UNIVERSITETET I AGDER

Optimization of Wind Farm Layout taking Load Constraints into Account

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ABSTRACT

Optimization of a wind farm layout is of utmost importance due its economical aspect. The primary aim of optimizing layout is to increase the overall energy production. The higher energy production creates more revenue from wind farm during its operational life time. Wind turbines situated within wind farms are subjected to wake losses due to numbers of factors one of such factor is wind disturbance from the wind turbines installed in front. Therefore, the wind turbines will produce less output as compared to front wind turbines facing winds in free stream. Thus, to have an economically feasible performance, it is necessary to optimize wind farm layout in terms of both maximum energy and load constraints for life time of wind turbines. The turbines in the large wind farm causing increased turbulence that increases the fatigue damage levels, and the increased loads must be analysed. The thesis is devoted to the optimization of wind farm layout to maximize the energy production, and verifying the significance of wake loss effects with respect to optimal placement of wind turbines within wind farm. Thesis is divided into two followings parts:

In the first part, in the WFDs approach, the WindSim software for CFD simulations is used to calculate flow fields at various heights over the planned layout to set number of turbines as per IEC 61400-1 standard. Then, the resulting layout from WindSim is fed into the Wind Assessment Tool (WAT) to check if the chosen position of turbines verifies the IEC compliance criteria for effective turbulence. Next, the Park layout is used as in Park Optimizer tool to verify the project constraints, such as exclusion of areas where it is not possible to set up turbines, layout is optimized by calculating the energy production, etc. The Park optimization is based on the following factors: i) minimum distance between turbines, ii) to check the effective turbulence if it's not violating IEC criteria, and iii) minimizing wake deficits.

In the benchmarking of software tools, Wind Farm Designs (WFDs) optimization approach is used to maximize the annual energy production (AEP) by optimizing the turbine positions and comparing it with OpenWind (OW) software tool. OpenWind tool is used significantly for the layout optimization. The difference between both WFDs and Openwind optimization results compared based on gross and net annual energy production, and array efficiency from the park layout. Based on the results, it was found that the WFDs estimated lower net energy and array

efficiency as compared to OpenWind optimizer for the entire wind farm layout, differs same for both -1 %. However, the gross energy is estimated almost similar by both the tools, but WFDs optimizer estimated slightly lower.

In the second part of thesis, an analytical approach is used to check the sensitivity of wake losses at distances that are IEC compliant for simple cases between two turbines. Jensen wake model is used for the wake loss analysis due its high degree of accuracy. Frandsen model is used to satisfy effective turbulence criteria. The energy production of downwind turbines decreases from 2 to 20% due to the lower wind speeds as they are located behind upwind turbines, resulting in decreasing the wind farm overall energy production. Higher wake loss also increases the effective turbulence that leads to reduction in overall energy production within wind farm.

ACKNOWLEDGMENTS

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1 INTRODUCTION

1.1 OVERVIEW

When the oil crisis started in 1970s, afterwards, there has been immense efforts to find the alternative source of energy by many developed as well as developing nations. The wind energy sector evolved to primary source of electricity generation. The worldwide business of wind energy increased to 50 billion euros in terms of revenue and it employed 550,000 people around the world [1]. From the Fig. 1.1, we can see the top ten nations with their total wind capacity from the last decade almost. In table 1.1, we can see that China tops in the share of wind world power production, contributing 34.7% followed by US comes second, 16.9% and Italy ranks 10 in term of wind power production, having 1.9% share in total production.

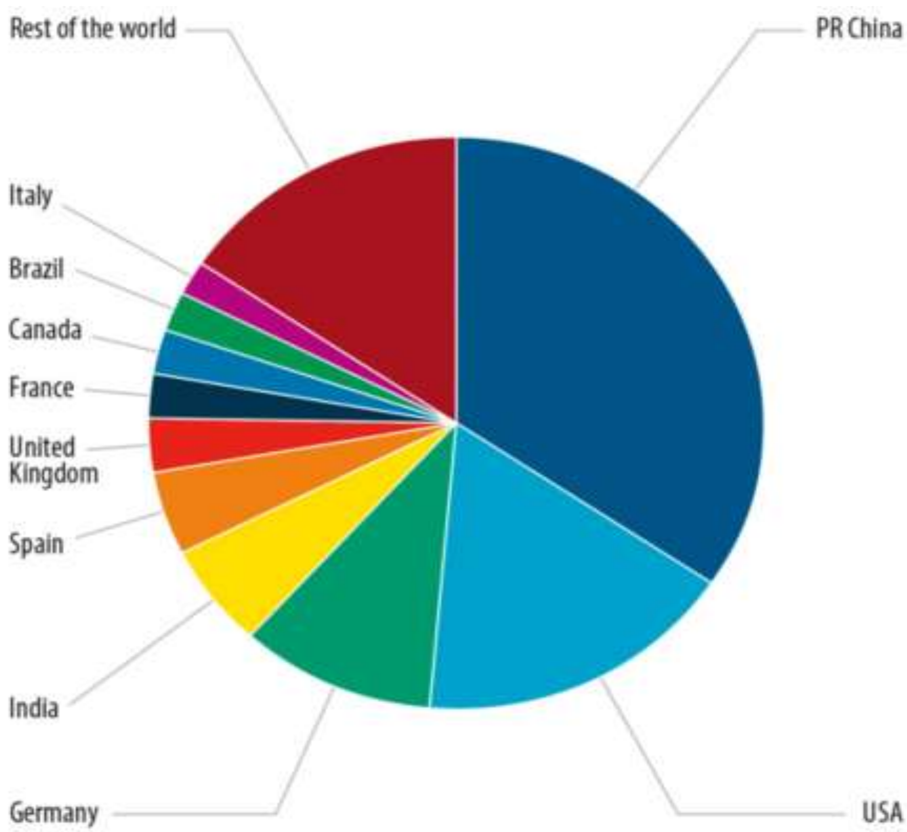

Figure 1.1. Top 10 nations with Installed capacity [MW] of wind power in Dec. 2016[2].

Table 1-1. Cumulative Capacity Dec 2016[2]

Country	MW	%Share
PR China	168,690	34.7
USA	82,184	16.9
Germany	50,018	10.3
India	28,700	5.9
Spain	23,074	4.7
United Kingdom	14,543	3.0
France	12,066	2.5
Canada	11,900	2.4
Brazil	10,740	2.4
Italy	9,257	1,9
Rest of the world	75,577	15.5
Total Top 10	**411,172**	**84**
World Total	**486,749**	**100**

The Fig. 1.2. shows the location of a site in Trøndelag, northern Norway, which is located on the coastal line. The wind resources analysis around this region will be assessed. The data set is obtained through a met mast over 80 meter of hub height.

Norway generates most of its energy through hydropower, which is 96% of the total energy, whereas wind power only amounted to 1.5%. In the recent years, Norway is actively increasing its share in the field of wind power, having the installed capacity 2.214 GWh, in 2014. Fosen Vind is one of the Europe's largest onshore wind farms under construction since 2016 in Norway, having total capacity of 1 GW [3, 4].

The capacity a large wind farm is over 100 MW, in general. The capacity of wind farms depends on the size of the wind farm. Generally, location is carefully selected depending on the wind speed and wind direction in site-specific region. For large wind farms, the local wind data is analysed for a year at least before construction begins. The turbine positions must be optimized for optimum energy production during its operation, especially in hilly areas [5]. Similarly, we are focusing on one such issue regarding the optimization of a wind farm layout to have maximum output energy production.

Figure 1.2. The google earth map shows the location around the site.

1.2 PROBLEM DESCRIPTION

In general wind conditions in complex terrain and its influence on turbine loads are not well understood. Norwegian sites often experience operational problems due to complex wind conditions that are believed to be problematic for turbines, because there are rapid changes in wind directions, high turbulence, and high flow inclination. The goal is to maximise production within wind farm while keeping turbine loads within constraints by using Wind Farm DesignS (WFDs) approach developed by Markedslabben AS[6]:

In this project, we will compare and optimize the wind farm layout situated in Norway, as per IEC (International Electrotechnical Commission)61400-1 constraints by applying two different wind farm design software tools WFDs and OpenWind. We compare the annual energy production (AEP) from both software tools.

WFDs is a newly developed tool that maximises energy production with respect to IEC constraints and its algorithm is incorporated with ParkOptimizer tool. WFDs optimization approach is developed by WindfarmDesigns to create an algorithm to optimize load compliant layouts as per IEC compliance.

IEC constraints are derived from the standard for wind turbines, which is a simplified check for turbine loads. WAT (Wind Farm Assessment Tool), WindPro Site compliance module, and OpenWind are INDUSTRY tools that are employed to check whether turbine layouts comply with the IEC standard.

1.3 GOALS

Our main goals are to verify IEC compliant wind farm layouts using windfarm design optimization approach using different tools like WAT, and using CFD results from WindSim. WFDs (WIND FARM DESIGNs) optimizer will be used for the verification of layout by using WindSim a CFD model, both WAT and WFDs Park Optimizer are employed to check if the layout is IEC compliant.

Then, we compare the output of the different optimization software WFDs and AWS openWind (INDUSTRY TOOL). We compare the softwares using the same layout based on gross and net energy production.

Afterwards, using an analytical approach, we will check the sensitivity of wake losses at different distances that are IEC compliant for simple cases, for example, how the wake effect from upstream turbine influences the downstream turbine, causing overall energy losses within wind farm. The effective turbulence criteria will be satisfied at certain distance in terms of load constraints.

2 THEORETICAL BACKGROUND

2.1 OVERVIEW

In this chapter, we will discuss about physical phenomenon and basic characteristics of wind, such as power in the wind and, turbulence and wind profile respectively, there some local factors influencing wind conditions such as surface roughness, turbulence intensity, hill effects. The standard procedure of wind farm layout verification will be discussed in the following section of this chapter.

2.1.1 THE KINETIC ENERGY IN THE WIND

The wind is resource for the wind power station. Small changes in wind speed produce greater changes in the commercial value of a wind farm. For example, a 1 % increase in the wind speed might be expected to yield a 2 %increase in kinetic energy. The extraction of the power by a wind turbine depends on various parameters, such as turbulence intensity, wind profile, wind wake, roughness, hill effects, and so on [7]. The kinetic energy of the wind is given as [1]:

$$E = \frac{1}{2} m v^2 \qquad (2\text{-}1)$$

where,

m - is mass [kg] and

v – is the mean speed [m/s]

Eq. 2.2, derives the theoretical power equation from the kinetic energy of the wind.

$$\dot{E} = \frac{1}{2} \dot{m} v^2 = \frac{1}{2} \rho A v v^2 = P = \frac{1}{2} \rho A v^3 \qquad (2\text{-}2)$$

where,

P - is the theoretical power of the wind [J/s];

$\dot{E}$ - is energy per second, which is the same as power P;

$\dot{m}$ - is the amount of matter contained in a cylinder of air of length v;

A - is the cross-section area [m²];

ρ- is air density at a standard value of 1.25 [kg/m³];

v – is the mean wind speed [m/s];

Figure 2.1, shows the volume of the air that is cylindrical, similarly in the case of horizontal axis wind turbine. The mass from which the energy is extracted is the mass contained in the volume of air which will flow through the rotor.

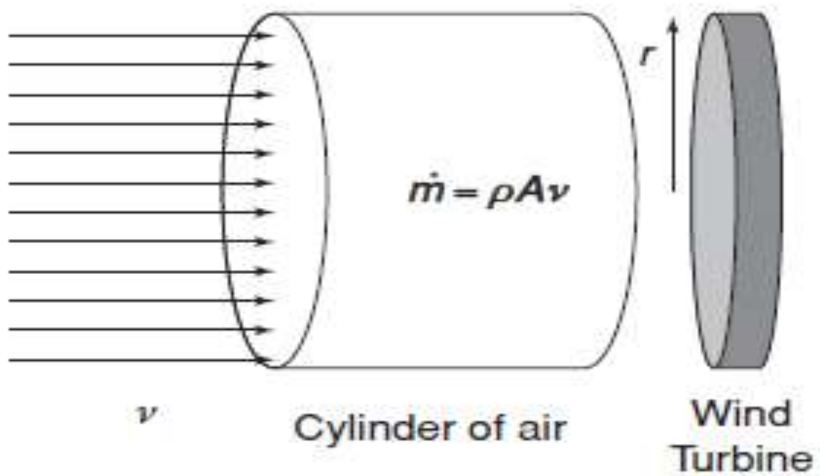

Figure 2.1 Cylinder of air in front of the rotor[1]

2.1.2 POWER IN THE WIND

The power in the wind is proportional to the cube of the wind speed. Small changes in wind speed can have significant impacts on potential energy production. The energy that can be harnessed from the wind will also increase with greater surface area.

The theoretical maximum amount of power that can be extracted from the free wind by a wind turbine is given by Betz law at 59%[8]. The power coefficient defines the power that each turbine can attain and is usually given in most turbine specifications. The power of the wind is expressed in Eq. 2.3, as[8]:

$$P = \frac{1}{2}\rho A v^3 c_p \qquad (2\text{-}3)$$

where,

c_p - is the power coefficient.

Fig. 2.2, shows the wind turbine power curve that describes how the behaviour of the wind turbine changes between the cut-in and cut-out wind speed. The turbine starts producing power at cut-in wind speed of 3 m/s, but turbine reaches at its maximum power at wind speed of 13 m/s. When turbine reaches at maximum wind speed of 25 m/s, it stops operating. The main reason for stopping is safety, because components of the turbines are not designed to handle the loads created by wind speed higher than the cut-out speed.

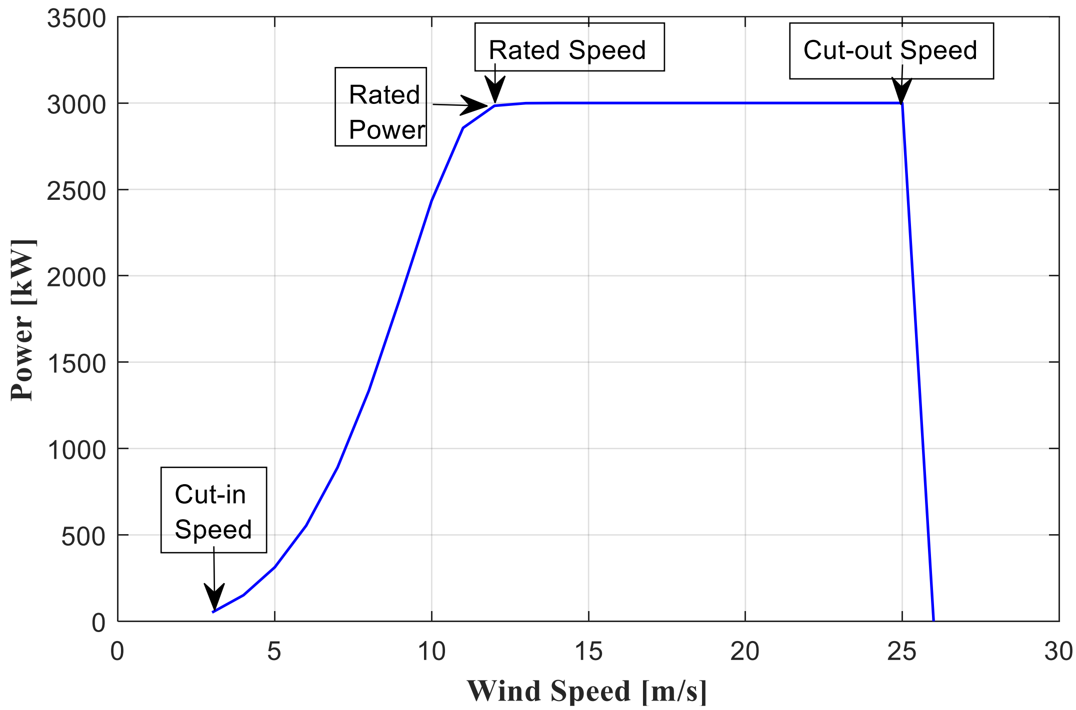

Figure 2.2. Power curve of the Siemens 108 3MW wind Turbine, for a range of wind speeds.

