VALIDATION OF CURRENT WAKE MODELS

FOR ONSHORE WIND FARM

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ABSTRACT

VALIDATION OF CURRENT WAKE MODELS FOR ONSHORE WIND FARM

Wake effects affect the performance of wind turbines and unsteady loadings on downstream wind turbines. In order to understand wake characteristic various wake models are developed and implemented for academic and industrial purposes. Estimation of wake losses is fundamental in order for power production analysis of wind farms.

In this thesis, far wake models are used for validation by using Bandırma Wind Power Plant measurement data. Calibration of turbulence intensity values are used for validating wake models.

Keywords: Wake, wind energy, turbulence intensity, analytical approach, wind farm

ÖZET

GÜNÜMÜZ RÜZGAR ÇIKMASI MODELLERİNİN RÜZGAR SANTRALİNDE DOĞRULANMASI

Rüzgar çıkması rüzgar türbinlerinin performansı etkilemektedir ve üzerine akış yönünde düzensiz yükler oluşturmaktadır. Rüzgar çıkmasının karakteristiğini kavrayabilmek için akademik ve endüstriyel amaçlarla çeşitli rüzgar çıkması modelleri geliştirilmiştir ve uygulanmıştır. Rüzgar santrallerinin enerji üretimini artırmak için de rüzgar çıkması kayıplarının tahmin edilmesi gerekli hale gelmiştir.

Bu tez çalışmasında Bandırma Rüzgar Santrali'nin ölçüm verileri kullanılarak uzak rüzgar çıkması modellerinin doğrulanması incelenmiştir. Türbülans yoğunluğu değerlerinin kalibrasyonu ile rüzgar çıkması modellerinin doğrulanması yapılmıştır.

Anahtar Kelimeler: Rüzgar çıkması, Rüzgar enerjisi, Türbülans yoğunluğu, Analitik Yaklaşım, Rüzgar Tarlası

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LIST OF SYMBOLS / ABBREVIATIONS

MW	Megawatt
GW	Gigawatt
RANS	Reynolds Averaged Navier Stroke
ABL	Atmospheric Boundary Layer
ψ_m	Correction term
I_a	Ambient turbulence intensity
σ_u	Standard deviation of the wind speed
$\overline{U}$	10-min average wind velocity
u_{n+1}	Velocity at the turbine in wake
U	Average wind speed
u_*	Friction velocity
U_{ref}	Undisturbed average wind speed
κ	von Kármán constant
z_0	Roughness length
z	Elevation from the ground level

LIST OF SYMBOLS / ABBREVIATIONS

z_{ref}	Reference height
α	Shear exponent
L_s	Obukhow length
g	Gravitational acceleration
T	Average temperature
H	Kinematic heat flux
C_p	Specific heat
ρ	Air density
C_T,	Thrust coefficient
x, s	Spacing
SCADA	Supervisory Control and Data Acquisition
TI	Turbulence intensity
D_{wake}	Wake expansion
k	Wake decay constant
β	Wake expansion parameter
A	Rotor area

LIST OF SYMBOLS / ABBREVIATIONS

A_w	Rotor area in wake
R_{wake}	Wake radius
$(\Delta U)_1$	Velocity deficit
r	Radial distance
p	Rate of wake recovery
I_w	Mechanical turbulence
I_t^u	Wake added turbulence
U_∞	Free stream velocity

1. INTRODUCTION

In recent days, wind energy is viable common alternatives to the energy production from conventional energy sources. Wind energy has a significant potential to reduce greenhouse gases emissions, and also, with the emissions of other air pollutants, by displacing conventional power plants. Wind turbines can balance all emissions from its construction nearly 0.5 percent of life time in operation, and works emission-free for its 20 years lifetime. [1] 13.7 percent of global energy needs are provided from zero-carbon sources in 2014. Wind, in particular, has a rapid growing, with output higher than doubling in the five years to 2014. Hence, renewable energy source use is rapidly increased lately. [2]

According to data from BP's Statistical Review in 2015, wind energy contributed 1.2 percent of the world's energy needs as seen in Figure 1.1 [2]

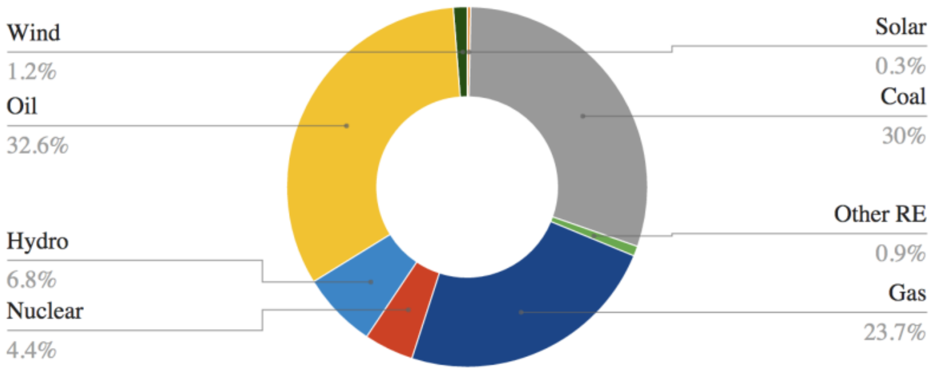

Figure 1.1 Shares of world demand met by different sources of energy in 2015. Other RE includes geothermal, biomass, biofuels wave and tidal energy. [2]

Wind energy or wind power is extracted from air flow by using wind turbines or sails in order to generate mechanical or electrical energy. Windmills are used for their mechanical power, wind pumps for water pumping, and also used for sailing to propel ships. Wind energy is very consistent from year to year, but it has important variation over shorter time scales. Hence, it is used in conjunction with other electric power sources in order to give a reliable supply.

Wind energy is mainly used for energy production in last decades. Wind turbine scale has significantly growth with a rated power 2 MW to 8 MW and exceeds 90 m of rotor diameter. In order for energy production need, wind energy facilities are increased their number of wind turbines that accompany a challenging impact in region such as siting.

Freestream air flow after wind turbine has lower speed and higher turbulence due to energy extraction. Due to lower wind speed and higher turbulence level, it is called wake effects; there are impacts on performance of wind turbines and unsteady loadings on downstream wind turbines. [3]

The consideration by determining the wake effects there is two main reasons that are environmental and atmospheric conditions, and wind turbine model. Both of them affect the wind velocity, turbulence level and atmospheric stratification throughout wind turbine. [4]

Wake size and magnitude can be affected by several variations in environmental impacts i.e. ambient temperature, wind speed, orography, roughness, relative humidity and atmospheric boundary layer conditions. [4]

The blade number, length, pitch, and angle of wind turbines have effects on wake evolution. Pitch-regulated wind turbine are adjusting the blades in order to get constant power output that are affected by blade pitch angle and rotor rotational speed, wind speed, turbulence. [4] Turbulence intensity also affects the wake formation and power production directly. Individual wind turbines are affected by turbulent wakes from another turbine with rotor area and spacing (distance between each turbine). Further, downstream wind turbines can be affected by cumulative impact of multiple wakes which leads to velocity decrement and loading. Due to wake effects, power production losses can reach higher than 20 percent annually. [5] For this purpose many wake model have been developed and implemented for academic and industrial software.

1.1. CURRENT WIND ENERGY SITUATION

Wind power generation has rapidly growth in last decades. As shown in Figure 1.2., wind power capacity has expanded to 432,419 MW by December 2015, [6] and total wind energy production is growing rapidly and has been reached around 4% of worldwide electricity usage. [7]

As of 2015, Denmark has been producing approximately 40 percent of its electricity from wind, [8] and at least 83 other countries around the world are using wind power to supply their electricity grids. [9]

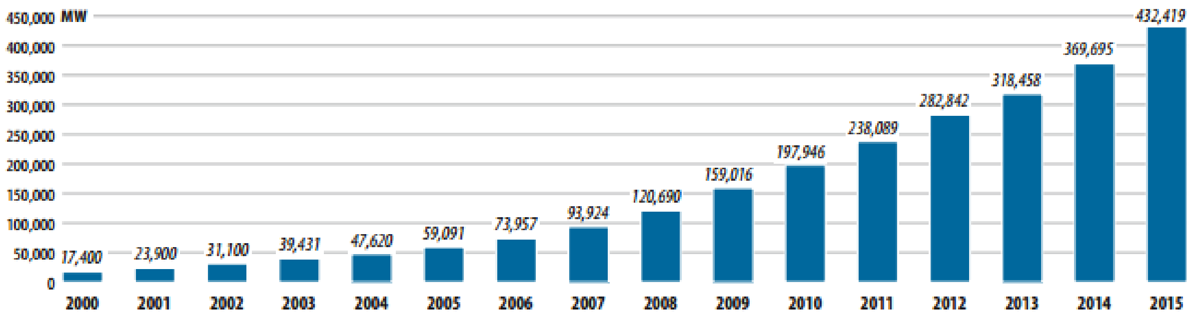

Figure 1.2.Global wind power cumulative capacity [6]

The new installed capacity of wind energy in China that has the biggest investment with 33 GW (51.8 percent of share). According to other countries, Germany and USA have biggest investment with 8.5 and 6 GW (9.5 and 13.6 percent of share) respectively. [10] These three countries have also significant share in cumulative capacity of wind power in world. Furthermore, Turkey has 1.5 percent of share in new installed capacity in world. As in mentioned in TWEA (is called TUREB in Turkish) report, it has 956.20 MW new installed capacities in 2015 and reached total capacity of 4.7 GW in Figure 1.3. [6] [11]

