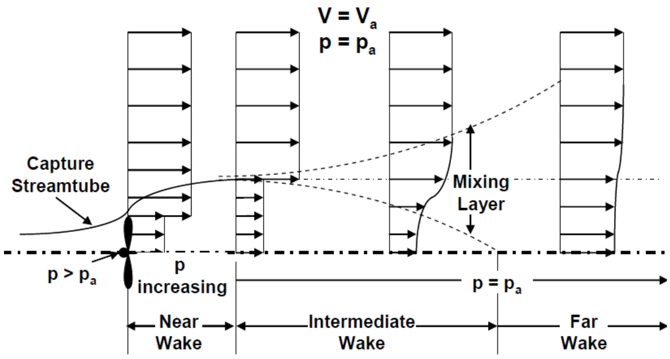

Figure 3. HAWT wake flow structure [13].

The intermediate wake has such properties as:

- The length is about 2-3 rotor diameters and ends when the mixing layer reaches the axial line and changes the centreline velocity;
- The pressure is fixed on the whole interval and equals to p_a;
- The centerline velocity has a fixed value as turbulent mixing increases at the wake outer boundary layer.

The far wake has the following features:

- The length is more than 5 rotor diameters;
- The pressure is constant and is equal to p_a;
- Due to the turbulent mixing the centerline velocity starts to steadily increase to the free stream value, V_a.

According to the properties of every zone the optimal distance between the wind turbines could be chosen in order to provide a minimal influence of one turbine on another.

Also for optimal planning of a wind farm the following parameters should be taken into account:

- Annual wind speed for predicting the expected energy yield as well as for wind turbine selection.
- Frequency of annual wind direction for wind farm structure design (the wind rose).

In Figure 4 the global wake effect in the wind farm is shown. Such an influence of array effect occurs when the wind blows more frequently in direction $V1_{wind}$ and the distance between wind turbines is *A*. With such layout a large shadowing is observed, so this wind farm structure is not effective if the primary wind direction corresponds to $V1_{wind}$. Such wind farm construction could be applied when the most frequent wind direction corresponds to $V2_{wind}$ because the distance between two neighboring wind turbines (*B*) is significantly larger than in the first case.

B. *Modelling of Wake Effect*

There are many different softwares to analyze the wake effect that are based on the different models from the rather simple wake models (for example WAsP, WindPRO, WindFarm) to the full CFD model (for example, ANSYS).

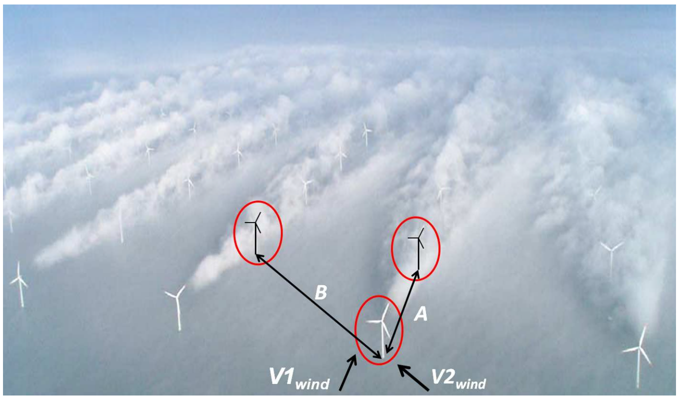

Figure 4. Wake effect in wind farm depending on wind direction [14].

These programs are based on the different mathematical models for wake effect calculations and include following models:

- Lissaman's model,
- Larsen's model,
- Jensen's model,
- Ainslie's model.

When such models are applied for the wind farm configuration, the calculation has two steps: in the first – the calculation of wake intensity for one wind turbine (so called, single wake) and then the superposition of several single wakes of each wind turbine inside the wind farm (multiple wake).

The first useful model was discovered by Lissaman in 1977 by the development of blade element theory and momentum theory. This model (Figure 5) is based on the empirical considerations of the fluid mechanics and the partitioning of the wake area into small regions. The corresponding wake parameters are defined for each region. The disadvantage of this model is the wake definition on the border between the regions [20], [21], [22].

The Ainslie's model uses the axial symmetric Reynold's equations and the numerical solution of the Navier Stokes equations for the turbulent boundary layer for determination of the wake development, [23], [24]. It is a more accurate method of wake determination but also more complicated because of the numeric solution. Such a model is used in commercial software GH WindFarmer [28].