The thrust coefficient curve, see Fig. 2.3, is also typically available from the manufacturer. Both the wind turbine power curve and thrust coefficient curve for the Siemens 108 turbine are also used for the study of wake loss effects, for more details see in Chapter 5.

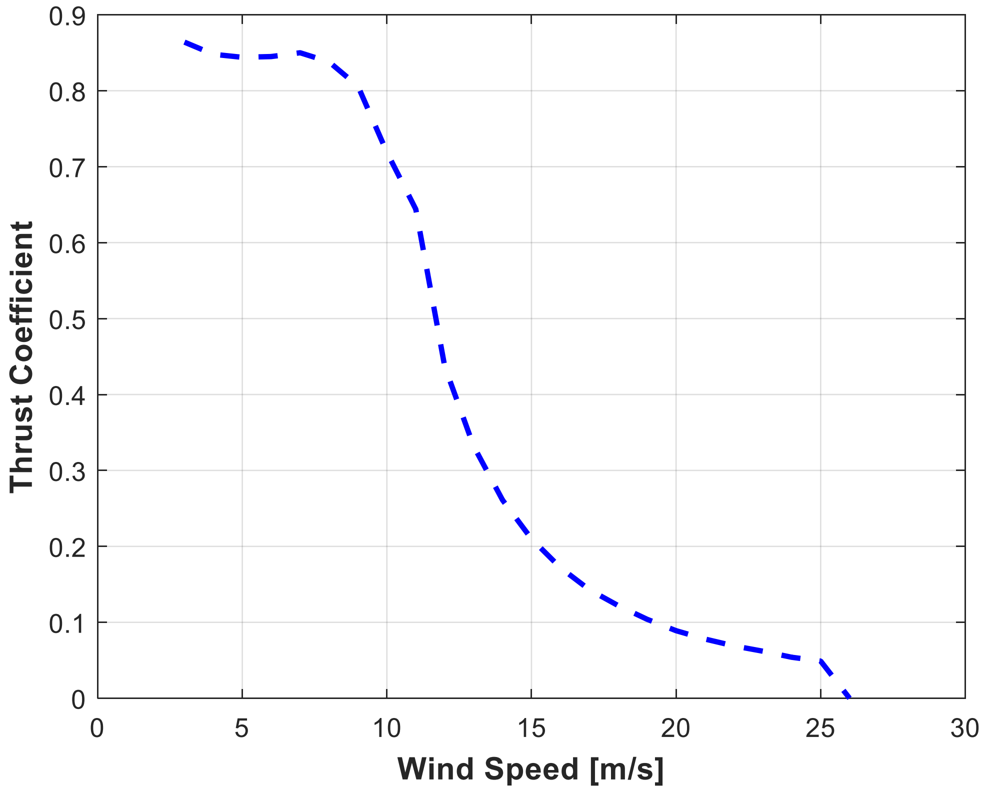

Figure 2.3 Thrust coefficient curve of the Siemens 108 3MW wind Turbine, for a range of wind speeds

2.1.3 PROPERTIES OF WIND

When making a site estimation, it is very important to know about the wind characteristics, because it is directly linked with the economy of wind farm layout. Having a poor knowledge of the site may lead to reduction in energy yield. The following are the characteristics of wind, such as:

2.1.3.1 Wind shear

Wind shear is described as change in wind speed as function of height. There are two methods to describe shear:

Logarithmic Law or Log-law

Log-law is the most common mathematical model for accounting the variation of the horizontal wind speed with height. Which has its origin in boundary layer flow in fluid mechanics and in atmospheric research [9]:.

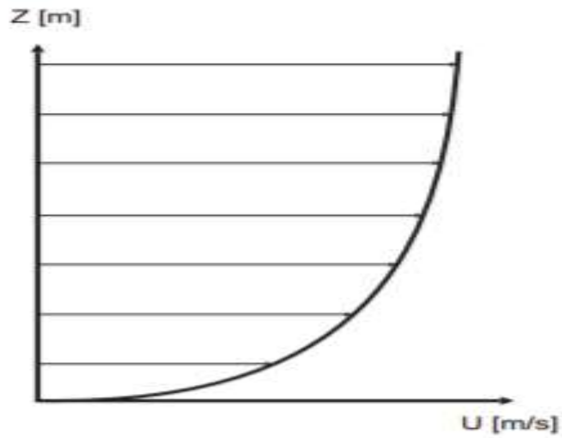

Figure 2.4. Logarithmic velocity profile[10]

we can see that the wind velocity U at ground level is zero, because there is no slippage on the surface. Wind speed increases with height logarithmically due to the variations in surface roughness. The friction is higher at rough surface and lower at smooth surface. The log-law gives the wind speed at a specific height as a function of the terrain parameters. Eq. 2.4, describes the log-law for low roughness and homogeneous terrain, that is for open areas [9]:

$$u(z) = \left(\frac{u^*}{k}\right) \ln\left(\frac{z}{z_0}\right) \quad \text{for } z > z_0 \tag{2-4}$$

where,

$u(z)$ – is the wind speed at height z above the ground, [m/s];

u^* – is the friction velocity [m/s];

k – is the Von Karman constant [-];

z_0 -is the surface roughness lenght [m]

Power Law

Power law is the most common method to describe wind speed with height. In addition to the theoretical shear profile, the engineering industry also uses the formula for wind shear, also employed in the Park Optimizer software[11], which is expressed in Eq. 2.5[12]:

$$V_2 = V_1 \left(\frac{h_2}{h_1}\right)^{\alpha} \tag{2-5}$$

where,

α – the wind shear exponent, also called power law exponent;

V_1 – the wind speed at the anemometer height [m/s];

h_1 – is anemometer level height [m];

V_2 – is the wind speed at the reference level height [m/s];

h_2 – is the reference level height [m/s].

The wind shear component (α), is mentioned in Eq. 2.6.

$$\alpha = \ln\frac{\left(\ln\frac{h_2}{z_0}\right)/\left(\ln\frac{h_1}{z_0}\right)}{\ln\frac{h_2}{z_0}} \tag{2-6}$$

To evaluate the wind conditions in a landscape, wind industry refer to roughness classes or roughness lengths. Table 2.1, gives the properties of roughness lengths for various landscapes. An open sea generates a shorter roughness length, indicating low friction between the wind and the surface. Thus, wind profiles over sea areas experience a rapid increase in wind speed with height, thus attaining better conditions for power generation at lower altitudes. However, the roughness length is much larger in the city area due to the high friction between the wind and surface.

Table 2-1. Roughness lengths for various landscapes[13]

Landscape	z [m]
City	≥2
Suburbs	1.0
Cultivated area	0.1
Grass prairie	0.03
Snow covered fields	0.005
Sea	0.0002

2.1.4 STATISTICAL DISTRIBUTION

The Weibull probability density function is the most common density function used to describe wind speed, is expressed as[1]:

$$pd(v) = \left(\frac{k}{A}\right) \times \left(\frac{v}{A}\right)^{k-1} e^{-\left(\frac{v}{A}\right)^{k}}, for\ v > 0 \qquad (2\text{-}7)$$

where,

v – is the wind speed [m/s];

k – is the shape factor (determines the shape of the curve) [-];

A – is the scale factor (determines the scale of the curve) [m/s].

2.1.5 TURBULENCE

Turbulence is a very significant property of wind. Turbulence is based on analysis of the short-term data (in seconds), whereas the Weibull statistics work with hourly or 10 min averages. Turbulence is the random variation in wind speed superimposed on the mean wind field. We can see from Fig. 2.5 (Ellipse), how the flow forces on the tower and over dynamic rotating blades are acting and becomes the main contributor to structural loading.

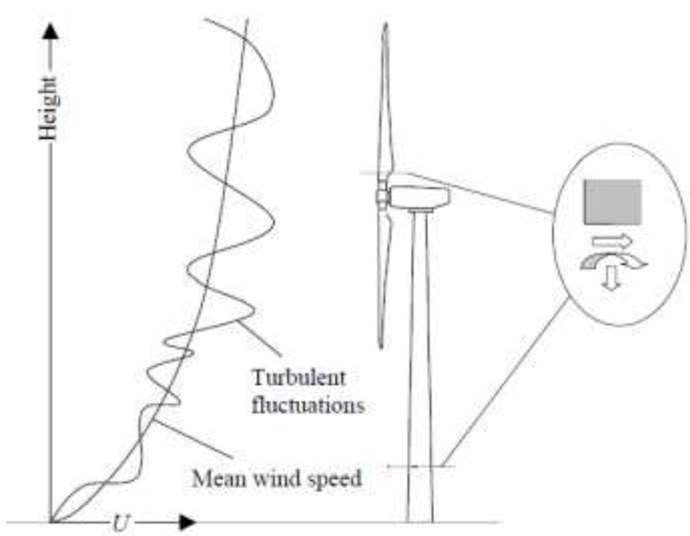

Figure 2.5. The impact of turbulence intensity as wind speed is increasing with height[14]

.

Turbulent flows are also analysed by Reynolds decomposition equation, see Eq. 2.8 [15]. This equation decomposes the turbulent flow quantities in mean and turbulent components.

$$u(x,t) = \bar{u}(x) + u'(x,t) \tag{2-8}$$

where,

t – is the time;

$\bar{u}(x)$ – is the steady state or average component function of direction;

$u'(x,t)$ – is the turbulent component function of both direction and time.

2.1.5.1 Turbulence intensity

Fluctuations in wind speed over short periods can however be measured and give helpful means with which to measure turbulence. Turbulence intensity (TI) is described as the ratio of standard deviation to the mean wind speed[1], see Eq. 2.9.

$$TI = \frac{\sigma}{v_{mean}} \tag{2-9}$$

where,

σ – is standard deviation

v_{mean} – mean wind speed

2.1.6 HILL EFFECT

Hill effect described in terms of complex terrain. A complex terrain is described as areas with mountains and valleys. Generally, it is difficult to predict the behaviour of wind in such complex terrains. In the complex terrain, wind has an effect of the hill by its steepness and roughness, and creating a natural turbulence caused by obstructions and topography. However, over a flat terrain the wind will increase in speed up to a maximum height[7]. We can see the flow separation behaviour in case of real wind conditions as shown in Fig. 2.6.

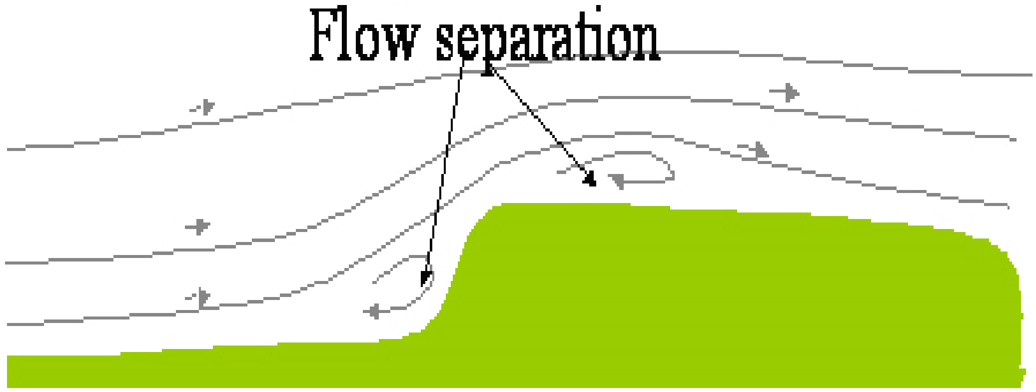

Figure 2.6. Flow Separation over hill[7]

2.2 WAKE MODELS

When turbines are in their normal operation within windfarm, the rotor blades interact with the incoming wind field that generates a pressure drop at the site of interaction converting the kinetic energy of the wind into output power[16]. This interaction influences the incoming wind field, that slow down the wind velocity of the downwind. In turn, turbines placed behind of these turbines will therefore be in the wake of the front turbines will create wake loss. In the next section, we will discuss more about the two wake models Jensen and Frandsen [17], both are widely used due to their result accuracy and ease of implementation. Wake models check how the velocity deficit causes reduction in output energy of the downwind turbines.

2.2.1 JENSEN WAKE MODEL

Jensen developed a simple analytical wake model. This model is used significantly in optimizing the position of wind turbines. Jensen wake model based on global momentum conservation and on the assumption of a wake with linearly expanding with diameter (see Fig. 2.7) to predict the velocity deficit in downstream region. Wake loss is characterized by a uniform velocity profile, often termed „top hat", which is only dependent on the distance downstream from the turbine. Due to the simplification of velocity profile, the model cannot be used to make wake predictions in the near wake region. Instead of using Gaussian distribution this model is made to give an estimation of energy content in the wind field seen by the downwind turbines, rather than to describe the velocity field accurately [18].

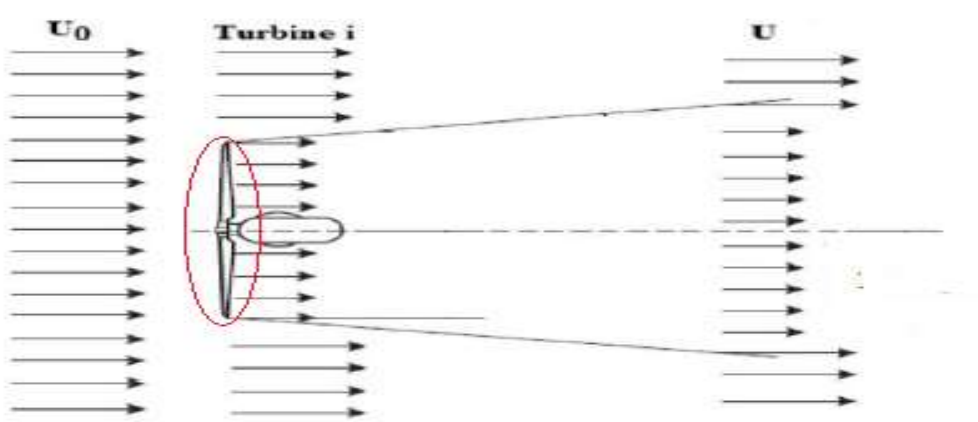

Figure 2.7. Jensen Wake Model[18]

The Normalized wake loss is explained by N.O. Jensen wake model. From the Eq. 2.10, we solve for the velocity deficit in wind wake, can be expressed as following[19]:

$$\sigma_{wake\_loss} = 1 - \frac{U}{U_0} = \frac{1-\sqrt{1-C_t(V_{hub})}}{(1+2kx)^2} \tag{2-10}$$

where,

RD - is the rotor diameter (in our case is 108 m);

k - is the slope or wake decay constant, Onshore value of k = 0.075 and for offshore value of k = 0.04 are commonly used;

x - is the normalized distance in RD;

$C_t(V_{hub})$ – is the thrust coefficient which is function of wind speed at hub height.

2.2.2 FRANDSEN EFFECTIVE TURBULENCE MODEL

The Effective turbulence check is together with the Extreme wind check one of the most important IEC checks. Where Extreme wind represents the extreme loads, the Effective turbulence mainly represents the fatigue loads, a more long-term degradation of structural integrity of the turbine.

The Frandsen [11] model defines the effective turbulence as a combination of ambient and wake generated turbulence integrated overall directions in a way that accounts for accumulation of fatigue using material properties, see Fig. 2.8. The effective turbulence is calculated using the 90th percentile of ambient turbulence as per IEC61400-1 edition-3 2010 amendment [20], and m is the material parameter Wöhler exponent.