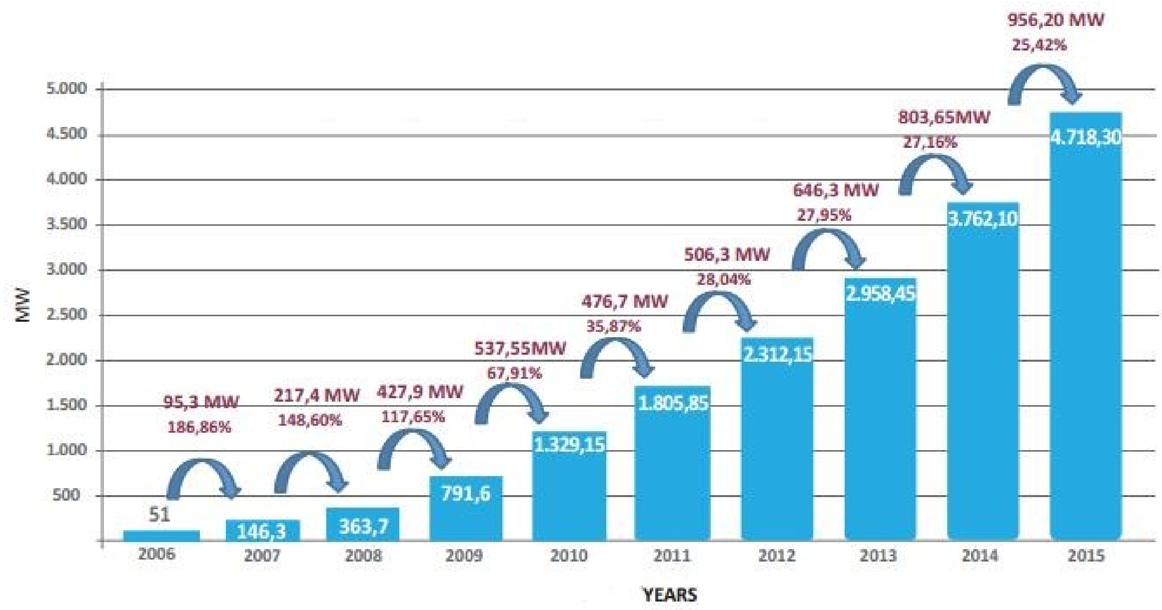

Figure 1.3. Wind power cumulative capacity in 2015 [11]

1.2. OBJECTIVE OF THESIS

In order to validate far wake models with measurements obtained from the wind farm. Velocity deficit, wake propagation and turbulence intensity will be examined on wake models. Also, wind farm efficiency will be analyzed by comparing SCADA data and WAsP software.

1.3. LITERATURE REVIEW

Wake effects mainly cause power production losses and unsteady fatigue loading on wind turbines. In order to comprehend the impact of wake effects several studies are done analytically and experimentally.

Wind turbine wake models identify the air flow behind rotor that can be divided by two regions in wake near wake and far wake. [12] The near wake starts behind the turbine with 1-4 rotor diameter downstream [13] [14]

Far wake starts behind the turbine and expands to nearly 5 rotor diameter downstream and more than it. Barthelmie, [5] 2010 as mentioned in study, the wake propagation is a function of ambient turbulence, mechanical turbulence [15], wind velocity, wind direction, atmospheric stability and the position is effected ground by wake. [16]

Kinematic models are researched numerical studies in order for examination of far wakes. Preliminary approach to wind turbine wakes are mentioned by Lissaman. [17] These models are based on similarity theory of velocity deficit profiles. Lissaman, Voutsinas velocity deficit studies based on Abramovich co-flowing jets model. Vermeulen is used Gaussian shape profile and Katic assumed to velocity profile as a hat profile. In order to obtaining initial velocity deficit generally momentum conservation law is used as a function of thrust coefficient of wind turbine. [17]

Field models are another approach of wake studies that calculate the flow values at each point of flow field in wind farm. Ainslie is developed a model by using eddy viscosity method for turbulence that assumes axial symmetry in wake and uses RANS equations in order to calculate wake structure. It assumes pressure gradients in wake are neglected, but not valid in near wake region. This model is implemented in WindPRO, GH WindFarmer, and Flap software. [18] [19]

UPMWAKE model has developed by Crespo and colleagues that is a numerical study for far wake region. [20] The model uses 3D parabolized RANS equations including κ-ε turbulence model. This model assumes the wake fully extended at turbine rotor and velocity deficit profile is Gaussian shaped. Further, the study addresses significance of surface roughness modelling in order to involve terrain properties for validation of model. [21]

2. BACKGROUND THEORY

This section provides an overview to understand wind turbine wakes which is based on several theoretical backgrounds.

2.1 ATMOSPHERIC BEHAVIOR

Wind turbines operate in the minimum level of the atmospheric boundary layer of the Earth. The characteristics of the atmospheric flow are determined by orography, roughness regarding the stability of atmosphere that can be modelled by several ways.

2.1.1. Atmospheric Boundary Layer

The wind profile of the atmospheric boundary layer (ABL) can be derived in mainly two ways that are power law and logarithmic law. [22] [14] [23] [24]

2.1.1.1 Logarithmic law

The logarithmic velocity profile is expressed as,

$$U(z) = \frac{u_*}{\kappa} ln\left(\frac{z}{z_0}\right),$$

where $u_*$is the friction velocity, U is average wind speed, κ s the von Kármán constant (~0.4), z_0 is the roughness length that ranges from 0.001m to 0.3 , z is the elevation from the ground level.

2.1.1.2. Power Law

Power law is another description of velocity profile which is mostly used in wind energy issues. It is formulated as,

$$U(z) = U_{ref} \left(\frac{z}{z_{ref}}\right)^{\alpha},$$

with U_{ref} is the undisturbed average wind speed at reference height, z_{ref}, α is shear exponent.

2.1.2. Atmospheric Stability

Atmospheric stability has impact on air flow behavior and is connected to Obukhow length L_s. It is height from the ground level that ratio of mechanical to thermal turbulence production.

$$L_s = \frac{-u_*^3}{\kappa\left(\frac{g}{T}\right)\left(\frac{H}{C_p \rho}\right)} \quad ,$$

with g is the gravitational acceleration, T is average temperature, H is kinematic heat flux, C_p and ρ specific heat and air density.

The height of the ABL and turbulence intensity is changed by thermal stratification. [22] ABL can be determined as neutral, stable and unstable conditions. The stability characteristic of atmosphere can be considered by the sign of H.

Although stability of atmosphere has impact on flow characteristic, atmosphere is generally accepted as neutral condition in several wind energy application. Atmospheric stability is given by,

$$U(z) = \frac{u_*}{\kappa}\left[ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L_s}\right) + \psi_m\left(\frac{z_0}{L_s}\right)\right],$$

where ψ_m is a function depending on stability or correction term.

2.1.3. Turbulence Intensity

Atmospheric turbulence is affected by surface roughness, atmospheric stability and distance from the ground level. [22] Ambient turbulence intensity is expressed as

$$I_a = \frac{\sigma_u}{\overline{U}},$$

where $\overline{U}$ is 10-min average wind velocity, σ_u is the standard deviation of the wind speed in the mean wind direction.

2.2. WAKE SUMMATION

Including the impacts of all the upstream turbines to the total wind speed deficit, wake superposition concept is applied in wake models. 4 approaches are primarily used in wake models such as [14],

Linear Sum:

$$\left(1 - \frac{u_{n+1}}{U_\infty}\right) = \sum_{j=1}^{n}\left(1 - \frac{u_{j+1}}{u_j}\right),$$

Geometric Sum:

$$\left(1-\frac{u_{n+1}}{U_\infty}\right)=\prod_{j=1}^{n}\frac{u_{j+1}}{u_j}$$

Energy Balance:

$$(U_\infty^2-u_{n+1}^2)=\sum_j^n\left(1-\frac{u_{j+1}}{u_j}\right),$$

Quadratic Sum:

$$\left(1-\frac{u_{n+1}}{U_\infty}\right)^2=\sum_{j=1}^{n}\left(1-\frac{u_{j+1}}{u_j}\right)^2,$$

where n is the total number of turbines and the velocity at the turbine in wake is called as $u_{n+1.}$ Van Leuven and Habenicht studies show that linear sum method has a good agreement with the measurement data and its significance is stated. [25] [26]

2.3. ACTUATOR DISK CONCEPT

Actuator disk concept is referred as 1-D momentum theory that the wind turbine is modelled as actuator disk. The free stream before and after actuator disk is decided to be incompressible, homogeneous, isotropic, and asymmetric with constant pressure profile, non-turbulent, inviscid, neutrally stable and non-rotational. [14] The wind speed towards to disk is assumed steady and thrust has uniform distribution through the area of actuator disk. This concept is using equations of conservation of mass, momentum and energy. [22] The control volume and velocity profile in wake of turbine is shown in Figure 2.1.