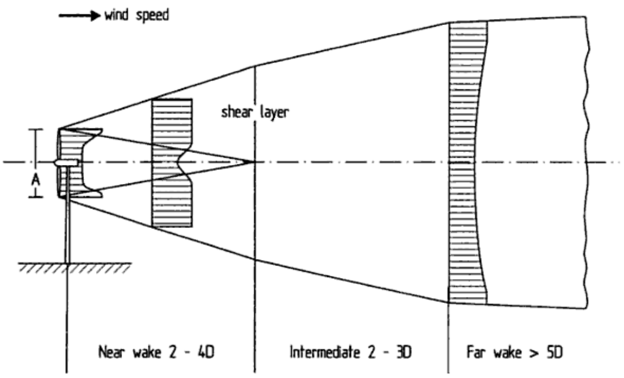

Figure 5. The structure of Lissaman's wake model [9].

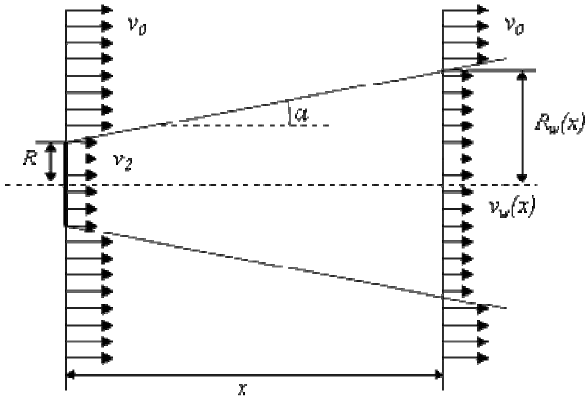

Figure 6. The structure of Jensen's wake model [8].

The Larsen's wake model is based on the Prandtl's turbulent boundary layer equations for definition of the wake behind the wind turbine. The wake flow is considered as incompressible, stationary and axis-symmetric. This model is significantly sensitive to the turbulence intensity changes [8].

The Jensen's wake model is simpler and requires a short time for calculations. In this model the wake flow is controlled by the entrainment constant *k*, the values of which are defined from the simulation results and measurements [25], [26], [27]. The wake flow is supposed to be linear and the near-wake region behind the rotor is neglected.

The wind speed profile for total wake is assumed to be a rectangular area. The structure of Jensen's wake model is presented in Figure 6. From this picture it is possible to calculate the wake radius $R_w(x)$ at any distance x with Eq. (2):

$$R_w(x) = kx + R \tag{2}$$

The wind speed in the wake at any distance *x* can be calculated with Eq. (3):

$$v_w(x) = v_0\left[1-\left(\frac{R}{kx+R}\right)^2\left(1-\sqrt{1-c_T}\right)\right] \tag{3}$$

Where:

- v_0 – is the incoming wind speed [m/s],
- v_2 – is the wind speed behind the rotor [m/s],
- $R_w(x)$ – is the wake radius at distance *x* behind the rotor plane [m],
- R – is the radius of the wind turbine rotor [m],
- k – is the entrainment constant [-], $k = tan(\alpha)$,
- c_T – is the thrust coefficient [-], see Figure 7,
- $v_w(x)$ – is the wind speed in the wake at any distance x.

The thrust coefficient depends on the wind speed and the type of wind turbine. The entrainment constant *k* was experimentally defined and for offshore systems equals $k = 0.04$, and for onshore $k = 0.075$ [8].

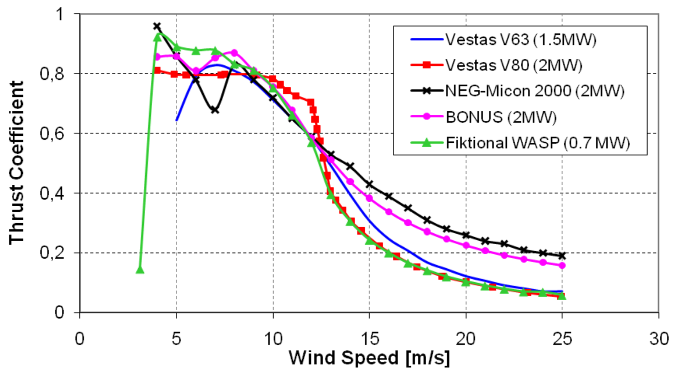

Figure 7. Thrust coefficient c_T for different wind turbines (created based on [10], [11]).

With lower constant k the wake area is narrower and stronger in a given downstream distance [29]. The Jensen model is applied in many commercial software programs for wind farm calculations, such as WAsP, WindPRO, etc [16], [17].

The Jensen's model of wake effect is also used in the LENA Tool [30]. The calculation algorithm of wake effect with the help of this program is as follows (see Figure 8):

- Input data definition:
  - o wind profile: wind speed v_m and wind direction φ_m for some period (one month or half year for more exact calculation),
  - o coordinates x_n, y_n of each wind turbine (wind farm structure),
  - o type of wind turbine: height h_n and rotor radius R_n for each WT,
  - o thrust coefficient c_T,
  - o entrainment constant k.
- As a result the wind speeds and the pictures of wind roses for each wind turbine are calculated.
- The next step is the verification of calculated wind speeds with a measured data and correction with the correction-coefficients (which are presented in the form of coherency matrix and are specified for all available (for the wind farm place) wind speed values and wind directions for every WT).