Wöhler exponent is the general material parameter which is used to weight fatigue accumulation as described for the Frandsen Effective turbulence model. Usually, the value 10 is assumed as it represents reinforced fiberglass and thus the WTG (Wind Turbine Generation) blades. A value of approximately 3 represents steel and e.g. the tower or main shaft. Generally using a high value e.g. 10 will be a conservative assumption for materials with a lower Wöhler exponent[11].

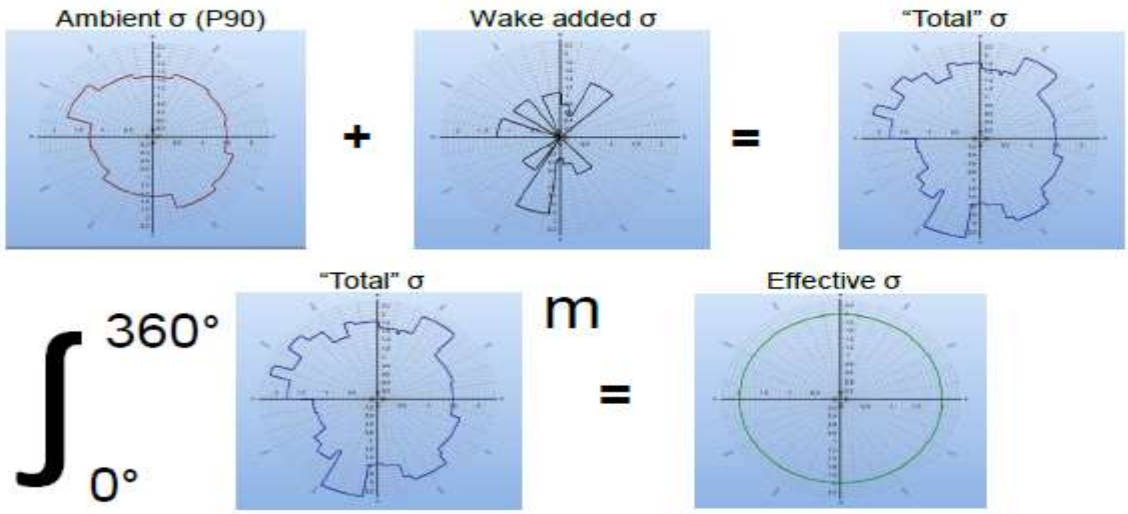

Figure 2.8. Simplified illustration of the main calculation steps in the Frandsen effective turbulence model [11].

For each WTG (wind Turbine Generation) position in the calculation, the Frandsen model needs the following inputs[11]:

1. $\hat{\sigma}(\theta, V_{hub})$ and $\hat{\sigma}_{\sigma}(\theta, V_{hub})$ – Ambient turbulence (mean and standard deviation functions of direction and wind speed)
2. $W(A_i, k_i)$ and $f(\theta_i)$ – Weibull distributions and sector-wise frequencies
3. C_T – Turbine thrust curve and park geometry
4. m – Relevant material fatiue property Wöhler exponent

Input 1 is used to calculate the ambient characteristic turbulence, i.e. the 90th percentile.

Input 2 is used to calculate the directional wind sped distribution conditioned on wind speed.

Input 3 is used to calculate the wake generated contribution to turbulence.

Input 4 is used in the fatigue weighted combination model of single directions to obtain an omnidirectional effective turbulence as a function of wind speed only.

2.2.3 CALCULATION OF THE EFFECTIVE TURBULENCE

In the Fransdson model, various inputs are used for each wind turbine generator position to calculate ambient characteristic turbulence, sector wise frequencies f(s) and Weibull distributions, turbine thrust curve, and relevant material fatigue property that is Wöhler exponent(m). Maximum Wöhler exponent coefficient (m = 10) will be chosen in case of complex terrain, is meant for glass fibre[21] .

Effective turbulence is calculated as function of wind speed only. This done by integrating the directional variation of turbulence over all directions for each wind speed bin. However, effective turbulence is not a measurable quantity as it combines the directional contributions with a special weighting that accounts for material fatigue via use of the material parameter, the Wöhler exponent. The estimated wake added turbulence (σ_{wake}) contribution is combined with the 90th percentile of the ambient turbulence at each wind turbine generation. The normal turbulence model is illustrated below for each of the three turbulence classes. From the Eq. 2.11[22], we solve for effective turbulence(σ_{eff}).

$$\sigma_{eff}(V_{hub}) = [\sum_s \sigma_{total}\,(s, V_{hub})^m . f(s)]^{\frac{1}{m}} \tag{2-11}$$

where,

s – is the number of sectors, (in our case s=1);
f – is the frequency sector-wise:
m – is Wöhler exponent (in our case m=10):
V_{hub} – is the wind speed at hub height:
σ_{total} – is the total turbulence;

If we consider only one wind direction and Wöhler coefficient (m=10), then the effective turbulence, σ_{eff} reduces to the Eq. 2.12.

$$\sigma_{eff}(V_{hub}) = \sigma_{tot}(V_{hub}) \tag{2-12}$$

2.2.3.1 Total Turbulence

The total turbulence ($\sigma_{\ tot}$) is different from effective turbulence(σ_{eff}), is calculated in each direction combining of measured 90th percentile of ambient turbulence or characteristic turbulence (σ_c) and calculated wake added turbulence (σ_{wake}), see Eq. 2.13[11].

$$\sigma_{\ tot} = \sqrt{\sigma_c{}^2 + \sigma_{wake}{}^2} \tag{2-13}$$

The characteristic turbulence (σ_c) is calculated as the 90th percentile of the estimated turbulence. Standard deviation ($\hat{\sigma}$) and standard deviation of estimated standard deviation ($\hat{\sigma}_\sigma$) (The correction factor should only be applied to $\hat{\sigma}_\sigma$), see Eq. 2.14, We apply the **correction factor 1.15** [20], because the results of the complexity check are used in the Effective turbulence calculation via a correction factor called turbulence structure correction factor which is required by the IEC standard. The factor 1.28 is estimated from the normal distribution curve of standard deviation, where the value of 90% percentile is sought[23].

$$\sigma_c = (\hat{\sigma} + 1.28\hat{\sigma}_\sigma) \tag{2-14}$$

2.2.3.2 Wake added turbulence (σ_{wake})

Wind turbines are in their normal operation periods within wind farm changes the ambient turbulence that causes wake from the neighbouring or nearest turbines. By using the Eq. 2.15 we calculate the wake added turbulence to verify that how much wake added turbulence is there. We calculate the wake added turbulence (σ_{wake}), for distance with less than 10RD, to verify with $I_{ref} = 0.14$, We verify the effective turbulence variations over distance less than 10RD.

$$\sigma_{wake} = \begin{cases} \dfrac{V_{hub}}{1.5 + 0.8 \times \dfrac{x}{\sqrt{C_T(V_{hub})}}},, \; x < 10RD \\ \sigma_{wake} = 0, \; x > 10RD \end{cases} \tag{2-15}$$

where,

V_{hub}- is the wind velocity at hub height;

x – is the normalized distance in RD (x=d/RD);

RD – is rotor diameter;

C_T – is the thrust coefficient.

2.3 WIND RESOURCE ASSESSMENT

In this section, we will discuss about the standard procedures of a site assessment. For most prospective wind farms, we must undertake measurement and analysis for the suitable layout. The energy production of a wind farm is possible to predict by using methods such as the Wind Atlas Methodology within WAsP [24]. Such analyses are generally used only to assess the initial feasibility of wind farm sites[8]. It is also necessary to make careful selection of wind turbine and layout design process based on environmental conditions such as turbine noise, compliance with electrical grid requirements, commercial considerations associated with contracting for the supply of the turbines and detailed turbine loading considerations. Fig. 2.9, shows the scheme of the process of a wind farm Energy production for an optimum layout.

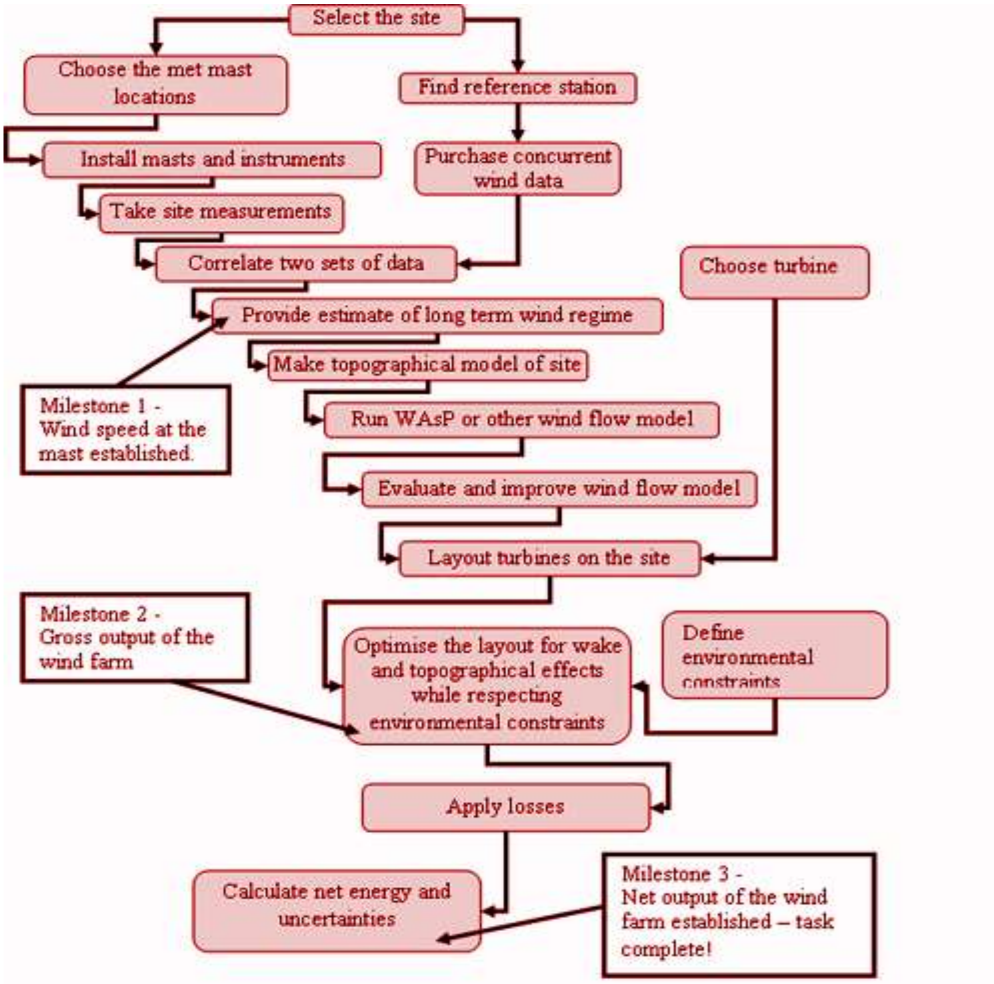

Figure 2.9. Overview of energy production process in Wind Farm Design[8]

2.3.1 CLASSIFICATION OF WIND TURBINES

In general, when designing a wind farm, it is important to choose a certified turbine as per IEC 61400-1 edition 3[20, 25], which defines the standard wind turbine design classes, see Table 2.2. The selection of wind turbines must be made in terms of its capacity of withstanding with severe wind conditions, and structure of wind turbines such as mainly the rotor blades, must comply with certain Load, that is basically choosing a suitable turbine model to develop a wind farm.

The wind speed class is described in roman letters from I to III, and. the turbulence class is defined in Latin letter from A (high turbulence class = 0.16) to C (lower turbulence class = 0.12). Wind speed classes are characterized as Vref, an extreme wind speed with 50 year's gust. Turbulence classes[11] are characterized via Iref, a mean turbulence intensity at 15 [m/s].

Table 2-2. Wind Turbine Classes as per IEC 61400-1 [25].

Wind Turbine Class	I	II	III	S
V_{ref} [m/s]	50.0	42.5	37.5	Values Specified by the designer
A I_{ref} [-]	0.16			
B I_{ref} [-]	0.14			
C I_{ref} [-]	0.12			

2.3.2 MAIN CHECKS FOR SITE ASSESSMENT

When we make an assessment for a site-specific condition, we must verify that the actual site-specific conditions are less severe than assumed in the turbine certificate. Site conditions do not compromise the structural integrity of the wind turbine design class. To make this assessment it defines several parameters, mainly relating to the wind climate, which must be estimated for each wind turbine position. The following important criteria's are explained that applies for wind climate for each turbine and are listed in Table 2.3[19, 26].

The table 2.3, shows some of the important parameters for IEC checks with respect to site conditions, where, the extreme wind speed (V_{50y}), is 50-year of recurrence, must be lower than the reference wind speed (V_{ref}). Effective turbulence (σ_{eff}) must be lower or equal than the ambient turbulence (σ_1), that is applicable in IEC NTM model. The wind speed distribution must be lower than assumed in the turbine certificate in the range from $0.2V_{ref}$ - $0.4V_{ref}$, ($V_{mean} = 0.2V_{ref}$), higher limit in the range of wind speed would cause fatigue damage.

The mean wind shear (α_{Mean}) exponent at hub height must be positive, but less than 0.2. If the wind shear is negative, there can be risk of collision between blade and tower. Similarly, if the value of α_{Mean} is more than 0.2, there can be a chance of increasing fatigue damage.

Inflow angle (φ_{Max}) at hub height must be within the range of $\pm 8^{\circ}$ for all wind directions. The average value of air density (ρ_{Mean}) must be less than 1.225 kg/m^3.

Table 2-3. Shows the main IEC checks for site conditions, and the limits[26]

IEC main check	IEC Limit
Terrain complexity	$I_c = 0$
Extreme wind	$V_{50y} < V_{ref}$
Effective turbulence	$\sigma_{Eff}(Vhub) < \sigma_1(Vhub, I_{ref})$
Velocity distribution	$f(Vhub) <$ Weibull ($k=2$, V_{mean})
Wind Shear	$0 < \alpha_{Mean} < 0.2$
Inflow angle	$-8^\circ < \varphi_{Max} < +8^\circ$
Air density	$\rho_{Mean} < 1.225$ kg/m^3

3 OPTIMIZATION METHODS

3.1 OVERVIEW

Our aim is to do an optimization for energy gain while controlling and minimizing the loads. The layout optimization problem is highly complex combinatorial problem because of the wake interaction between turbines. Wind Farm Layout optimization refers to the optimization task that chooses the best turbine positions, an optimal positioning of the wind turbines within wind farms. In first section, we will describe about various softwares available for the optimization of wind farm layout. In the next section, a background on optimization algorithm is given, and then we make comparison between standard INDUSTRY site assessment procedures and WFDs process. A brief explanation of heuristic evolutionary algorithm is given in the following section. Then, we discuss the followings tools which are significantly used on site assessment procedures:

3.1.1 HEURISTIC EVOLUTIONARY ALGORITHM

These algorithms follow the way of heuristic technique to find an approximate global optimum by making the locally optimal choice at each stage. These algorithms are working on partial solutions and recursion. Heuristic is needed for making the decision of the best at each step of optimization regarding future consequences. The best ‘profit’ is chosen at every step. The heuristic algorithm is not always good to obtain the overall optimum. because the algorithm assumes that choosing a local optimum at each step, one will end up at a global optimum[27, 28].

3.2 SOFTWARE TOOLS FOR MICRO SITING

There are various software tools available for the wind farm layout design and optimization capabilities. But most of the available tools have been designed for onshore, the functions of each one of them shall be briefly described in this section, and a brief analysis of their characteristics is given in the following sections. we try to explain in detail state of the art of wind farm design tools.