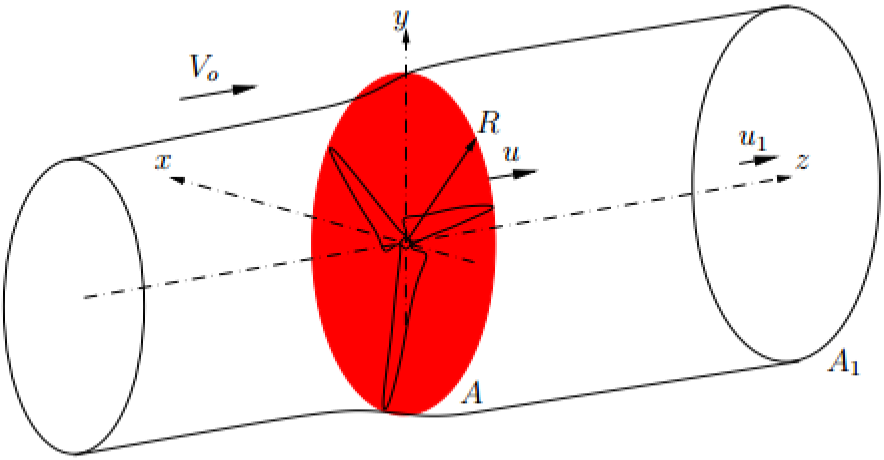

Figure 2.1. Velocity profile in the wake of a wind turbine. [27]

The wake deficit is formulated as,

$$\frac{u_1}{V_0} = 1 - \alpha\left(1 + \frac{2x}{\sqrt{1+4x^2}}\right),$$

where x refers spacing between each turbine and $u_1$is the wind speed in the wake. α is given as a function of C_T ,

$$\alpha = \frac{1 - \sqrt{1 - C_T}}{2}$$

2.4. WAKE DEVELOPMENT

The wind turbine wake essentially consists of near and far wake as region from downstream position of turbine. It affects the turbine performance, wake modelling, and wake interference, turbulence modelling and topographic impacts. [22] Development of velocity in wake is shown in Figure 2.2.

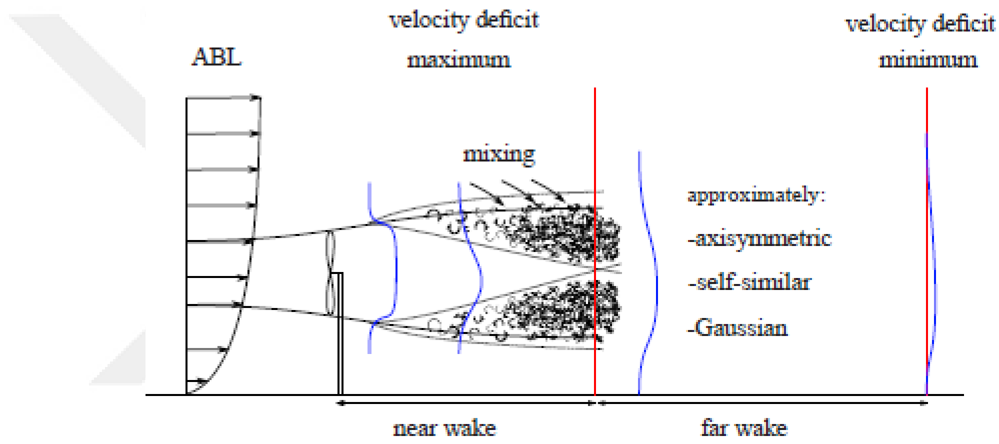

Figure 2.2.Velocity profile in the wake of a wind turbine [22]

2.5. SCADA DATA

The meaning of SCADA is that Supervisory Control and Data Acquisition. SCADA system gathers data from wind turbines and transfers it to a main computer for purpose of control and monitoring. Two major components are included in SCADA systems for wind turbines such as hardware and software. Remote terminals in hardware part collects data from sensors on wind turbine and transfer it to central station in order to display and store. The part of software in SCADA system can control to all hardware that the data is routinely collected to display for monitoring purposes and stored in long duration storage. [28]

2.6. POWER AVAILABILITY

WAsP is software that predicts wind climates, wind resources and annual energy production of each turbine and of wind farm by given power curve of wind turbine and wind farm layout. [29] The methodology of WAsP software is shown in Figure 2.3.

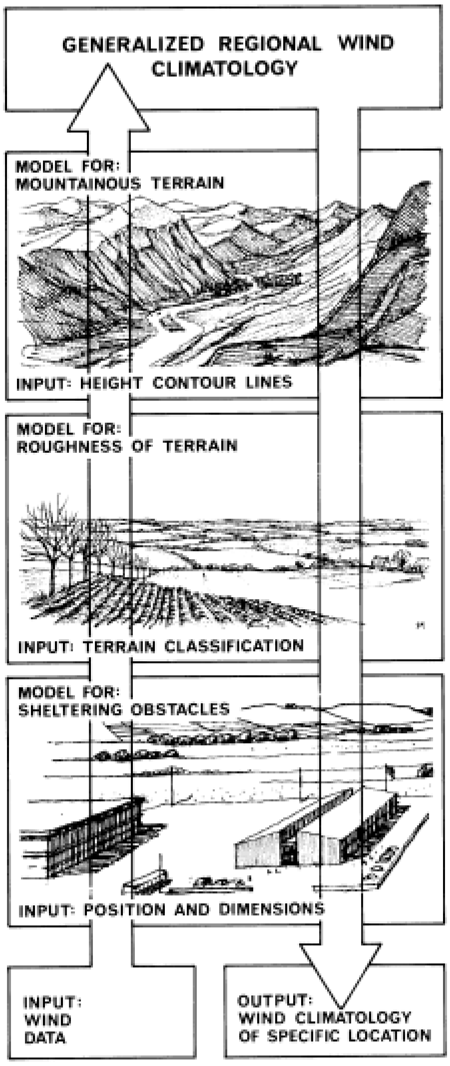

Figure 2.3. The wind atlas methodology of WAsP [29]

Wind farm efficiency or power availability is defined by the ratio of the total energy output of the wind farm and the power output of the wind turbines at the same location unless affected by surrounding wind turbines. Wind farm power production output is based on the measured power production of the individual wind turbines. The power availability or wind farm efficiency is formulated as,

$$Power\ Availability = \frac{Estimated\ Power\ Production}{\frac{1}{2}\rho A_{rotor} C_p U^3 * 8760}$$

3. CASE STUDY: BANDIRMA WIND POWER PLANT

In this section, wind site information and selected wake cases are detailed.

3.1. SITE SPECIFICATIONS

Bandirma wind farm is located in Bandirma from northern side of Turkey as seen in Figure 3.1. There is a total rated capacity of 89.7 MW and consists of 20 Vestas-V90 wind turbines with a rotor diameter of 90 m. The orography and layout of wind farm are shown below.