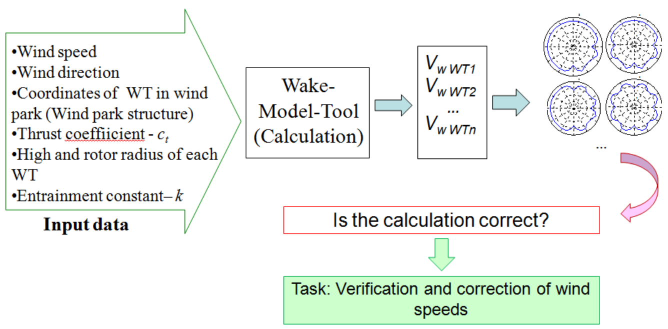

Figure 8. The algorithm of calculation for the corrected wind speeds.

IV. Test System and Exemplary Calculation

To best understand the program operational behavior exemplary wind farm was considered. The structure of this wind farm was based on the Horns Rev I off-shore wind farm that is connected to the Danish power system, as shown in Figure 9. It consists of 80 wind turbines, type Vestas V80 with 3 blades, which can generate the maximal power of about 2 MW. The rotor diameter and height are equal to 80 m.

For calculation the measured data from the measuring mast that is situated 2 km northwest of the first WT were used. The wake effect was simulated with the LENA-Tool and the results about wind speed reduction were received, such as the wind roses for each wind turbine (see Figure 10) and the general wind farm shadowing pattern (see Figure 11).

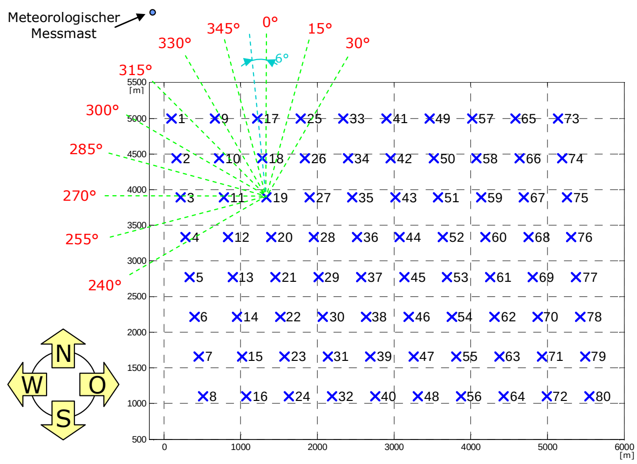

Figure 9. The structure of wind farm [30].

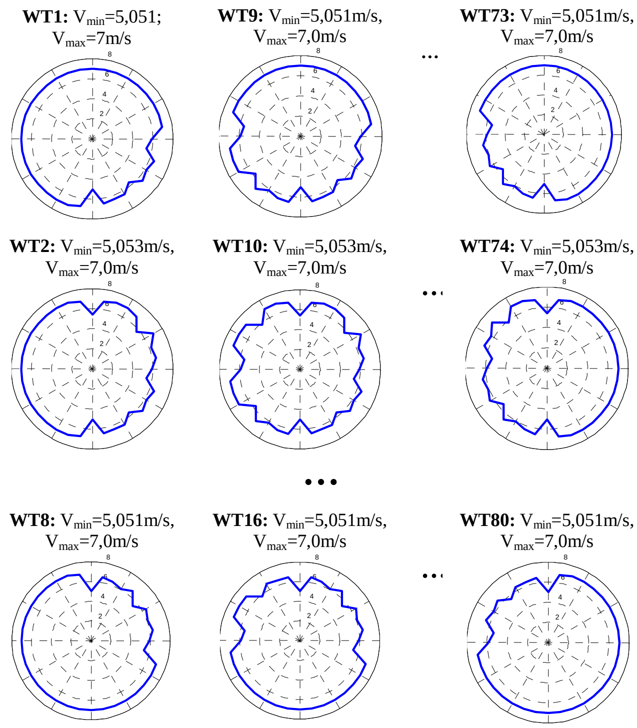

Figure 10. The results of wake-effect calculation in wind farm.