3.2.1.1 EMD WindPro

This software is designed by EMD International A/S, which is a software and consultancy company based in Denmark, the most robust wind farm design and optimization tool available in the market. The software provides a wide array of module and tools that take into consideration virtually all aspects that are related to wind farm design. A detailed description is available on reference [25]

3.2.1.2 AWS OpenWind

A wind project design and optimization software that provides professional wind developers with the tools they need to design, analyze and optimize a wind farm. An intuitive GIS-based interface, can optimize for cost of energy, assess deep array impacts, define and analyze strategies for managed shut-down of turbines, and manage uncertainty[29].

3.2.1.3 WAsP

WAsP, Wind Atlas Analysis and Application Program was developed in 1987 by the Wind Energy Department at Risø National Laboratory (DTU Wind Energy) and since then has been employed for over 25 years within wind power meteorology and in the wind power industry. WAsP can estimate wind resources and annual energy output from wind turbines using linear equations. It has become the industry standard PC software for wind resource assessment and siting of wind turbines and wind farms. WAsP is a computer program for the vertical and horizontal extrapolation of wind climate statistics. It contains several models to describe the wind flow over various terrains and close-to-sheltering obstacles[30].

3.2.1.4 WindFarmer

WindFarmer was developed by wind energy consulting company DNV GL to facilitate the design of wind farms, maximizing the power produced by the wind farm whilst minimizing environmental impact. WindFarmer offers advanced, validated wake models suitable for all types of wind farms, enables the optimization of turbine layout, the inclusion of different constraints and allows for data exchange with other programs such as GIS software. It further includes an MCP (Measure-Correlate-Predict) module[31].

3.2.1.5 WindSim

WindSim software uses CFD simulation to optimize wind turbine placement in onshore and offshore wind farms, this software is used significantly in wind energy industry. For more details see section 4.1.1 in chapter 4.

3.2.1.6 ParkOptimizer

Park Optimizer is used for micro sitting of turbine. It optimizes layout based on annual energy production with IEC constraints. For more details see section 4.1.4 in chapter 4.

3.2.1.7 Wind Farm Assessment Tool (WAT)

WAT is a software for site suitability assessment of wind turbines. It uses mainly result from WAsP. For more details see section 4.1.2 in chapter 4.

3.3 INDUSTRY STANDARD APPROACH FOR OPTIMIZATION

INDUSTRY tools are more focused on optimizing energy with wake losses, but ignore turbine loads created by effective turbulence and wake induced turbulence. Software tools like WindPro and OpenWind[25] are significantly used in the wind energy industry for the optimization layouts. To verify the IEC compliant layouts, the current- assessment procedure used by INDUSTRY tools goes through a lengthy process requiring a lot of iteration and rework for siting engineers, and after layout is approved the rework is required if the client changes requirements, see Fig 3.1.

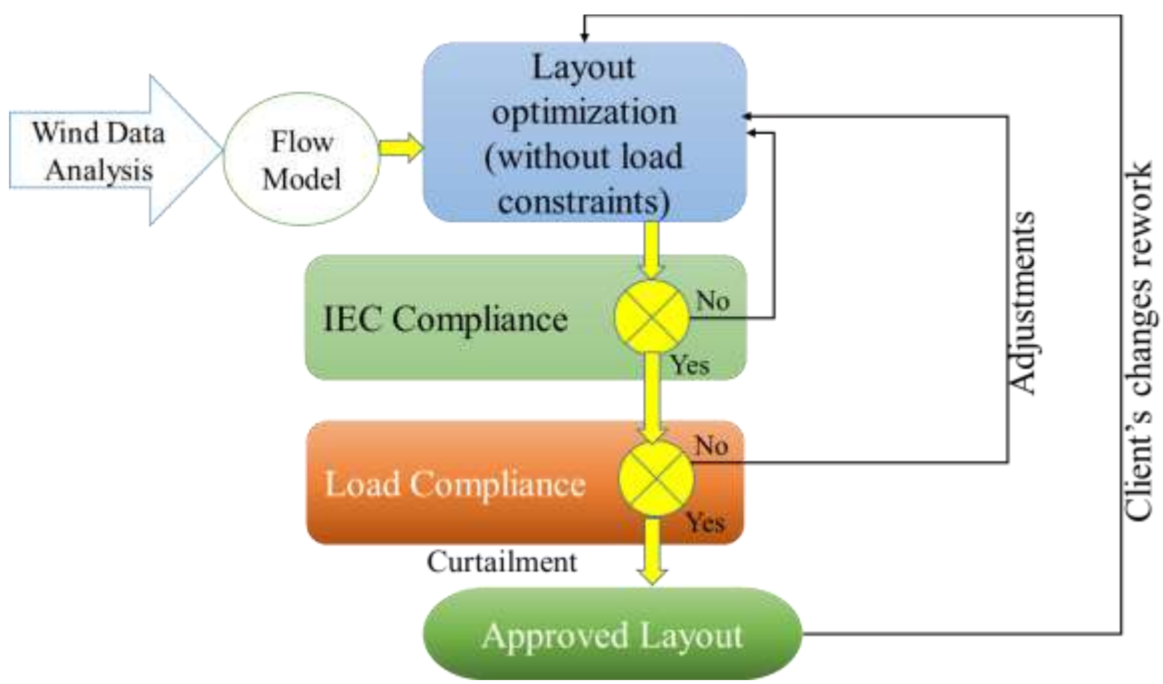

Figure 3.1. Demonstrates the Industry standard approach for optimization process, reproduced from[6]

Most of the INDUSTRY tools rely on heuristic evolutionary algorithms to find good and approximate solutions. But the trial-and-error process is slow and we do not know in actual the quality of the solution. When the constraints of effective turbulence are added, using the trial-and-error procedure it is increasingly difficult for the algorithms to find feasible solutions, that are generally applicable and easy to implement. Here are the following properties for INDUSTRY tools:

- Are suitable for wake optimization
- Are easy to implement
- Cannot handle effective turbulence and load constraints efficiently. In other words, cannot find feasible solutions for the optimum results
- Cannot guarantee optimum results
- Quality of result is unknown
- Are generally applicable and independent of the problem

3.4 WIND FARM DESIGNS (WFDs) APPROACH

WFDs claims that its approach is better that the INDUSTRY tools methods. The optimization algorithm is designed to include IEC constraints representing the turbine loads[32]. The wake loss is not considered in the WFDs approach, because it is not considered an absolute constraint (it just reduces the energy production), whereas, IEC constraints or turbine loads are absolute constraints. Turbines loads are caused by the turbulence that increases the fatigue damage levels. Normally, both concerns result in increased turbine spacing.

WFDs model performs layout optimization that maximizes energy production with respect to IEC compliance and turbine loads, that in turn reducing the cost of energy (COE)[6, 32]. The Fig. 3.2, gives an illustration of the structure of the optimization model.

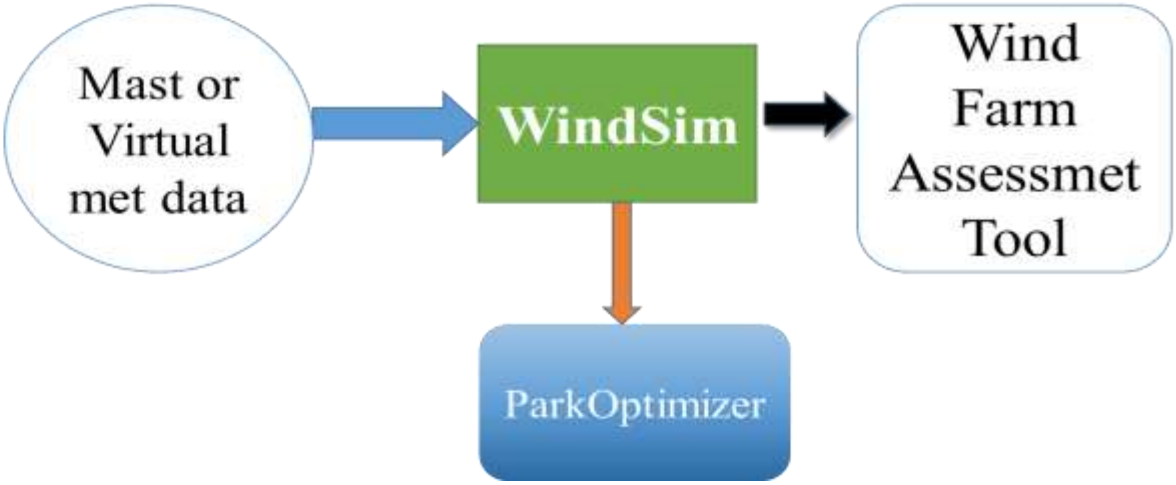

Figure 3.2. The General Structure of the optimization model

The mast data or virtual data from site is used as an input to Software tools for micro siting. WindSim calculates the flow field maps at given height over the layout site, such as capturing terrain effects on wind conditions more realistically. WFDs software architecture is flexible and can easily be integrated with in-house tools. In the Fig. 3.3, we can see the optimization approach from WFDs, that eliminates many steps during a layout verification process as compare to Industry approach.

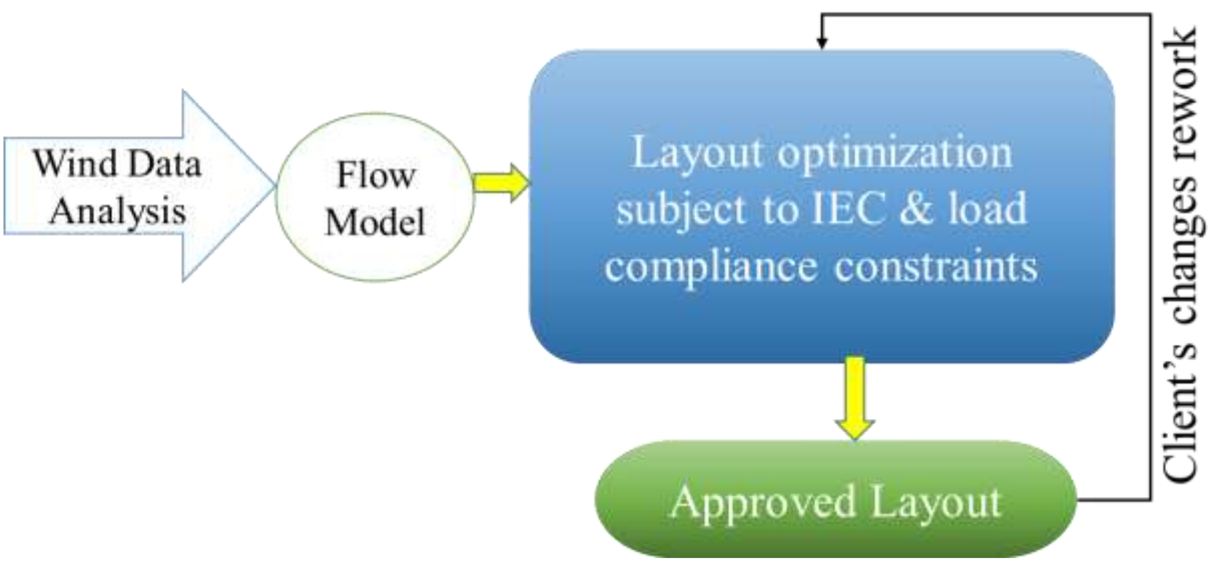

Figure 3.3. Describes the WFDs approach for optimization process reproduced[6]

The optimization method is a Mixed Integer Programming(MIP)[33] formed algorithm based on formal optimizations techniques. MIP is powered by FICO Xpress solver[34] that can handle complex problems. The WFDs approach has following properties i.e.:

- Reduces lengthy time on sitting by incorporating the IEC load compliance into the layout optimization
- Improves the energy yield of load compliant layouts, and reducing cost of energy (COE).
- The software architecture is flexible and can easily be integrated within house tools.

4 VERIFICATION OF LAYOUT

4.1 OVERVIEW

In this chapter, we optimize the small wind farm layout to verify IEC compliant (for effective turbulence criteria). Initially, we verify only with four SWT-108 wind turbines. WindSim software for CFD simulations is used to calculate flow fields at various heights over the planned layout. Using the WAsP results from WindSim, we verify the effective turbulence criteria for IEC 61400-1 in Wind Assessment Tool(WAT). Afterwards, we verify the project constraints using Park Optimizer software that maximizes the energy production by optimizing the position of turbines.

4.2 SIMULATION OF FLOW MODEL USING WINDSIM

First, we use WindSim, which is a computational fluid Dynamics (CFD) software. WindSim has hierarchal calculation modules: i) Terrain, ii) Wind fields, iii) objects, iv) Results, v) Wind Resource, and vi) Energy. These are briefly explained in the next section. For more information on the software, refer to [35-37].

4.2.1.1 Terrain

A digital terrain model in 3D is generated from a 2D data set based on the elevation and roughness data. Height and roughness data are imported in map-file, and converted into gws-format combining roughness and terrain grid data. Fig. 4.1, shows the project layout area marked within squared box. The layout area has a maximum height of 80m which is extracted from full grid.

From the Fig. 4.2, we can see the resolution of the grid. To specify a grid, the numerical model uses height and roughness information. The accuracy of the resolution is not desired due to restricted computational resources. Typical a resolution in the order of 100x100 meter is used for meso-scale modelling within larger areas in the order of 1000 kmxkm, while a finer resolution in the order of 10x10 meter is necessary for micro scale modelling.

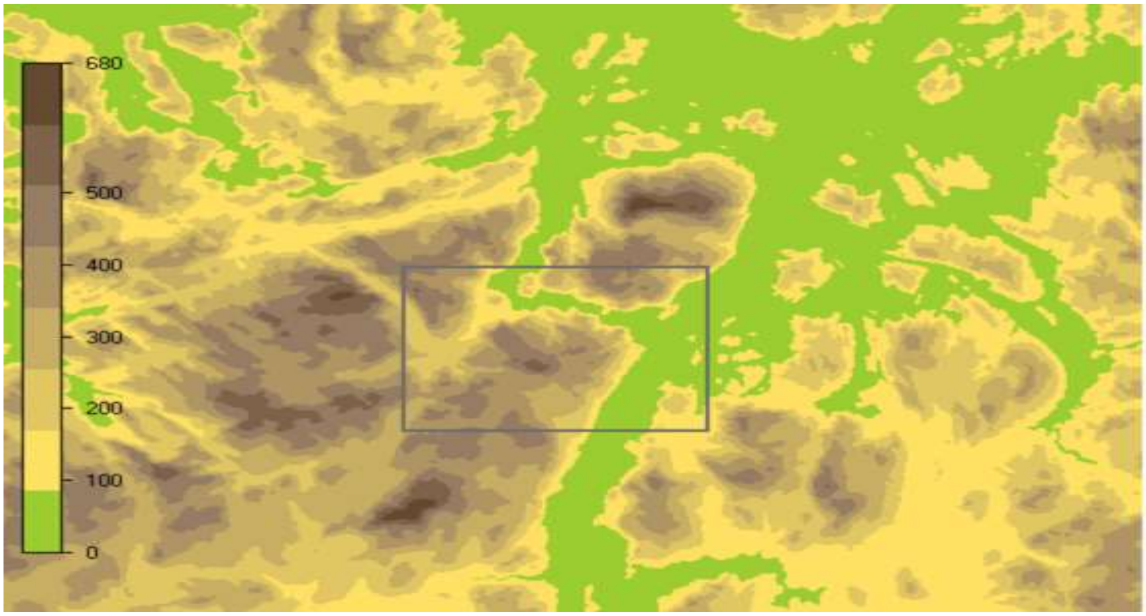

Figure 4.1 Digital terrain model marked in a box, is extracted from grid*.gws. The elevation level is represented by the color coding with different shades i.e. dark brown shade shows the highest elevation level with 680m.