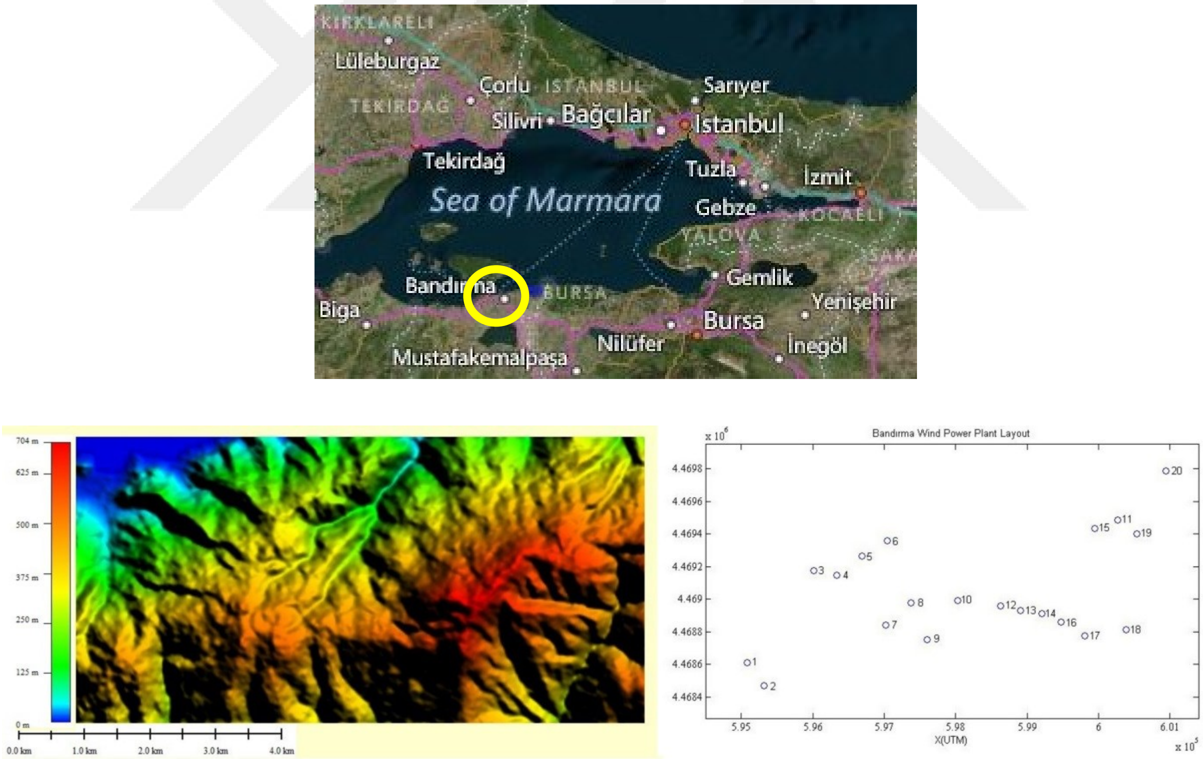

Figure 3.1. Site location, orography and wind farm layout

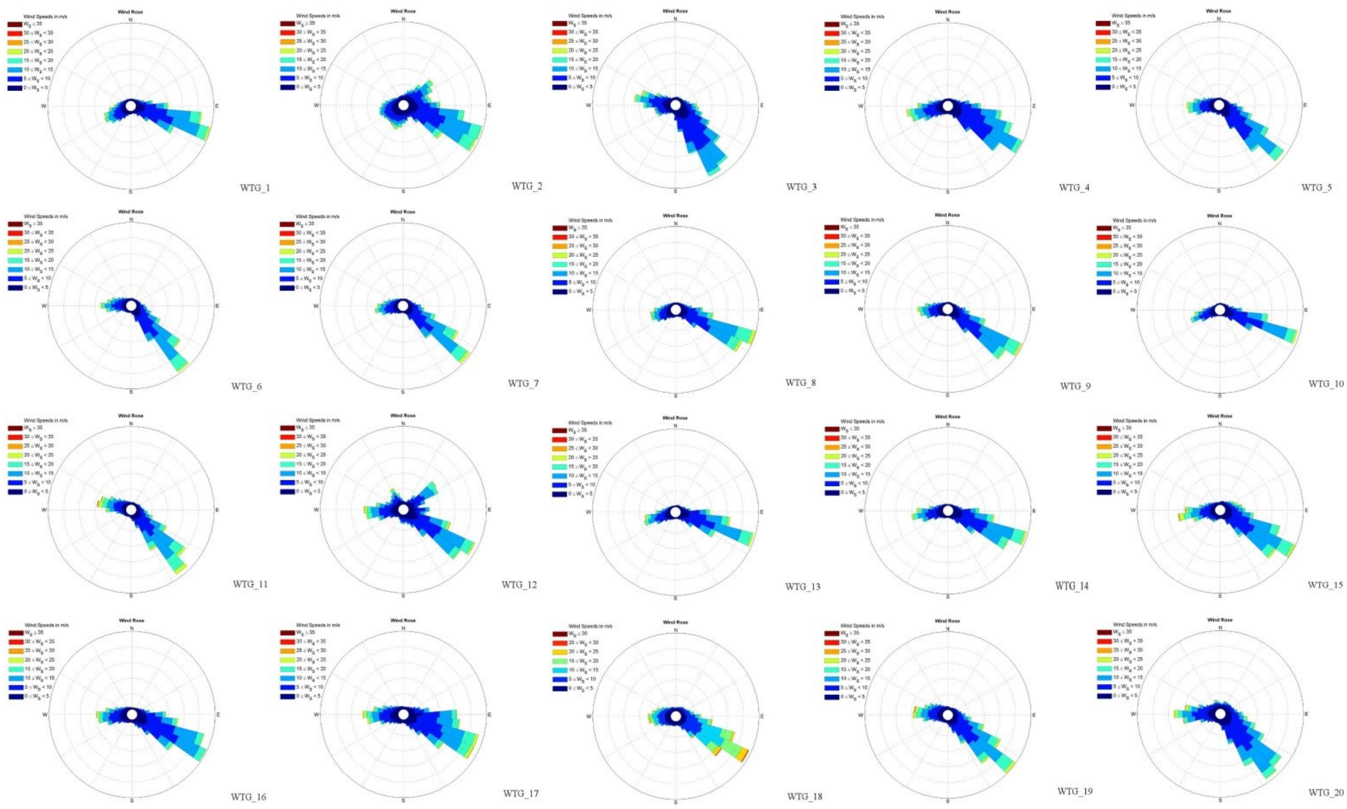

Figure 3.2. Wind rose of each turbine

Figure 3.2. shows that the annual frequency and speed of wind blowing from each direction (sector) and the prevailing wind direction is southeast in wind site. Of the prevailing wind direction, wind speeds are most often in the 5-10 and 10-15 m/s range (dark blue and light blue on legend).

3.2. SELECTED WAKE CASES

The selected wake cases are determined that turbines are in wake of each other by given Figure 3.3. All of these cases are examined in further section.

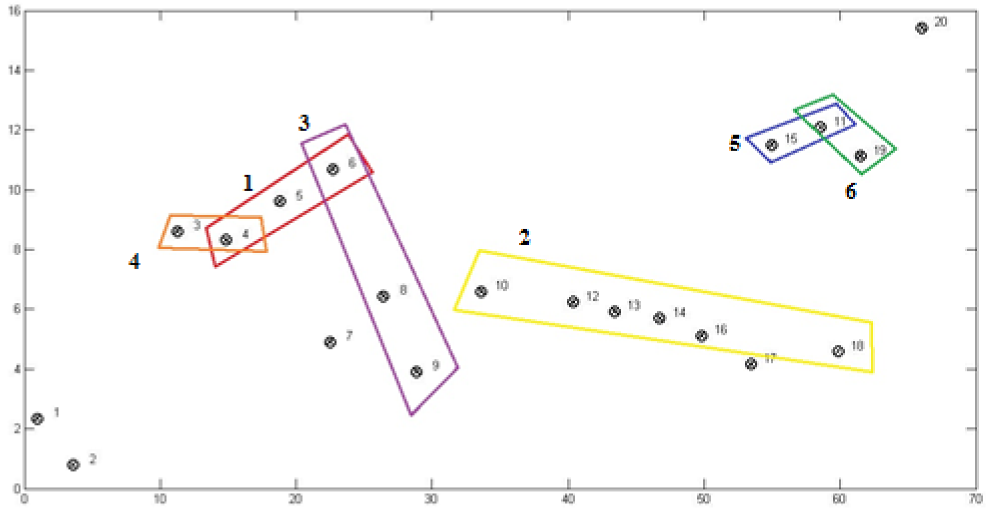

Figure 3.3. Layout of the wind farm and selected group of turbines for validating with developed framework as wake cases

4. METHODOLOGY

4.1. MEASUREMENTS

Wind farm data from SCADA system is a requirement for wake studies in large wind farms. Parameters involve grid power output, pitch angle, rotor rotational speed, wind speed and direction, temperature in period of 2012-2013. Mean, standard deviation, minimum, maximum variables are also recorded as ten minutes statistics in storage. The used data set is just provided by rotor anemometer of each turbine. The SCADA data of Bandirma Wind Power Plant is provided by Borusan EnBW Energy for the purposes of the study.

10 min average of wind speed are filtered by range of cut-in (4 m/s) and cut-out speed (25 m/s) for purpose. The grid power is filtered that does not produce under cut-in speed by same method. In order to increase performance of cases wind speed and wind direction are binned by $\pm$0.5 and $\pm$1.5 respectively.The data set has several recording error that is struggled to filtering process. There are many missing and erroneous data between logged data due to data logger fault. All of them is filtered and further made ready to available process. Lack of met mast data has impact on turbulence intensity calculation in some way.

4.2. WAKE MODELS

The wake characteristics can be modelled with empirical approaches by using analytical expressions based on simplifications corresponding wake models. The analytical models are used in this study that is not cover the turbulence intensity change in wake. In order to overcome the its impact on flow that is needed to applied a turbulence model.

4.2.1. N.O. Jensen Wake Model

N.O. Jensen wake model is a simple model that is quick and has low computational time. It is firstly presented in Jensen study in 1984 [30] and further study developed by Katic in 1986 [31] that is implemented in WAsP.

Assumption of model is that wake expands linearly with a velocity deficit, as a function of downstream distance x. It is also assuming a top-hat inflow profile from the mass balance and initial velocity is derived from the thrust coefficient, C_T and wake decay constant, k. Further, it assumes ideal axially symmetric flow, no rotation, no turbulence and conic shape wake profile. [14] The wake expansion formulation, D_{wake} is described as,

$$D_{wake} = D(1 + 2ks) ,$$

where D is diameter of wind turbine, $s = x/D$ is spacing between each turbine, and velocity deficit in wake as follows,

$$u_{def} = U_\infty \left(\frac{1-\sqrt{1-C_T}}{(1+2ks)^2}\right),$$

with U_∞ is free stream wind speed where k is generally used 0.075 in onshore sites. As mentioned in Pena and Rathmann study, the parameter k is shown as a function of height roughness, atmospheric stability and turbulence separation. [32]

4.2.2. The Frandsen Wake Model

The semi-analytical wake model is developed by Frandsen [33] that predicting the velocity deficit in wake position. It assumes the wind farm with a rectangular grid and equally spaced wind turbines between rows.

The wake diameter in model is formulated as,

$$D_{wake}(x) = D(\beta^{k/2} + \alpha s)^{1/k},$$

with the wake expansion parameter, β is

$$\beta = \frac{1+\sqrt{1-C_T}}{2\sqrt{1-C_T}},$$

where the parameter α is the initial wake expansion and normalized downstream distance after turbine is referred as $s = x/D$. The parameter k values can change by 0.07 and 2 respectively.

The velocity deficit u_{def} is given by,

$$u_{def} = \frac{U_\infty}{2}\left(1 \pm \sqrt{1 - 2\frac{A}{A_w}C_T}\right),$$

with rotor area is A, and rotor area in wake is A_w.