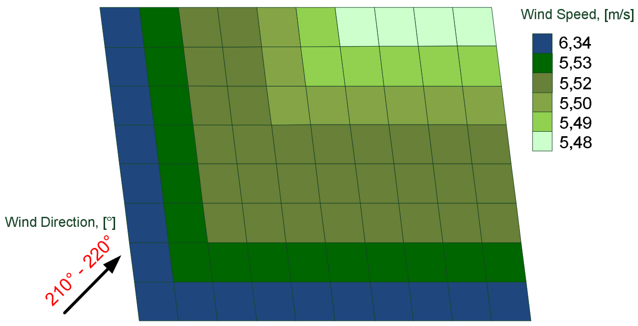

Figure 11. Wind farm shadowing pattern.

The structure of wind farm shadowing pattern shows the resulting wind speeds for each wind turbine for the incoming wind profile corresponding to wind speed V_{wind} = 6,341 m/s and wind direction φ_{wind} = 217°. It is easy to see that the last wind turbines (according to the wind direction) have lower input wind speed than the front wind turbines and are marked with light colours in the Figure 11. In order to see the influence of wake effect on the energy production of the wind farm, it is better to calculate the energy yield for the wind farm with and without shadowing. To calculate the energy yield during the month the power curve of the wind turbine Vestas V80 2.0 MW and the wind profile curve for this period are used as input data (Figure 12 (a) and (b), respectively).

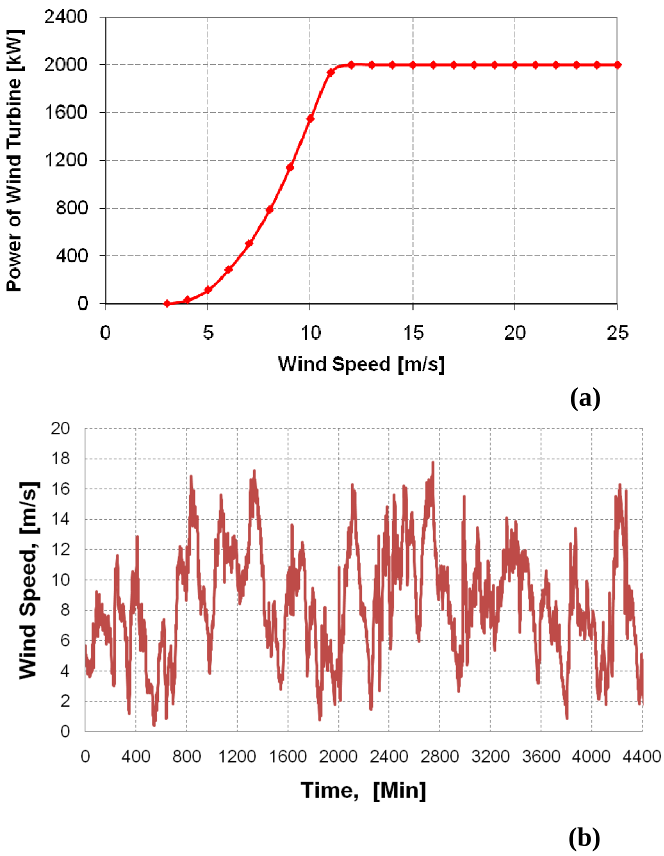

Figure 12. Input data for energy yield calculation: Assumed power curve (a) and wind profile during the considered month (b).

TABLE I. DIFFERENCE IN ENERGY YIELD WITH AND WITHOUT WAKE EFFECT CONSIDERATION

Type of calculation	Parameters			
	Energy yield [MWh]	*Full load hour [h]*	*Profit [k€]*[a]	*% difference*
With wake effect	52276,7	327	4704,9	12%
Without wake effect	59525,6	372	5357,3	

a. Assumption: wind energy price is equal to 9 Ct/kWh [31]

In the first variant the energy yield of the wind farm without influence of wake is obtained. In this case the energy production for one turbine is calculated for one single turbine and then is multiplied by the number of wind farm units. In the second case, the wake effect is taken into account. So the total energy yield is calculated as the sum of energy yields for each turbine. The calculation results are presented in TABLE I. It can be noticed that the reduction of the energy yield due to the wake effect is significant and equals to 12%.

V. CONCLUSION

In this paper the planning of wind farms was discussed regarding the mutual interaction between the wind turbines that are specified by the wake effect. It was shown that the wake effect plays a significant role during the assessment of the energy yield of a wind farm and the forecasted production. Therefore, if this phenomenon would be considered already during the planning phase of the wind farm an optimal structure of the wind farm for the considered location can be gathered on the one hand, and on the other hand, a more realistic estimation of the energy yield can be performed.

Apart from the planning tasks that have a more static character, the consideration of wake effect also plays a significant role during the operation of the wind farms. Thus, an interesting issue regards the optimization of the overall energy yield from the farm by adapting the yaw angle of individual wind turbines within the farm as well as by optimizing the pitch angle settings in the individual wind turbines. This will be the subject of further investigations.

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