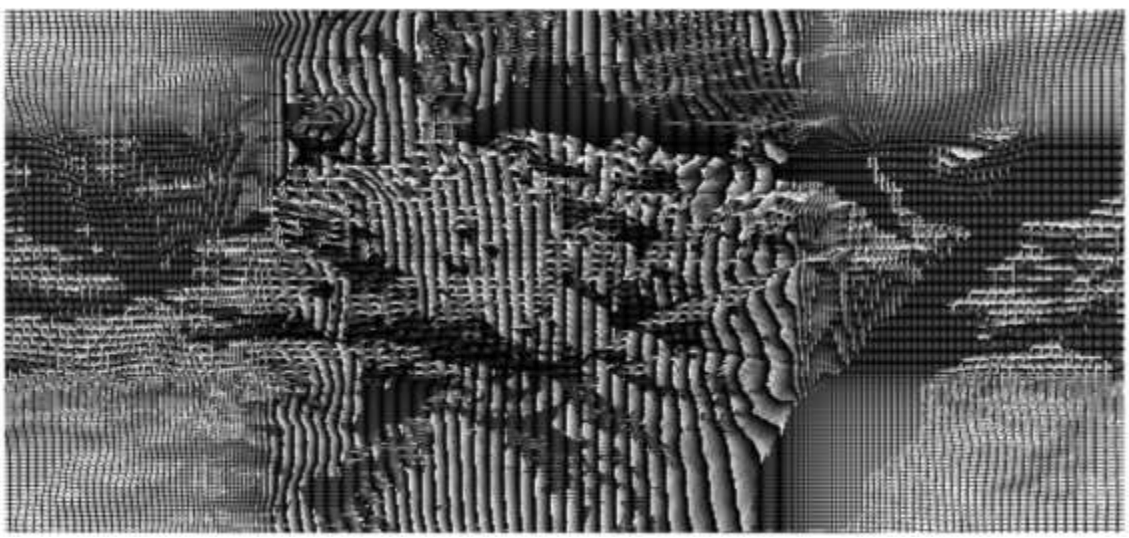

Figure 4.2. Displays the resolution of grid (x, y) at ground level.
Body fitted coordinates are used in grid generation. Resolution could be much better if the grid is iterated for some more time.

4.2.1.2 Wind Fields

The second module calculates the wind fields using the boundary conditions from 3D terrain map. RANS equations are used along with k-epsilon equations to solve for each sector and each grid point by iteration steps. From the Fig. 4.3, we can see the calculated flow variables such as components of velocity (u, v, w), Turbulent Kinetic Energy (TKE) and Turbulent Dissipation Rate (EP) [35]. The convergence of wind field simulations are evaluated by inspection of the residual values for the velocity components (U1, V1, W1), the turbulent kinetic energy (KE) and its dissipation rate (EP). All variables are scaled per the min. and max. values given on the right side.

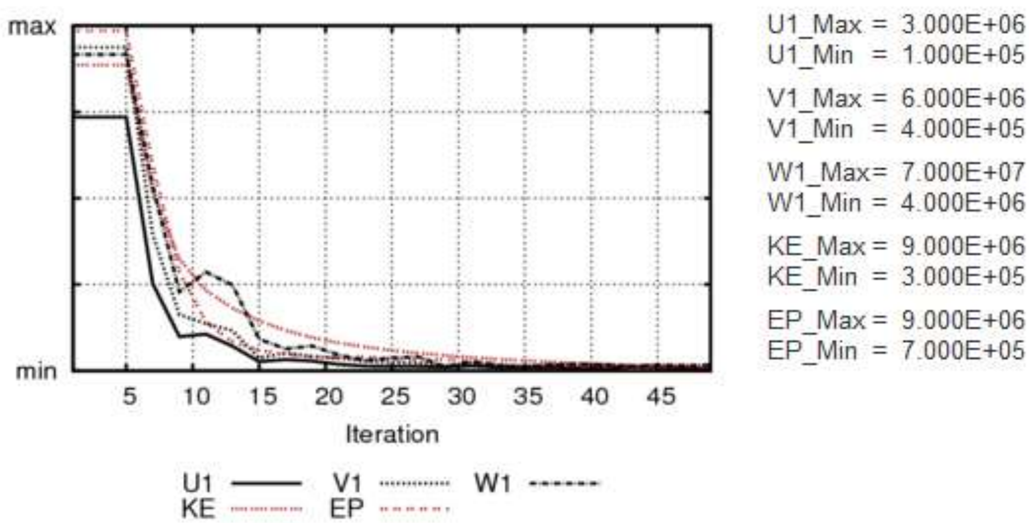

Figure 4.3. Represents the convergence of wind field simulations.

K-epsilon (k-ε) turbulence model is the most common model used in Computational Fluid Dynamics (CFD) to simulate mean flow characteristics for turbulent flow conditions. It is a two-equation model which gives a general description of turbulence by means of two transport equations (PDEs). The original impetus for the K-epsilon model was to improve the mixing-length model, as well as to find an alternative to algebraically prescribing turbulent length scales in moderate to high complexity flows[38].

4.2.1.3 Objects Module

The Objects module is used for positioning turbines, climatology's and transferred climatology's into the model. The turbines were positioned manually in WindSim. The turbines position and climatology station are shown in Fig. 4.4.

Figure 4.4. Depicts the positioning of wind turbines in the park layout. The elevation level is represented by the color coding with different shades i.e. dark brown shade shows the highest elevation level with 540m.

4.2.1.4 Results

From the result module, we can investigate the wind speed parameters as well as wind direction, and turbulence intensity parameters. All the parameters are not normalised to the local climate conditions as measured by the met mast and are referenced to the defined boundary conditions, see Fig. 4.5.

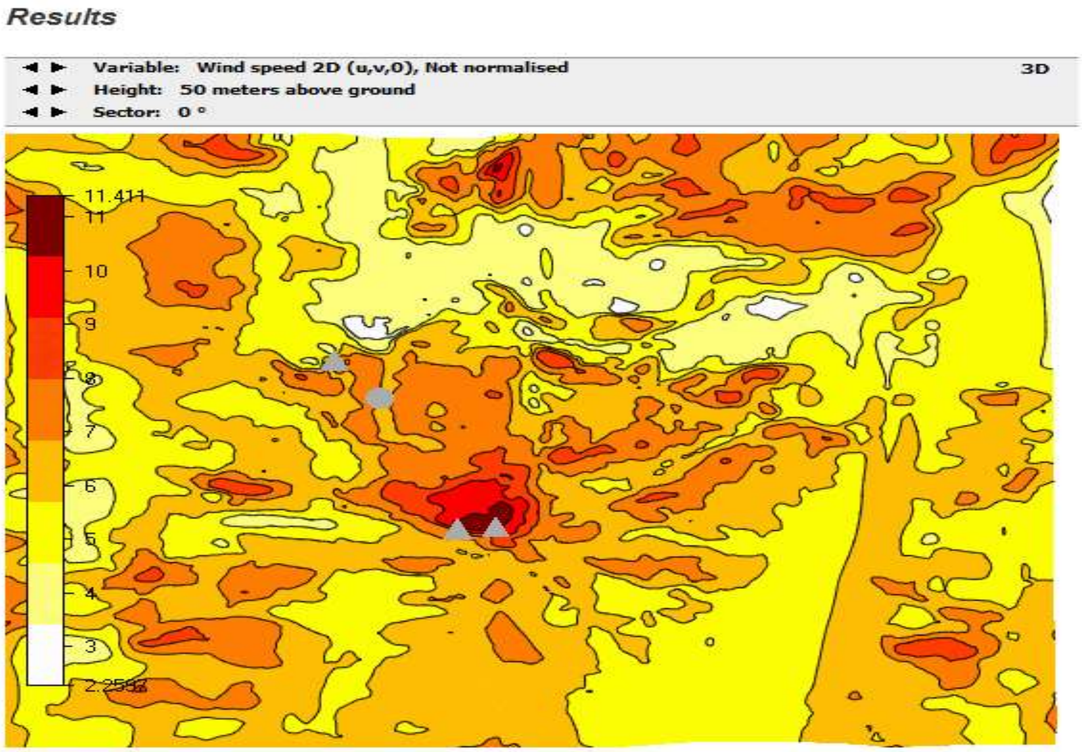

Figure 4.5. Wind speed analysis from result module. Wind speeds are shown by color codes in different shaded in m/s. Dark red color demonstrates the highest wind speed 11.411 m/s.

4.2.1.5 Wind Resource Module

The possible power production can be estimated with wind resource module based on the climatology data. Wake effects are disregarded when running the wind resource module from the user in the Objects module.

4.2.1.6 Energy Module

The Annual Energy Production (AEP) is the most important parameter to be estimated in most wind farm micro sitting, is calculated for all turbines objects given in the park layout. WindSim calculates the annual energy production disregarding the wake losses. The annual energy production for each turbine is based on the power curve and speed-up adjusted climatology, energy production is calculated based on Weibull and frequency distribution, see Tables 4.1 and 4.2. The turbine capacity is 3MW, producing gross annual energy production based on full load hours, wake losses are disregarded. The difference is insignificant between the energy production based on Weibull and frequency distribution, is only 0.3 %, see Tables 4.1 and 4.2.

The IEC classification of the turbines is performed for both the 2nd edition and 3rd edition of the standards[22, 35, 39], shown in the tables B1 and B2 in Appendix B. IEC class for each turbine, as described in the standards IEC 61400-1[20].

Table 4-1. Shows the energy Production based on Weibull distribution

Name	Power [kW]	Hub Height [m]	Density [kg/m^3]	Wind Speed [m/s]	Power Sensity [W/m^2]	Gross AEP [MWh/y]	Wake Loss [%]	Full Load hours [h]
Wecs1	3000	80	1.225	7.89	678.5	11555.2	-	3851.7
Wecs2	3000	80	1.225	7.66	610.7	11222.4	-	3740.8
Wecs3	3000	80	1.225	7.68	623.5	11217.6	-	3739.2
Wecs4	3000	80	1.225	7.56	605.1	10933.4	-	3644.5
All	12000	-	-	-	-	44928.6	-	3744.1
Mean	-	-	1.225	7.70	629.5	-	-	-

Table 4-2. Shows the energy Production based on frequency distribution

Name	Power [kW]	Hub Height [m]	Density [kg/m^3]	Wind Speed [m/s]	Power Sensity [W/m^2]	Gross AEP [MWh/y]	Wake Loss [%]	Full Load hours [h]
Wecs1	3000	80	1.225	7.89	678.5	11587.0	-	3862.3
Wecs2	3000	80	1.225	7.66	610.7	11250.3	-	3750.1
Wecs3	3000	80	1.225	7.68	623.5	11276.4	-	3758.8
Wecs4	3000	80	1.225	7.56	605.1	10972.4	-	3657.2
All	12000	-	-	-	-	45086.1	-	3757.2
Mean	-	-	1.225	7.70	629.5	-	-	-

4.2.2 VERIFICATION OF LAYOUT

From the WindSim software, we calculated the flow fields and its velocity gradients to predict site-specific wind conditions.The layout is optimized as per IEC 61400-1 by using Wind Farm Assessment Tool (WAT tool). The objective is to verify effective turbulence criteria at each turbine location using wind farm assessment tool (WAT) for wind farm layout. However, for the turbulence intensity, it is not straightforward to verify whether we have reached the optimal solution with respect to energy production. There exists no tool that neither generates optimal-IEC compliant solutions nor guarantee IEC compliant solutions.

The main objective of WAT is to calculate effective turbulence within wind farms. This is done for individual turbine sites using wind direction distributions conditioned by local wind speed. Wakes from neighbour turbines are estimated by the wind speeds at these neighbouring sites corrected for terrain-induced speed up and wake effects from upstream turbines [40].

4.2.2.1 IEC Assessment by Windfarm Assessment Tool (WAT)

We verify that if turbine is within the limit as per IEC 61400-1 standard, the effective turbulence must not exceed the Normal Turbulence Model(NTM) as per IEC site assessment rule [20], see Fig. 4.6. It corresponds to the selected wind turbine class in the wind speed range marked by orange shaded region.

Classification of the turbine must be well defined as per the site-specific conditions. To assess a potential wind farm site, we need to consider several parameters for complete design of wind farm site e.g. energy yield, wake effects, ambient turbulence and effective turbulence. But in our case, we are particularly focusing on the effective turbulence range for each turbine location within a wind farm.

The verification of effective turbulence intensity as function of wind speed as per IEC 61400-1, see Fig. 4.6. The turbulent intensity is changing with different wind speed .Our referred effective TI is 0.14 (see in Table 2.2 in Chapter 2) that must not exceed over the class b design limits (green line representing selected turbine class B, which must follow under reference TI = 0.14) within IEC turbulence intensity range (orange shaded region). Our IEC 61400-1 criteria is from 7m/s to 25 m/s.

The blue line refers to the Class A turbine having turbulence intensity 16%. The Green line represents the Class B turbine and red line demonstrates the Class C turbine, having turbulence intensity 14% and 12 % for each class. WEng (WAsP Engineering) turbulent Intensity the light blue line. Light grey line represents the Mean value for TI. Red dotted line represents the effective turbulence intensity. Grey shaded level represents the ambient TI, defined as the 90% percentile of a typical scattered distribution.

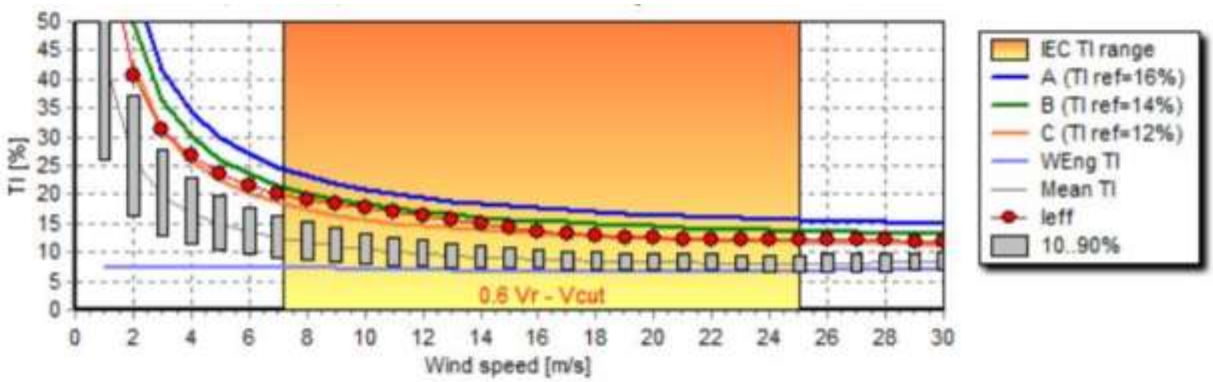

Figure 4.6. Shows the effective TI as a function of wind speed (did not exceed the IEC criteria).

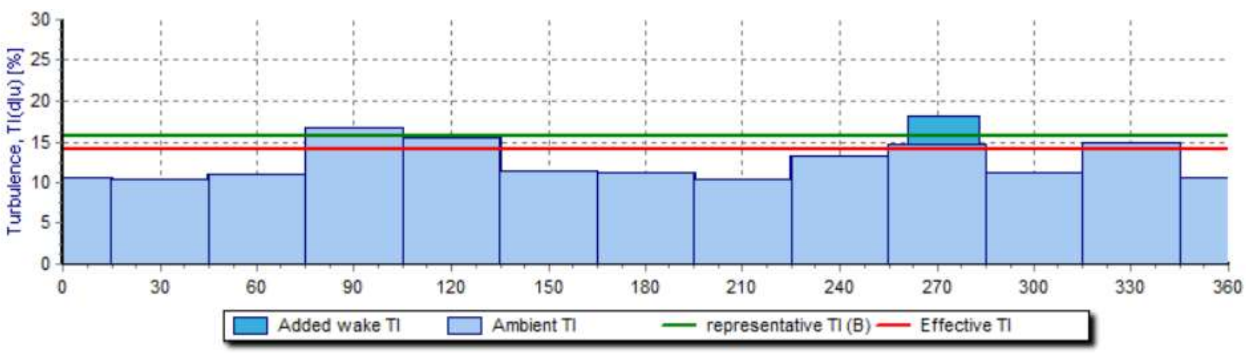

Figure 4.7. Added wake TI exceeds the criteria for IEC (see dark blue region). The ambient turbulence intensity is below the limit from different wind directions.