4.2.3. The Larsen Wake Model

The early version of wake model by Gunner Larsen is described in 1988 [34] and developed in 2009 [35] that is implemented in the WindPRO. It is based on the Prandtl's turbulent boundary layer equations and the closed form of the RANS equations with the thin shear layer approximation is used. Larsen used the solution of the RANS equations using first and second order approximations and the second order approximation is neglected in last version. The wake flow assumed to be incompressible, stationary and wind shear is neglected, thus it is axisymmetric. It uses the similarity theory for the velocity profile. [14]

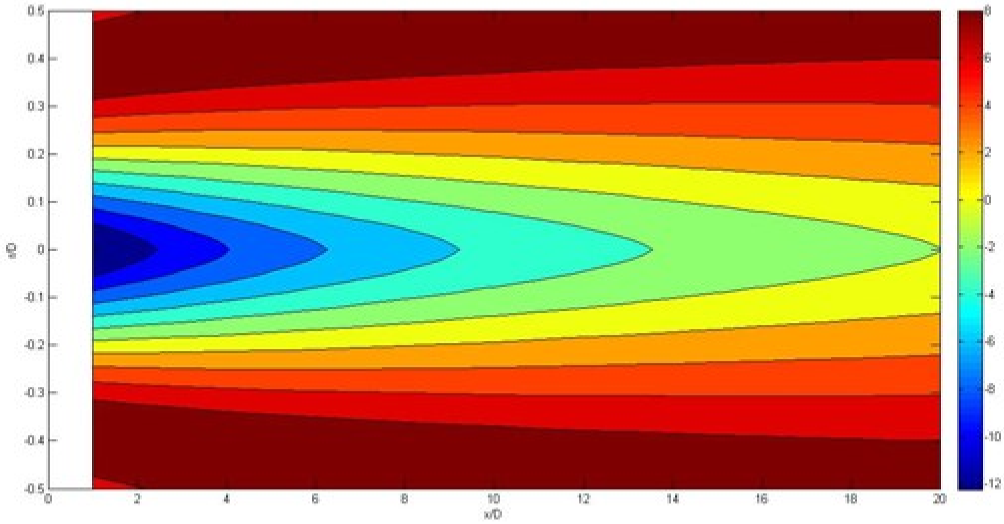

Figure 4.1. Wake expansion behind turbine, U=10 m/s

The velocity deficit and wake radius is considered as,

$$R_{wake}(x,r) = \left(\frac{35}{2\pi}\right)^{1/5} (3c_1^2)\left(C_T A(x+x_0)\right)^{1/3},$$

$$(\Delta U)_1(x,r) = -\frac{U_\infty}{9}\left(C_T A(x+x_0)^{-2}\right)^{1/3}\left[r^{3/2}\left(3c_1^2 C_T A(x+x_0)\right)^{-1/2} - (3c_1^2)^{-1/5}\right]^2,$$

with x is axial distance and r is radial distance of turbine where,

$$c_1 = \left(\frac{105}{2\pi}\right)^{-1/2}\left(\frac{D_{eff}}{2}\right)^{5/2}(C_T A x_0)^{-5/6},$$

$$x_0 = \frac{9.6D}{\left(\frac{2R_{9.6D}}{D_{eff}}\right)^3 - 1},$$

$$D_{eff} = D\sqrt{\frac{1+\sqrt{1-C_T}}{2\sqrt{1-\sqrt{1-C_T}}}},$$

with empirically calculated wake radius, $R_{9.6D}$ is described as function of C_T and I_a ,

$R_{9.6D} = a_1 exp(a_2 C_T^2 + a_3 C_T + a_4)(b_1 I_a + 1)D,$

where the constants of formulation a_1, a_2, a_3, a_4 and b_1 are given by,

$$\begin{cases} a_1 = 0.435449861 \\ a_2 = 0.797853685 \\ a_3 = -0.124807893 \\ a_4 = 0.136821858 \\ b_1 = 15.6298 \end{cases}.$$

4.2.4. Ishihara Wake Model

The analytical model is developed by Ishihara [36] in 2004 by using experimental data from Mitsubishi wind turbine in boundary layer wind tunnel. It aims by taking the impact of turbulence on the rate of wake recovery. The model is basically based on equation of momentum for axial symmetry flow and relation between drag force on the turbine and the loss of momentum flux.

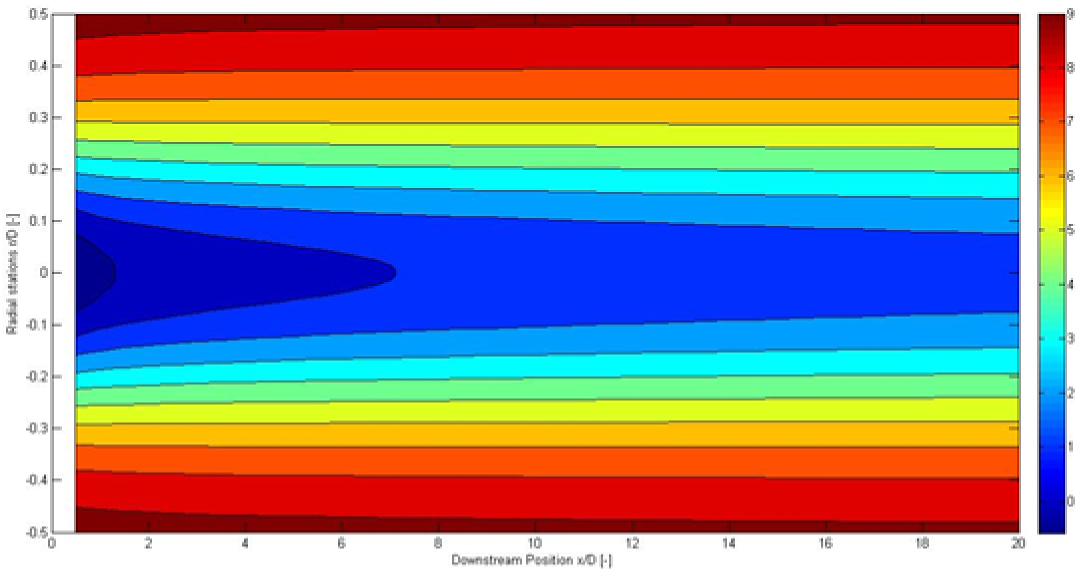

Figure 4.2. Wake expansion behind turbine, U=10 m/s

The model assumes similarity theory for wind speed profile, $u_1(x, r)$ is described as,

$$u_1(x,r) = U_0 \frac{\sqrt{C_T}}{32} \left(\frac{1.666}{k_1}\right)^2 \left(\frac{x}{d}\right)^{-p} exp\left(-\frac{r^2}{b^2}\right),$$

$$b(x) = \frac{k_1 C_T^{1/4}}{0.833} d^{1-p/2} x^{p/2},$$

Parameter p represents the rate of wake recovery as a function of turbulence.

$$p = k_2(I_a + I_w),$$

where I_a is ambient turbulence and I_w mechanical turbulence which is generated by wind turbine. I_w is expressed as,

$$I_w = k_3 \frac{C_T}{max(I_a, 0.03)} \left(1 - exp\left(-4\left(\frac{x}{10d}\right)^2\right)\right),$$

where parameters are determined as,

$$\begin{cases} k_1 = 0.27 \\ k_2 = 6 \\ k_3 = 0.004 \end{cases}.$$

4.3. WAKE ADDED TURBULENCE MODEL

Larsen turbulence model [37] just assumes that surface and wake shear mechanism are producing turbulence while these mechanisms are not numerically dependent, thereby it is added. The total turbulence intensity in the wake as the summation of ambient turbulence I_a and turbulence in wake which is function of spacing and thrust coefficient, I_w:

$$I_t^u = \sqrt{I_a^2 + I_w^2},$$

The wake added turbulence and ambient turbulence intensity are given by,

$$I_w = 0.29s^{-1/3}\sqrt{1 - \sqrt{1 - C_T}}.$$

4.4. DEVELOPED FRAMEWORK FOR WAKE MODELS

In order to compare wake models and calculate the wake parameters the framework is developed. The fundamental of framework is given in Figure 4.3.

The framework is considered that takes model inputs such as power curve of wind turbines (includes velocity, power and thrust coefficient), turbine diameter, free stream wind speed, turbulence intensity, and turbine locations for implementation. By using simple wake models and wake added turbulence model, the framework is iterated over each wind turbine in wake. Further, the wake superposition of each wake model is found by linear sum formulation. As result of iteration, reduced free stream wind speed is found and corresponding C_T interpolation and iteration over next wind turbine is continued, and induced turbulence intensity is calculated by turbulence model.

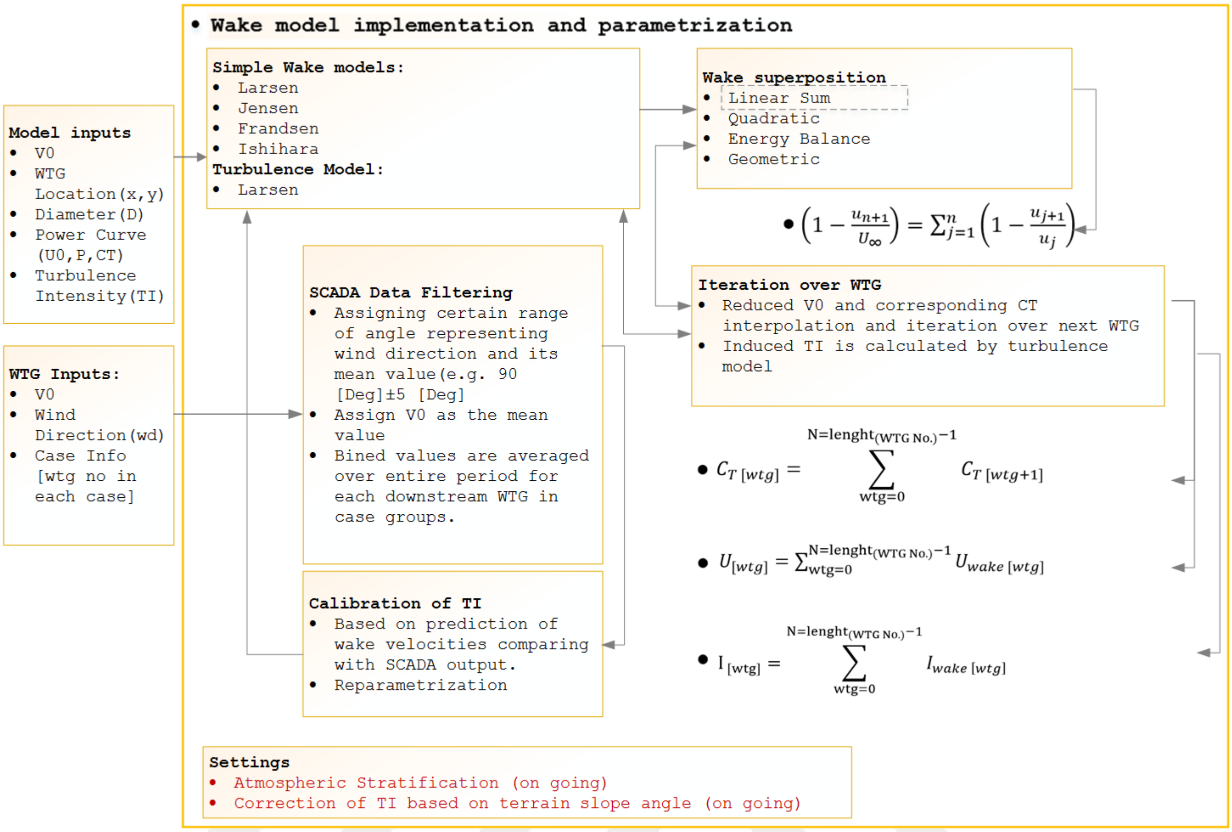

Figure 4.3. Developed framework for wake models

In order to validating wake cases, the wind turbine inputs are taken as wind speed, wind direction and case information (as turbine numbers). The wind turbine inputs are obtained from SCADA data which are filtered by assigning certain range of angle representing wind direction and its mean value and wind speed as the mean value. The binned values are averaged over entire period for each downstream wind turbine in case groups. As a purpose of framework, the calibration of turbulence intensity is applied based on prediction of wake velocities comparing with SCADA output.

5. RESULTS AND DISCUSSION

5.1. TURBULENCE INTENSITY LEVEL

Atmospheric turbulence impacts wind energy in several conditions that are through power performance impacts on each turbine and turbine loads and fatigue, and how wind turbines will affect their local environment through wake effects and noise propagation. In Figure 5.1 shows that turbulence intensity level of each sector between 4 and 25 m/s velocity bin.

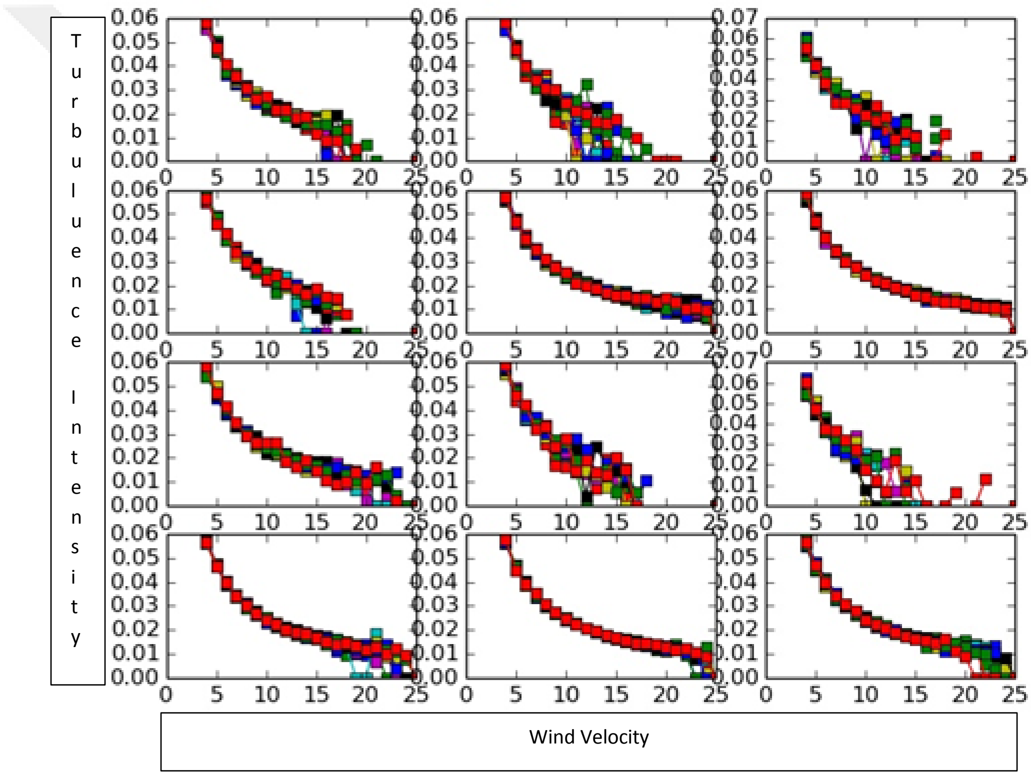

Figure 5.1. Turbulence intensity for inflow sector 0–360° with increment 30° and wind speed of each turbine

The turbulence levels are higher in lower wind speed due to higher fluctuations in flow. However, in higher wind speed turbulence intensity values are decreased as shown in Figure 5.1. In this study exception of met mast data and transfer function of ambient turbulence, these values are not reliable. The gathered data from nacelle anemometer is affected by rotor aerodynamics which creates fluctuations on flow.

Use of hub anemometer can be overcome that impact, nevertheless induction zone impact cannot be neglected. Also, data logger saves the data in one decimal although turbulence intensity fluctuates in small number.

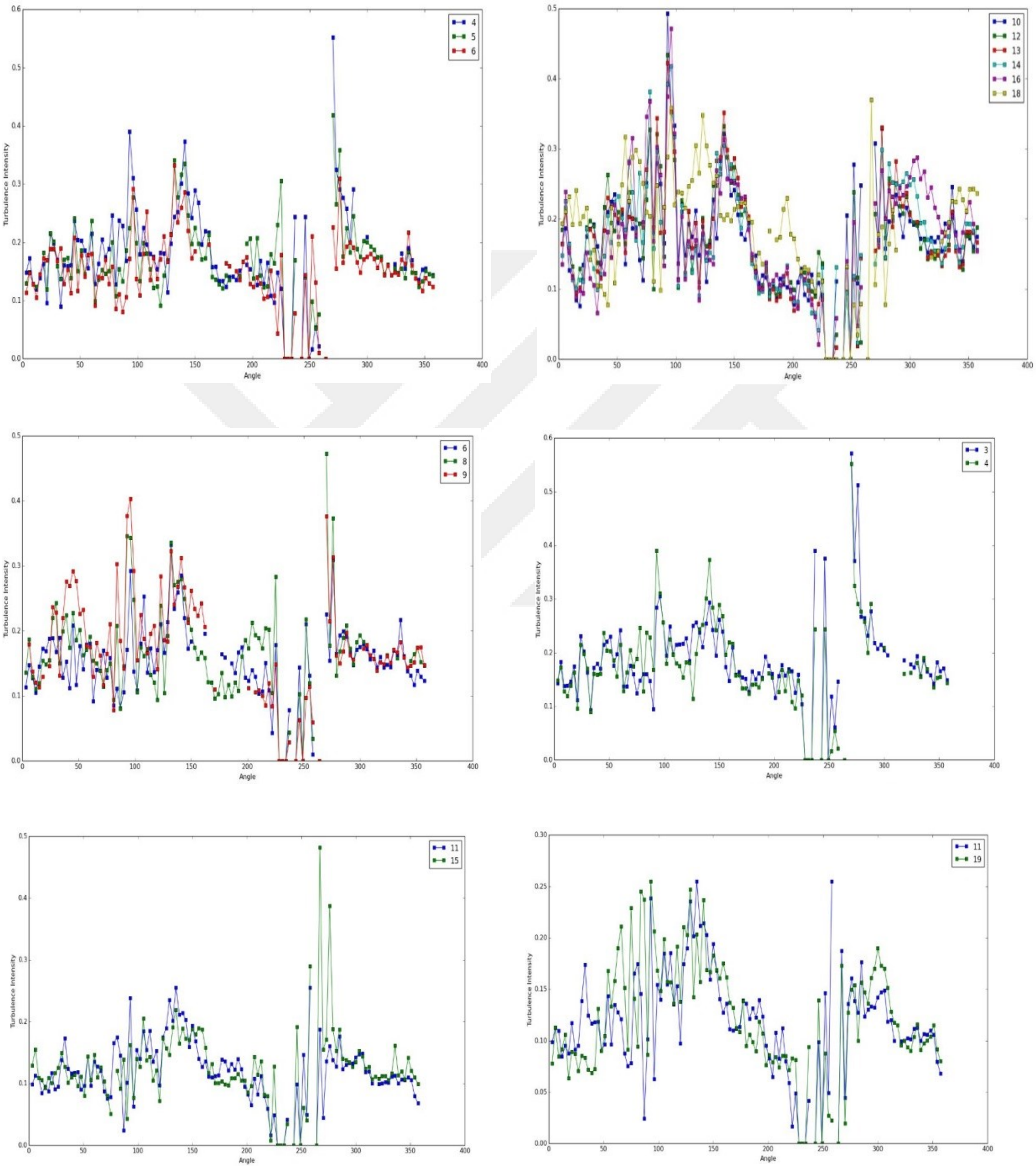

Figure 5.2. Turbulence intensity levels in each case according to angles

(case 1, case 2; case 3, case 4; case 5, case 6 are shown respectively)

The wake cases can be examined according to angles where the case angles selected is obvious to determine in Figure 5.2.

5.2. VALIDATION AND CALIBRATION OF TURBULENCE INTENSITY

The turbulence intensity values are tuned by selected angle for each case group as mentioned in developed framework section and given by Table 5.1.