The red circle indicates (see Fig. 4.8) effective turbulence for Wohler number m = 10. Background combined sectors with Ambient TI are shaded in light blue (ambient turbulence is under the limit)) and added wake turbulence intensity is shaded in dark blue from neighbouring turbine (added wake TI exceeding the criteria due to the proximity from turbine 3). Turbines locations shaded in grey dots are ignored from the IEC criteria of effective TI, because the distance is far away, more than 10 rotor diameters.

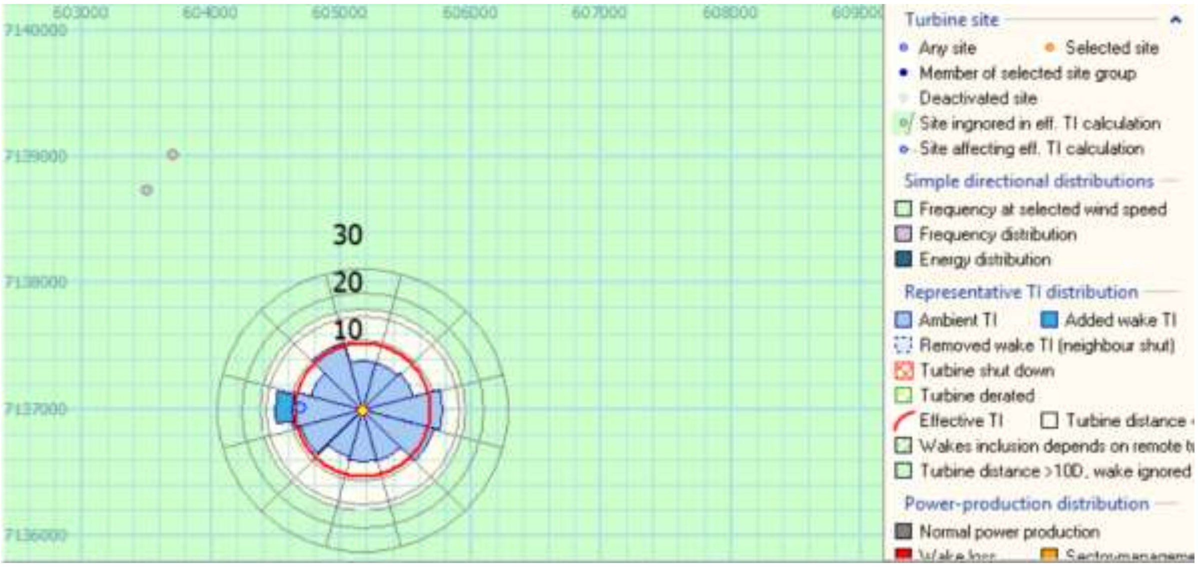

Figure 4.8. The calculated effective turbulence in dependence of wind direction. We have stronger turbulence due the wind direction from neighbouring turbine. Turbines with distance more than 10 rotor diameter are ignored from the turbulence criteria.

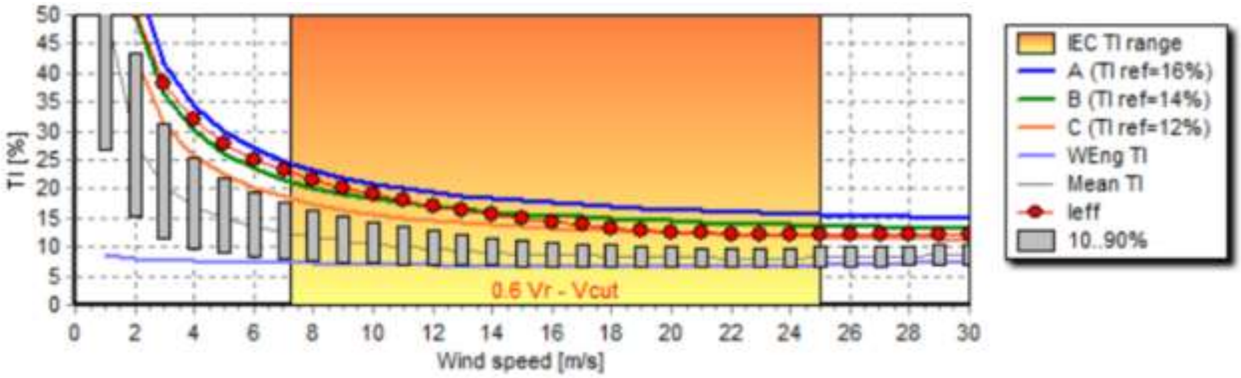

Figure 4.9. The effective TI exceeded the IEC criteria, as a red dotted line crosses over the green line within orange shaded region.

Figure 4.10. Added wake TI is within IEC61400-1 (ed.3) limit, whereas ambient TI exceeds the limit.

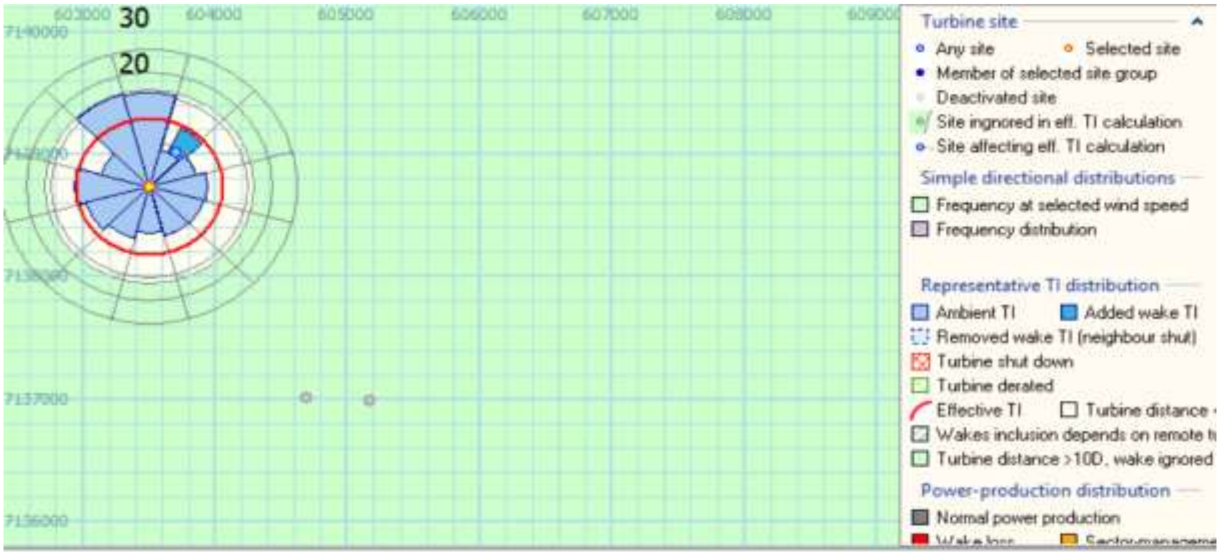

Figure 4.11. The ambient turbulence in dependence of wind direction. It exceeds the criteria.

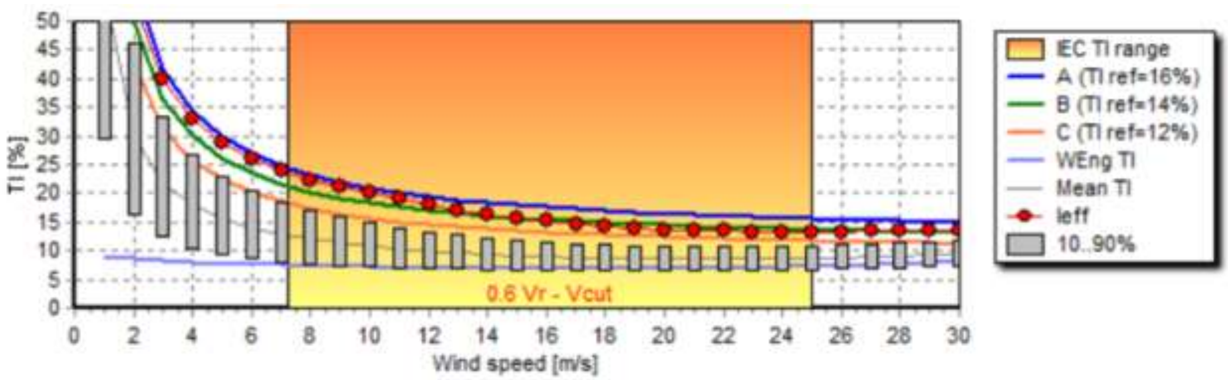

Figure 4.12. The effective TI is within IEC criteria for class b design limits.

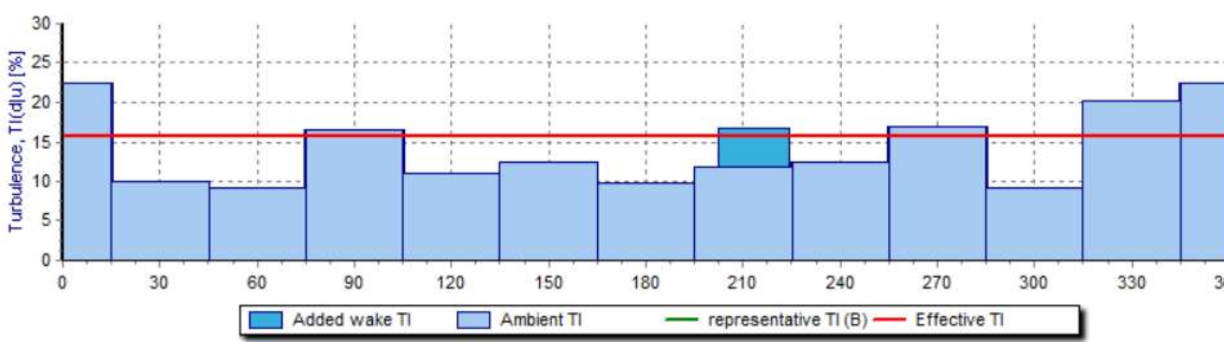

Figure 4.13. Added wake TI is within IEC limit, whereas ambient TI exceeds the limit (see blue shaded region).

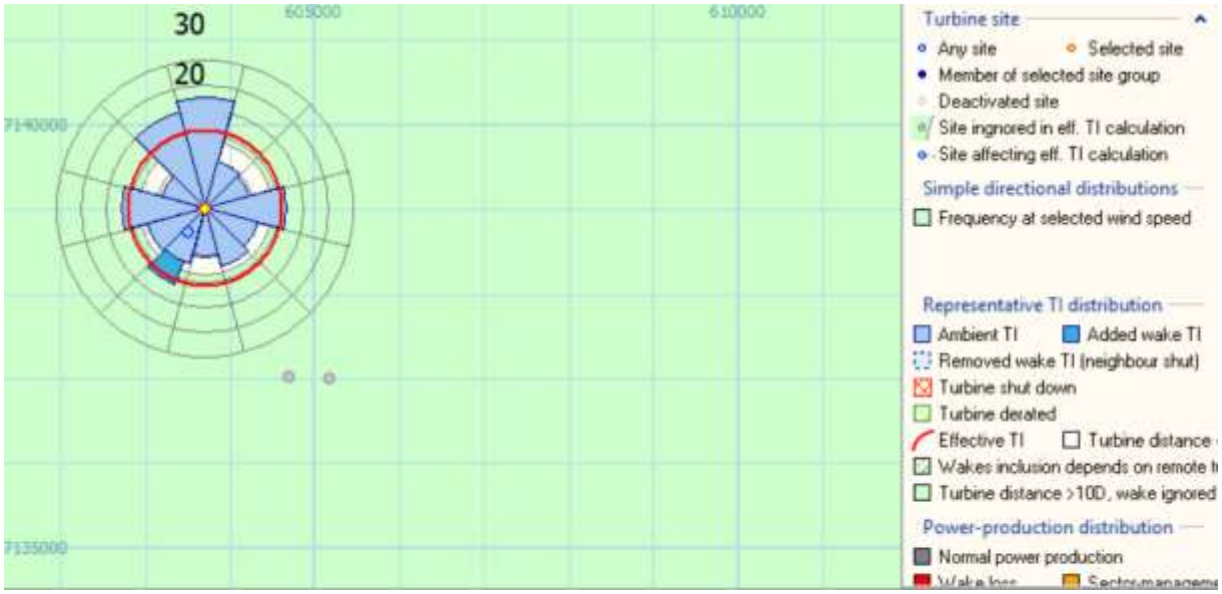

Figure 4.14. The effective turbulence in dependence of wind direction. The ambient turbulence is higher due to the different wind directions within wind farm.

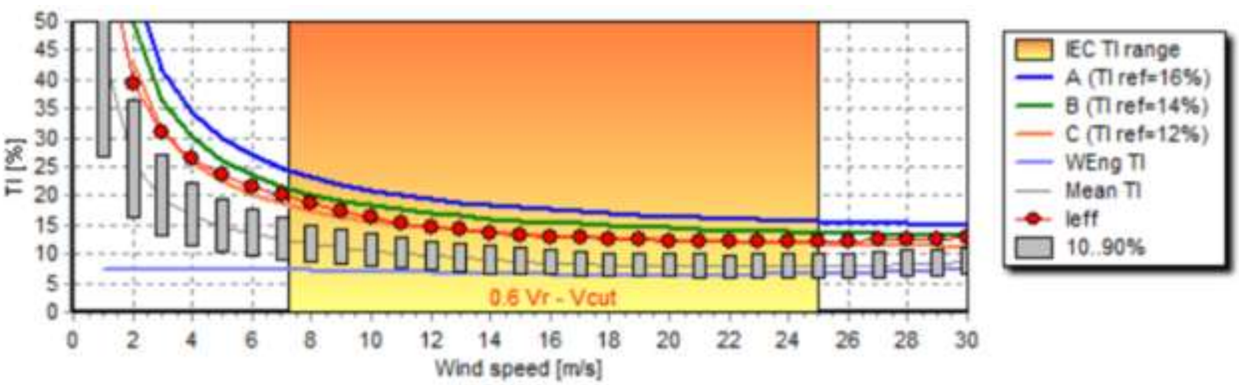

Figure 4.15. The effective TI exceeded the IEC criteria for class b design limits.

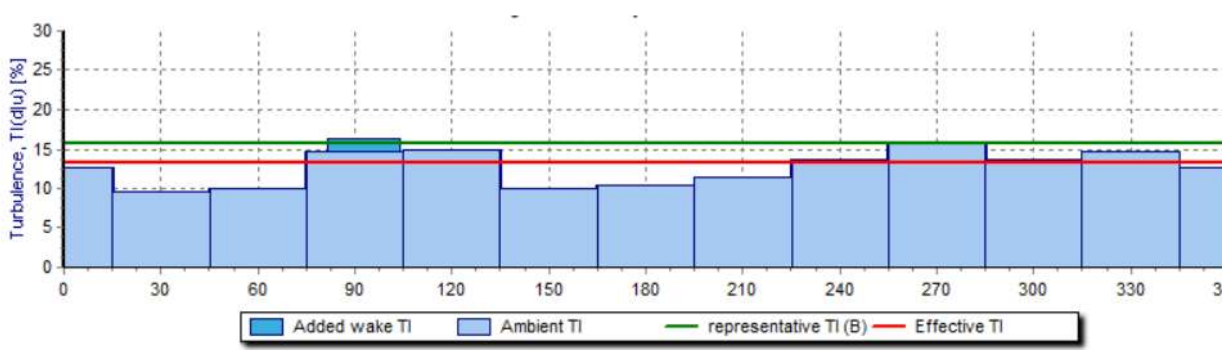

Figure 4.16. Added wake TI exceeded the IEC61400-1 (ed.3) limit due to the proximity with neighbouring turbine, whereas ambient TI within the limit.