Case Number	Angle	TI	Turbine Number
1	47	0.12	4,5,6
2	115	0.055	10,12,13,14,16,18
3	146	0.18	6,8,9
4	110	0.13	3,4
5	238	0.17	11,15
6	137.5	0.3	11,19

Table 5.1. Selected wake cases with specified angle and turbulence intensity by given turbine number of each case

5.2.1 VALIDATION AND CALIBRATION OF WIND SPEED

Wind speed validation and calibration for wake models are applied after turbulence intensity values are tuned by specified angle in each wake cases.

The wake model performance in case 1 is compared in Figure 5.3. Larsen wake model performs best fit although other wake models underestimate the velocity deficit in wake of second turbine. Further, Ishihara wake model has good wake recovery ability after second turbine wake. Underestimation of wake deficit can be caused by not including atmospheric stratification.

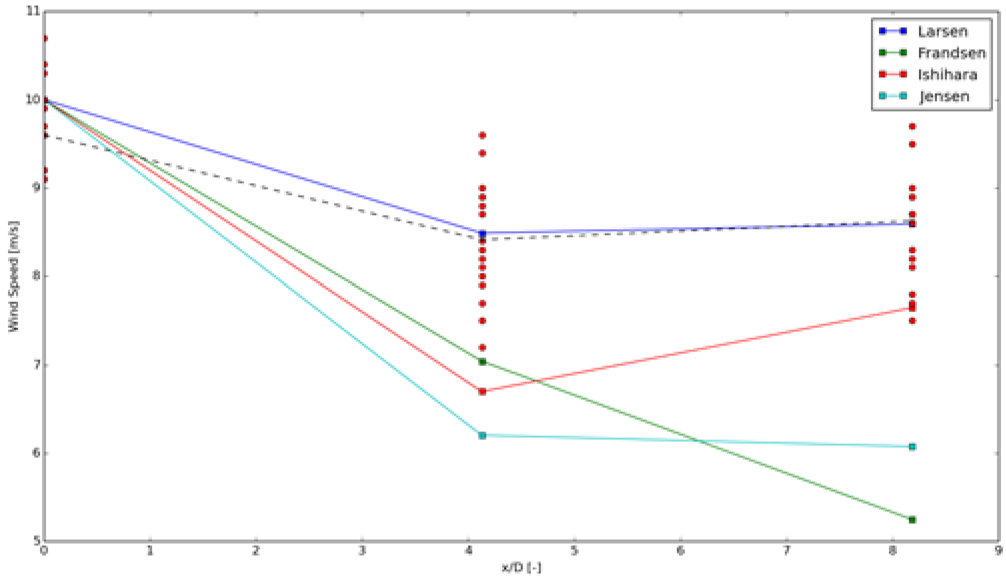

Figure 5.3. Case 1: wind speed in wake at downstream position with U =10 m/s ±0.5; wind direction 47 ±1.5; TI= 0.12. The red circles indicated the SCADA measurement at specified inputs. '– 'is average wind speed of measurement data.

The case 2 is using angle of ±1.5 bins as in case 1 that shows comparison of wake models. Larsen wake models performs very well in this case that over predict to last turbine of case as well as other models. It might be leading that last turbine is not in wake position of previous turbine it. Due to the wind speed is converging cut-in speed, models cannot assign a new C_T, hence its impact Frandsen and Jensen models' recover the wake immediately that are behave like there is no turbine.

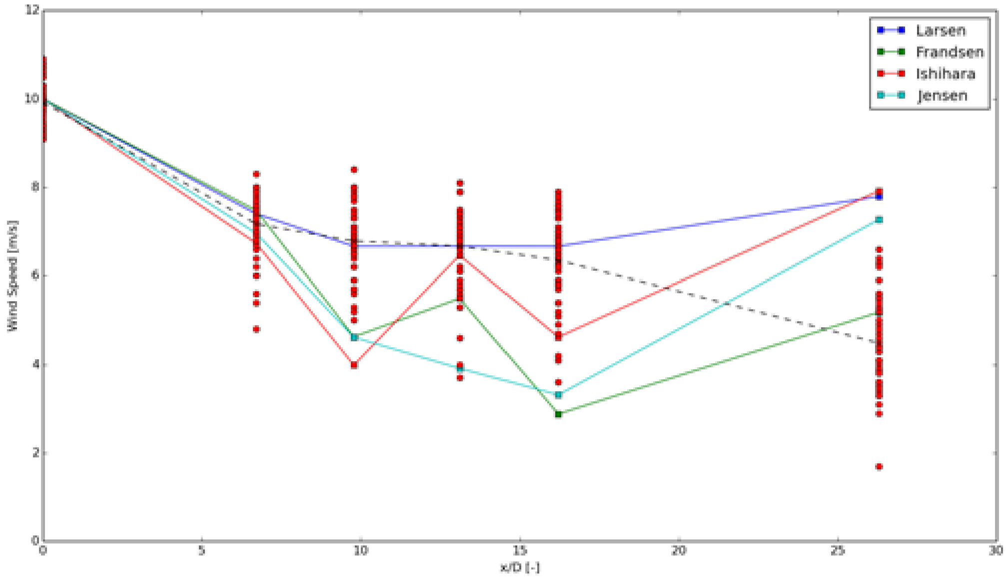

Figure 5.4. Case 2: wind speed in wake at downstream position with U =10 m/s ±0.5; wind direction 115 ±1.5; TI= 0.055. The red circles indicated the SCADA measurement at specified inputs. '– 'is average wind speed of measurement data.

The wake case 3 where turbulence intensity fairly high according to previous cases that is again performed best by Larsen wake model due to including turbulence application. All models under-predict the third turbine velocity in second turbine wake as shown in Figure 5.5. Because of simplicity of Frandsen and Jensen wake models which does not have implementation of turbulence, are performed badly in this case.

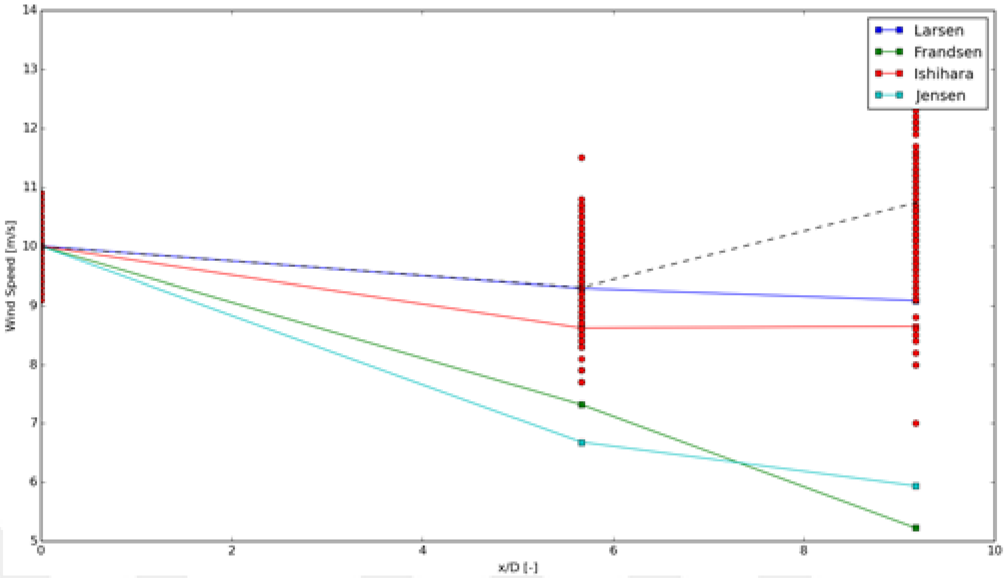

Figure 5.5. Case 3: wind speed in wake at downstream position with U =10 m/s ±0.5; wind direction 146 ±1.5; TI= 0.18. The red circles indicated the SCADA measurement at specified inputs. '– 'is average wind speed of measurement data.

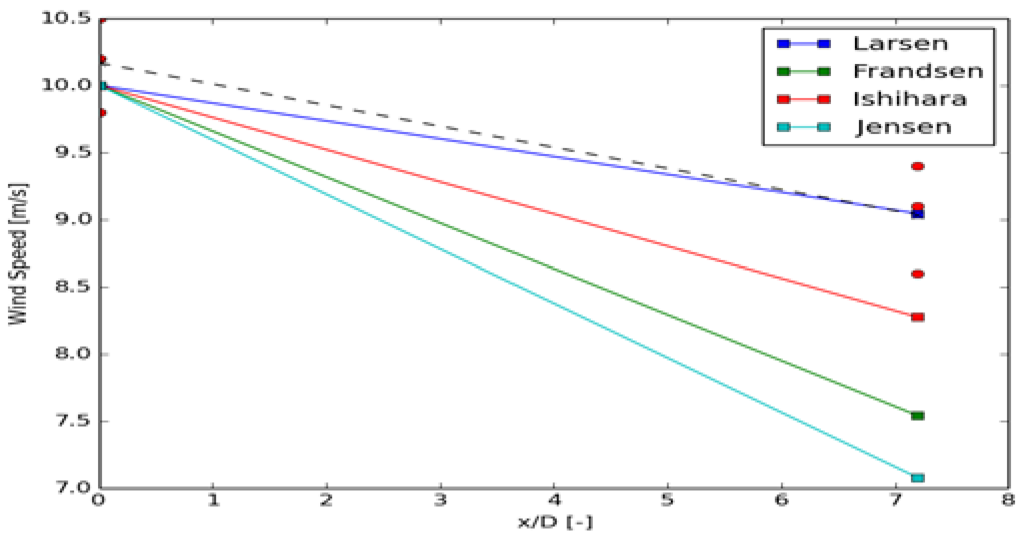

Figure 5.6. Case 4: wind speed in wake at downstream position with U =10 m/s ±0.5; wind direction 110 ±1.5; TI= 0.13. The red circles indicated the SCADA measurement at specified inputs. '– 'is average wind speed of measurement data.

In wake cases 4 and 5, Ishihara, Frandsen and N.O. Jensen wake models underestimate the velocity deficit of second turbine in direction of angle 110 where Larsen wake model has a good fit according to them.

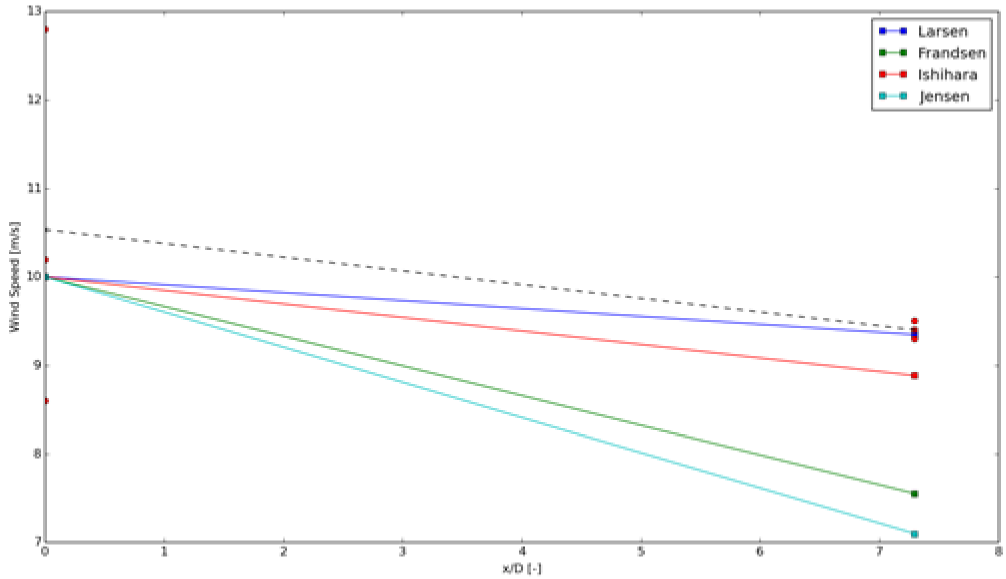

Figure 5.7. Case 5: wind speed in wake at downstream position with U =10 m/s ±0.5; wind direction 238 ±1.5; TI= 0.17. The red circles indicated the SCADA measurement at specified inputs. '– 'is average wind speed of measurement data.

The Ishihara and Larsen model are perfectly perform in the wake case 6; whereas, Frandsen and Jensen wake models under predict the velocity deficit badly. Ishihara wake model performance with higher turbulence intensity is based on its analytical background that turbulence impact on the wake recovery.

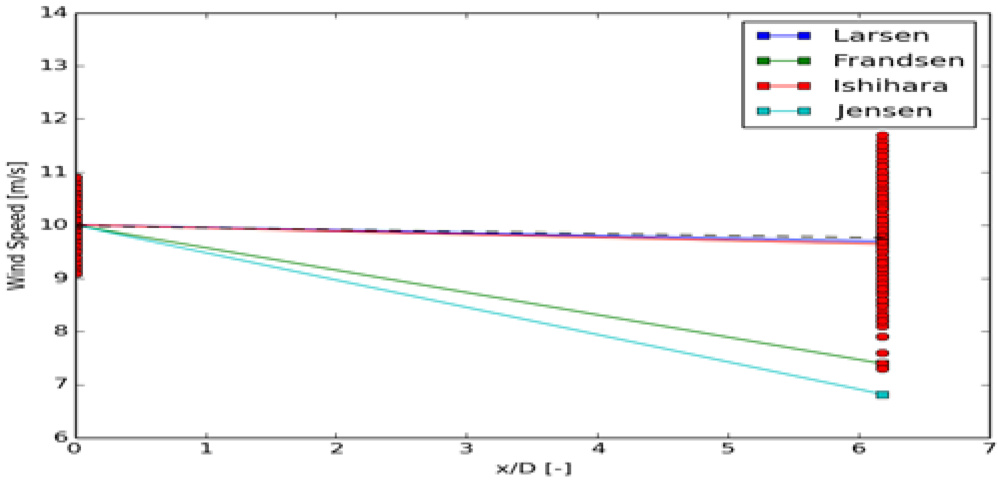

Figure 5.8. Case 6: wind speed in wake at downstream position with U =10 m/s ±0.5; wind direction 137.5 ±1.5; TI= 0.3. The red circles indicated the SCADA measurement at specified inputs. '– 'is average wind speed of measurement data.

5.3. POWER AVAILABILITY COMPARED WITH WAsP

In order to analyzing power availability of wind turbines, in other words, wind farm efficiency it is not affected by other turbines wake. Hence, it is based on calculated annual energy production that is applied by WAsP software.

The wind farm efficiency is around 0.83 by using year of 2012 and 2013 wind data and availability of each turbine is shown in Figure 5.9. Turbine availabilities are changed by 0.78 and 0.88, but the results are involving some uncertanies that are caused by software, nacelle anemometer, and wind regime distribution.

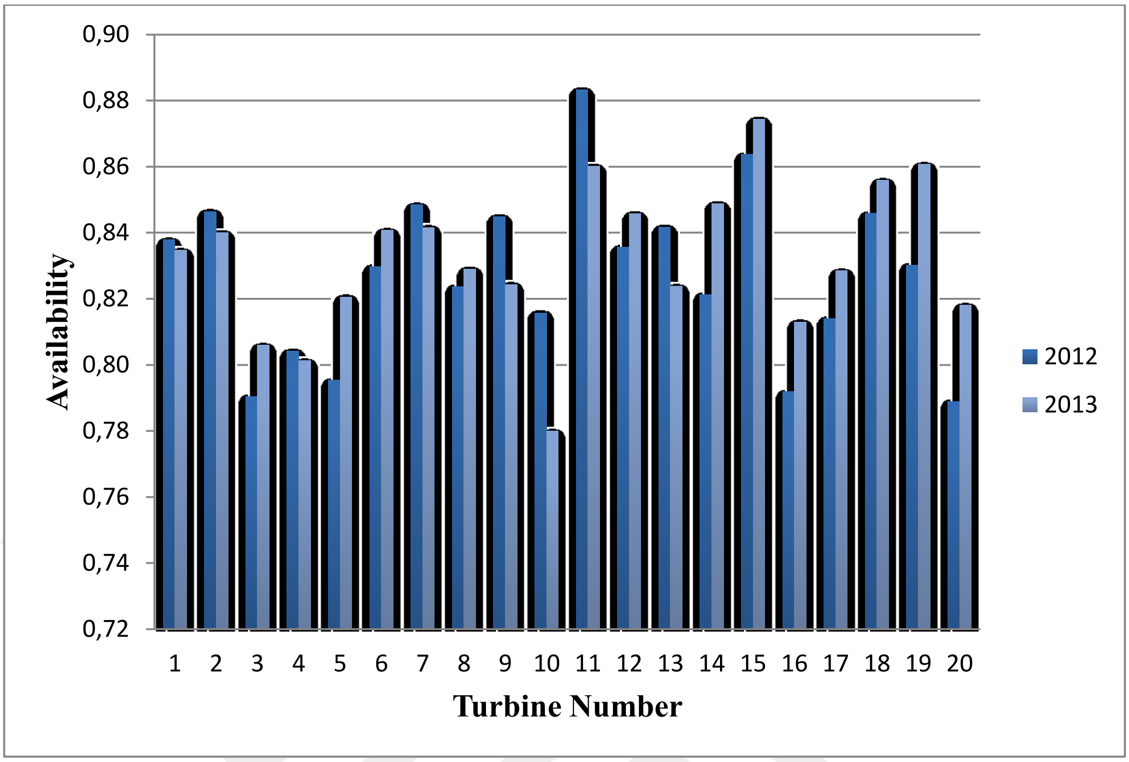

Figure 5.9. Power availability of each turbine in 2012-2013

6. CONCLUSION

This study researches the effect of wake models on the velocity deficit changes on downstream positions. Also, turbulence intensity calibration is applied to wake models in order to investigate the determined wake cases.

Turbulence intensities are required for further investigations due to neglecting atmospheric stratification which would reveal better calibration to the estimated turbulence intensities. It would allow estimating turbulence intensity levels with better accuracies. Therefore, turbulence intensities can be formulated as function of atmospheric stratification and terrain slop angle by providing more exact input for load models.

The analyzed SCADA data is not corrected with wind speed based transfer functions. This would cause higher turbulence intensities measured by nacelle anemometers, since the correlation between measurement tower and nacelle anemometer have to be calculated. Another issue on measured turbulence intensities relies on measured decimals of wind speeds.

Estimated turbulence intensities are depended on used turbulence model. However, only Larsen’s model is implemented in the study, inclusion of other turbulence models would answer weight of uncertainties in the wake of any number of turbines from certain range of wind direction. Since influence of implemented turbulence model affects wake characteristics and its propagation.

Wind farm efficiency is analyzed and it needs to more accurate calculation by disambiguating of software, nacelle anemometer, and wind regime distribution.

Advantage of using this wake framework has potential for developing online power forecast and fatigue damages due to rapidness and accuracy of the work. Validation of the framework is required to be expanded for more sites and longer operational data.

7. FUTURE WORK

In order to discover highly complex terrain sites CFD based validation is required. This developed framework for study can be extended for inclusion of radial and tangential component of wind speed that just conducted axial wind component in this study.

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