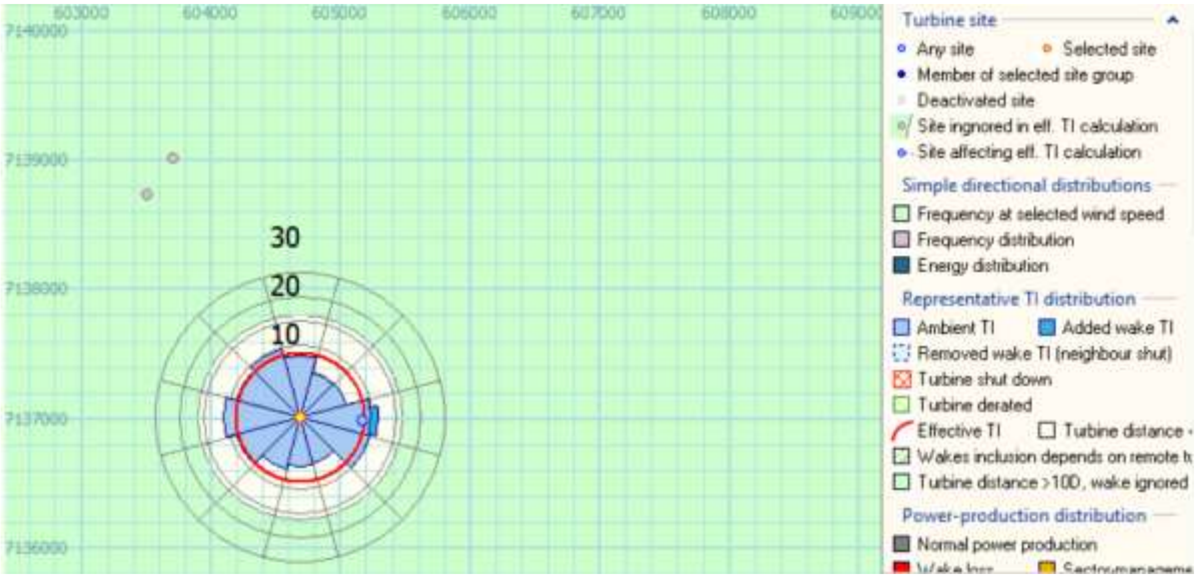

Figure 4.17. The effective turbulence in dependence of wind direction.

Table 4.3, gives the values of annual energy production (AEP) at each turbine position. here we can see the that only turbines at position 1 and 3 satisfy the effective TI criteria as per IEC61400-1 Ed.3. Turbines position at 2 and 4 are not satisfying the IEC effective TI criteria, leads to slightly decrease in net annual energy production.

Table 4-3. AEP production from WAT

Site	U [m/s]	netAEP [GWh]	I_{eff}	Turbine Type
wecs1	7,79	11,358	OK	Siemens 108
wecs2	7,72	11,206	Problem	Siemens 108
wecs3	7,75	11,225	OK	Siemens 108
wecs4	7,59	10,966	Problem	Siemens 108
Total	-	44,754	-	-

4.2.3 OPTIMIZATION OF LAYOUT IN PARK OPTIMIZER

The main objective is to verify the layout with respect to load constraints as per IEC 61400-1. The layout will not be able to fully compliant in terms of load constraints as per IEC criteria, because these load constraints were to be verified by WFDs algorithm which is incorporated with park optimizer tool (due to the bug in algorithm, it is not providing the IEC based results). It is still providing the results based on heuristic approach, which are not passing in the terms of load constraints (as two of the turbines in wind farm are failing the effective turbulence criteria, see Fig. 4.9 and 4.15).

Park optimizer is a tool that helps to maximize the profitability by optimizing the wind farm layout locating turbines and areas with IEC compliant wind conditions and helping to determine the right level of investment by identifying the optimum number of wind turbines within the wind farm sites. Park Optimizer uses WindSim CFD results[32].

In this project, we determine the configuration of wind turbines in a selected location. Then, the turbine placements are optimized with respect to energy production, and are in accordance with selectable IEC constraints. An economic-optimization feature is used to determine the number of turbines for the project. To run the Park Optimizer, we need the following WindSim simulations as Input files:

- time series data file from met mast within the area;
- a long term corrected Wind Resource(*.wrg) file;
- power curves files for the turbines, and
- file for wind flow variable at different heights extracted from WindSim project

We can see the park area which is loaded from our previously WindSim generated (.ws) file, see Fig. 4.18. The next step is to define our wind farm area within this park optimizer, an image shape(.shp) file is uploaded to define the layout area, can be seen in red marked circumference (see Fig. 4.19). On the left side of the module, we see the different features to execute the project layout.

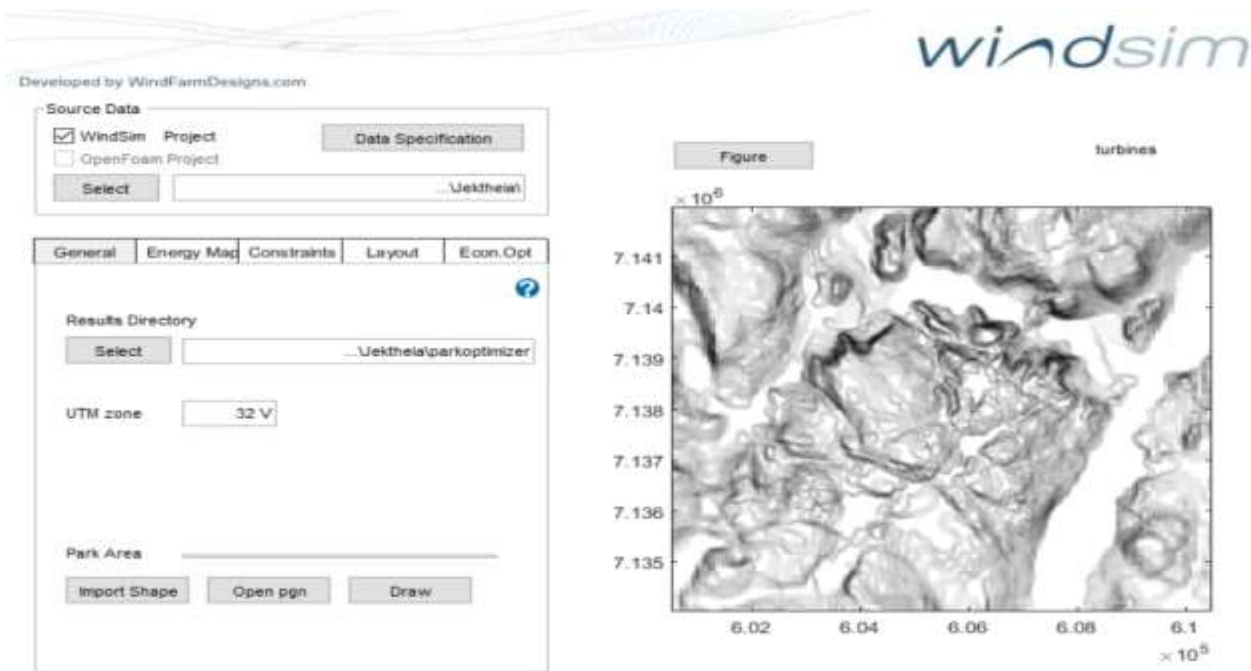

Figure 4.18. Initializing process of the Park Optimizer tool.

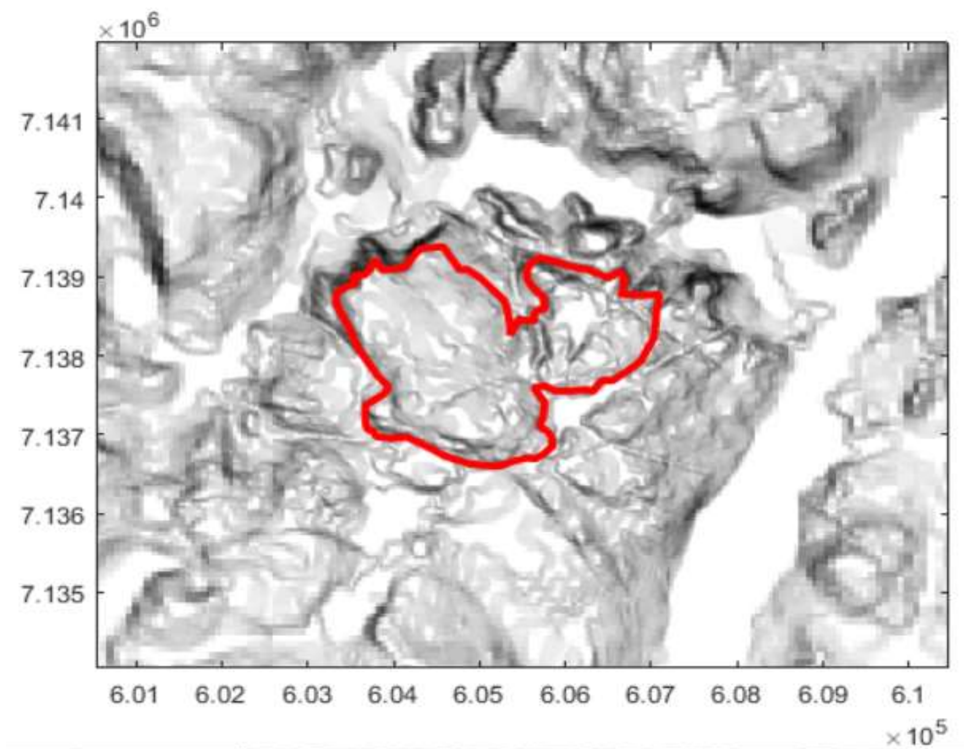

Figure 4.19. Defined park area which is in red mark circumference. The total area is scaled in meters.

Energy Map is calculated for wind farm in the next step. To make an energy map, we need to upload a Wind Resource file in wrg format and the power curve for our selected turbines from WindSim generated files in report folder. We import Siemens turbines characteristic SWT 80 files for the power curve. The calculations are initialized by pressing the energy map tab, and calculated energy map file is stored as CSV file in the directory.

As it can be seen from the Fig. 4.20, the area where turbines will be positioned having the maximum energy capacity, accounts to 1300 kW/h.

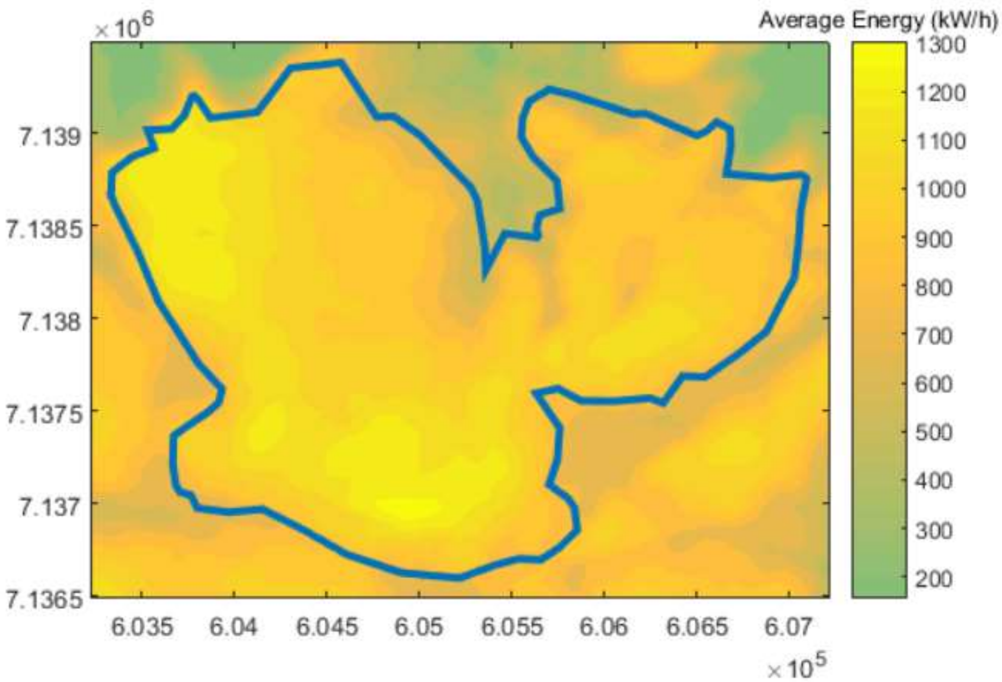

Figure 4.20. The energy map within the layout, in our case the wind resource looks quite good for the turbine locations.

To investigate the wind quality in the defined park area we setup our constraints. Park Optimizer evaluates the wind quality against the constraints that are selected in the IEC Constraints menu. In this regard, we are selecting type Class II-B turbine, thus the constraint for turbulence, extreme wind speed, shear, flow inclination and terrain inclination are set as per IEC standard (see Table 2.3). If area within the park layout violate these constraints would be excluded for turbine placements. Then by pressing the extract button the calculations will start. The resulting map (see Fig. 4.21) shows that the wind conditions violate the constraints in rather large areas. The turbines should be placed in white areas depicted within map for the layout to be compliant with all given constraints.

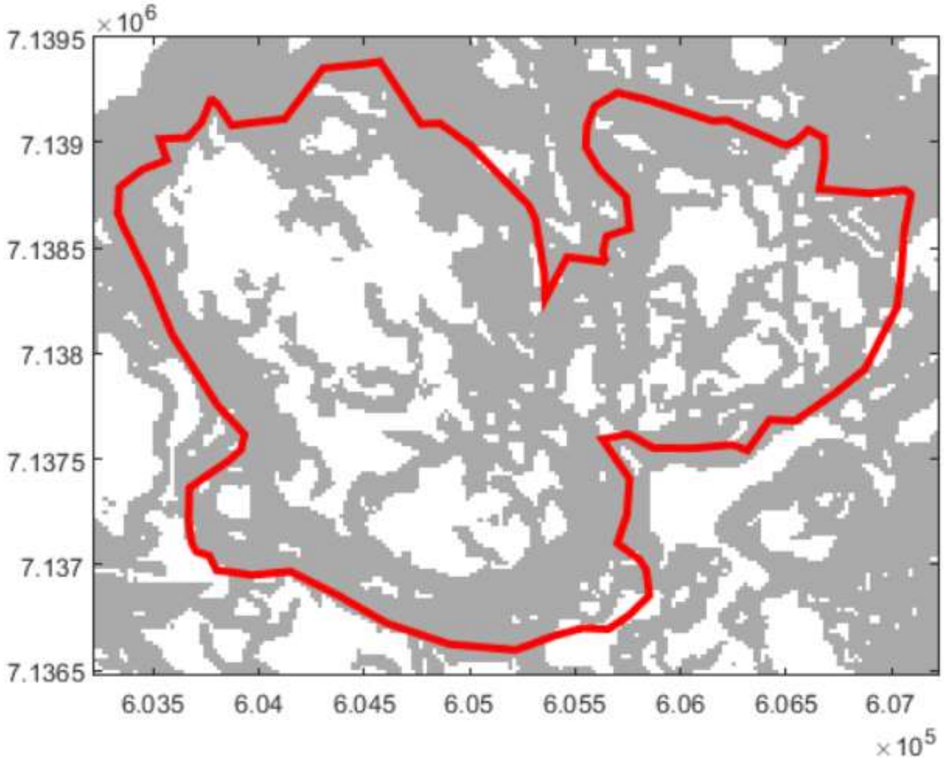

Figure 4.21. The IEC constrained resulting map (area is scaled in meter).

Now, we save and open previously made exclusion map in CSV file. Though, we can consider other constraints by drawing our own layout within the map. By importing the shape files from park optimizer folder, we can be certain that no turbine would be located on water.

Now we are ready to optimize our layout, by moving on the layout tab, we can specify the settings for the layout optimization. In our case, we have total number four turbines that are fixed, therefore we do not generate a new layout. it is recommended that four times the rotor diameter should be chosen as minimum distance between turbines, and we select the distance based on elliptic distance method. The rotor diameter is chosen 80 meter and k constant is 0.075, both values should be specified before we start optimization. However, the optimization algorithm is non-formal, so improvements can be made by running the optimization several times, and it can take some time depending on the number of turbines and the size of wind farm.

4.2.3.1 Layout

To investigate the layout, we import our previously generated layout in order by clicking the layout button. Fig. 4.22, shows the detailed investigation of turbine layout results.

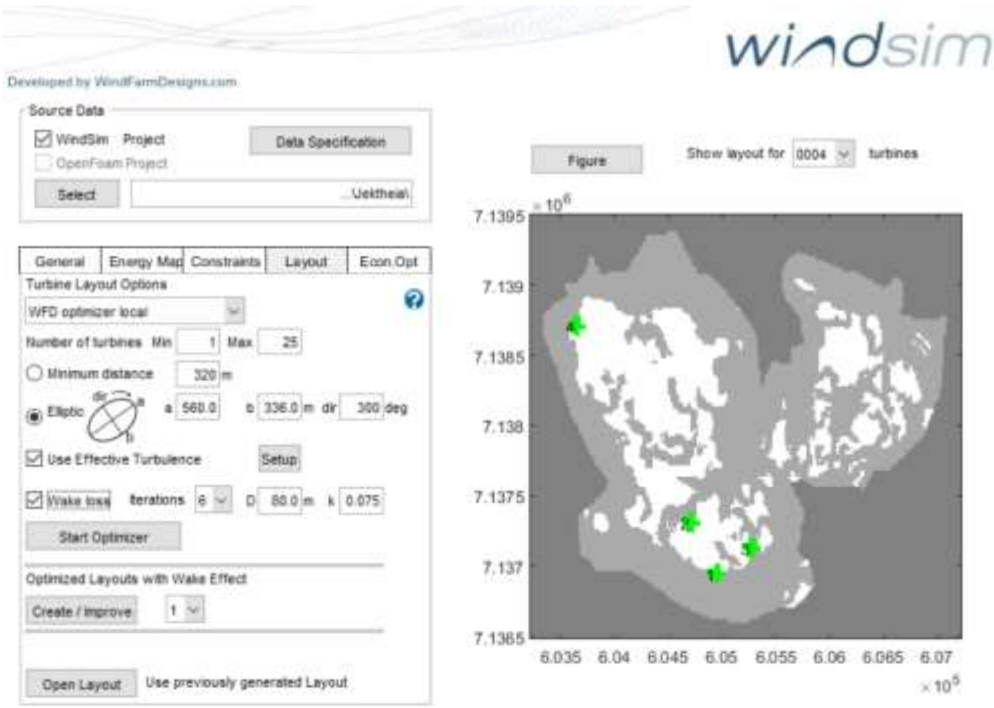

Figure 4.22. Optimization of turbine positions as per the wake adjustment.

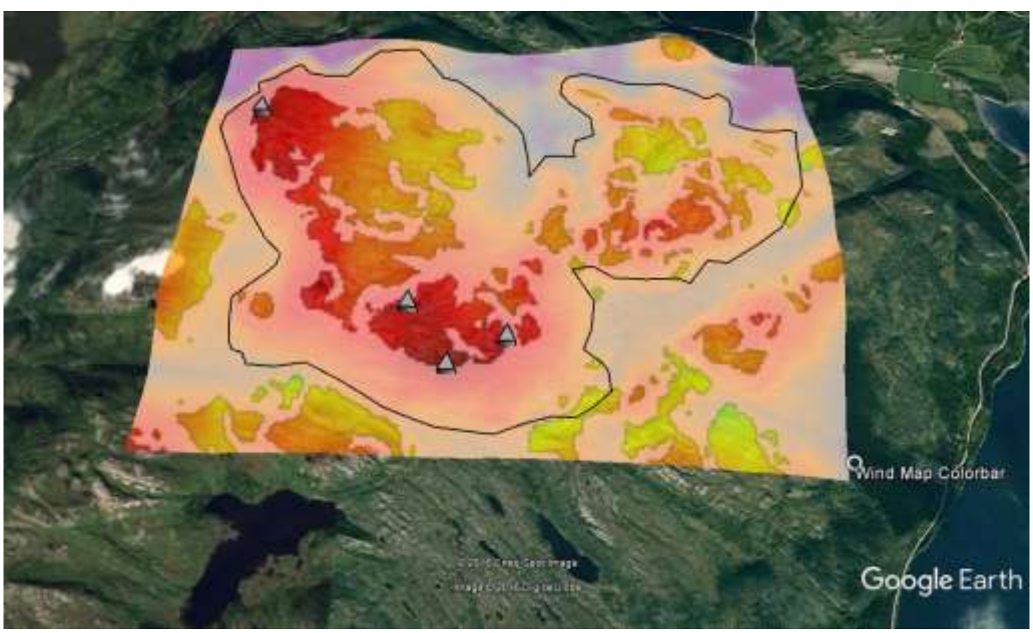

Figure 4.23. 3D view from Google Earth Park Optimizer layout.

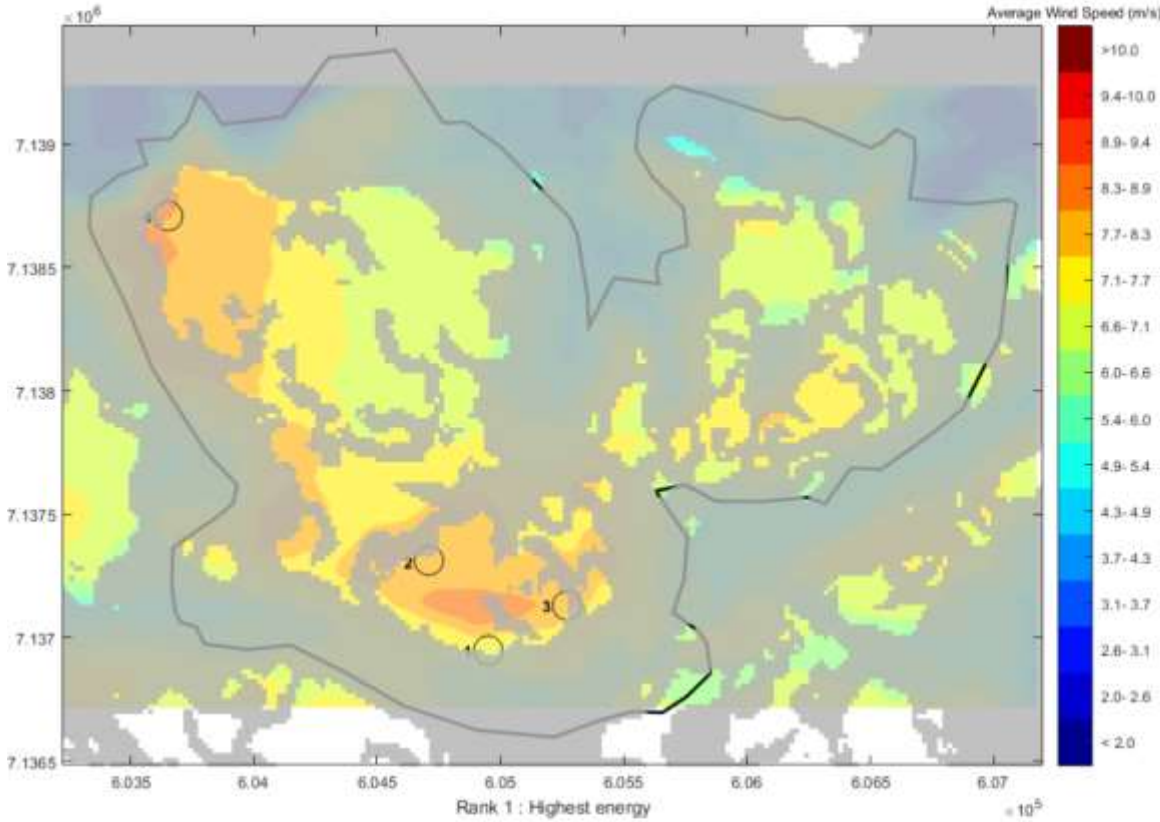

Figure 4.24. Wind Speed variations over the selected Park site (area is scaled in meter).

4.2.3.2 Economic Optimization

We excluded the task of economic optimization from ParkOptimizer. ParkOptimizer module can be applied for Economic optimization by using results from layout optimization, that establish an energy curve E(n) from each layout n = 1…. N, where N corresponds to the number of turbines of each optimized layout. The energy E(n) curve represents the energy output as function of project size, and is used as input to net present value (NPV) calculations. As seen from Fig. 4.25 and 4.26, there is a defined optimum at around 20 turbines. The total cost is increasing as the number of wind turbines are installed. Net profit value is summation of discounted rate when large number of turbines are installed. The profitability curve equation is given as:

$$\mathrm{NPV(n)} = -\mathrm{C_0} - \mathrm{C_1 n} - \mathrm{C_2 n} + \sum_{t=1}^{T}(1+r)^{-t}((p_t + s_t)E(n) - oc_t(n)) \quad (4\text{-}1)$$

where,

C_0 – Fixed costs: such as, external road, grid connection, transformer etc.;

$C_1 n$ – Variable costs: i.e. internal roads, cabling, foundation;

$C_2 n$ – Turbine costs;

T – Time horizon for the project;

T – number of time periods;

r – is the discount rate;

$E(n)$ – Energy production;

s_t – Revenue from power sales;

$oc_t(n)$ – Operational costs.

The Park Optimizer version uses currency EURO.

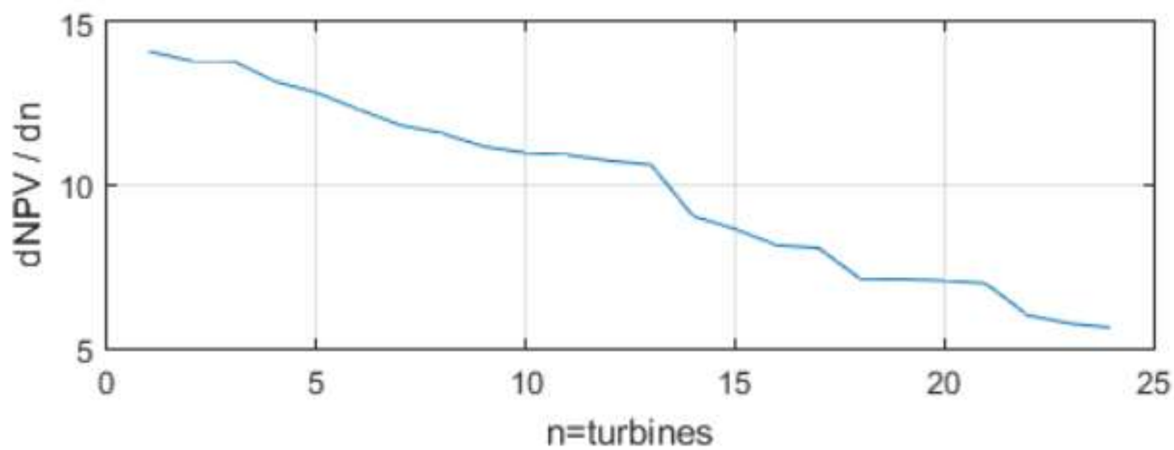

Figure 4.25. Net profit value (NPV) decreases as the number of turbines are increasing.

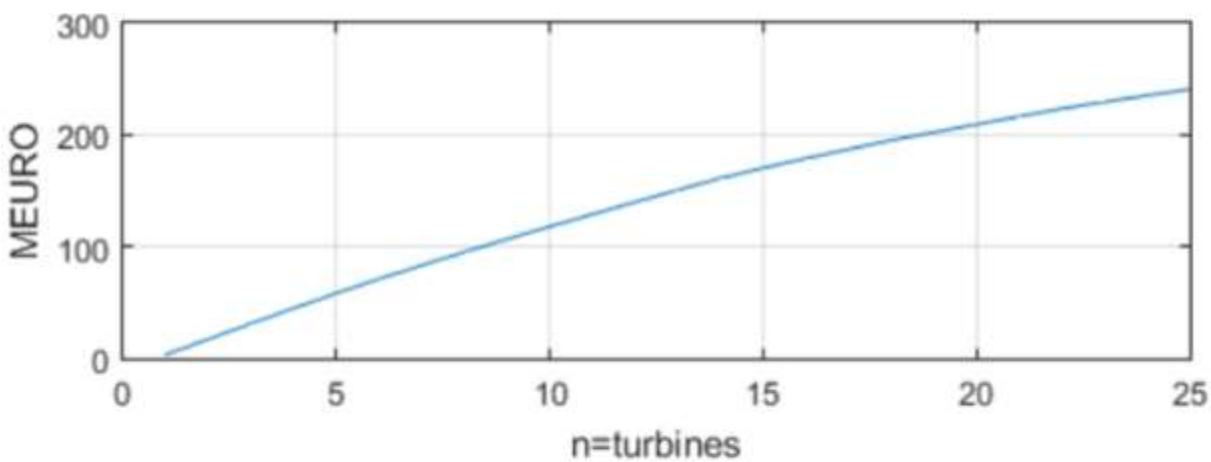

Figure 4.26. The cost of the wind farm layout increasing, as the number of turbines increases.

5 BENCHMARKING OF OPTIMIZATION

5.1 OVERVIEW

The main objective is to assess wind farm layout with 20 turbines using two different tools to verify the differences in energy production. This chapter compares the different optimization software WFDs and AWS OpenWind (INDUSTRY TOOL). First, we describe briefly about the OpenWind[41] tool structure in simulation methodology. Then we compare the software using the same layout based on gross and net energy production.

5.2 SIMULATION METHODOLOGY FOR OPENWIND

AWS OpenWind has various similarities with other site assessment software. Therefore, it provides the option for benchmarking the same layout file with WFDs, but OpenWind has different features in its own optimizer as compare to ParkOptimizer module. We import the same layout from file menu to execute in OpenWind. A brief explanation of OpenWind tool structuture is given in the following sections[29]:

5.2.1.1 Tool Structure

OpenWind is an open source software is used for the design, optimization and assessment of wind farm layouts. Format of the software is pattern from Geographical Information System (GIS) which enables the program to be applied effectively. The software is based on the heuristic algorithm, which is mentioned in the following steps[29]. AWS OpenWind has the option to use data within layers, all layers are defined in workspace, a layer hierarchy is shown in Fig. 5.1. Its user-control search order allows the user control over the type of layer we use for what purpose, we created and imported some layers. We created specific layers to optimize our layout to have valid results for energy estimation. which are explained in the followings:

- Site layer represents the turbine layout.
- Polygon layer is used to demonstrate site boundaries, land parcels, water bodies, areas of roughness or vegetation such as forestry plus for defining site constraints like optimization layout area, our layout area is named as 201002_Planområde_Rapheia.Shp.

- Vector layers include point layers i.e. site layers, line layers, and polygon layers. This layer is added from the main file menu by importing our layout file (WAsP shape file) inside OpenWind.
- Met Mast layers represent the wind speed and elevation measurements.

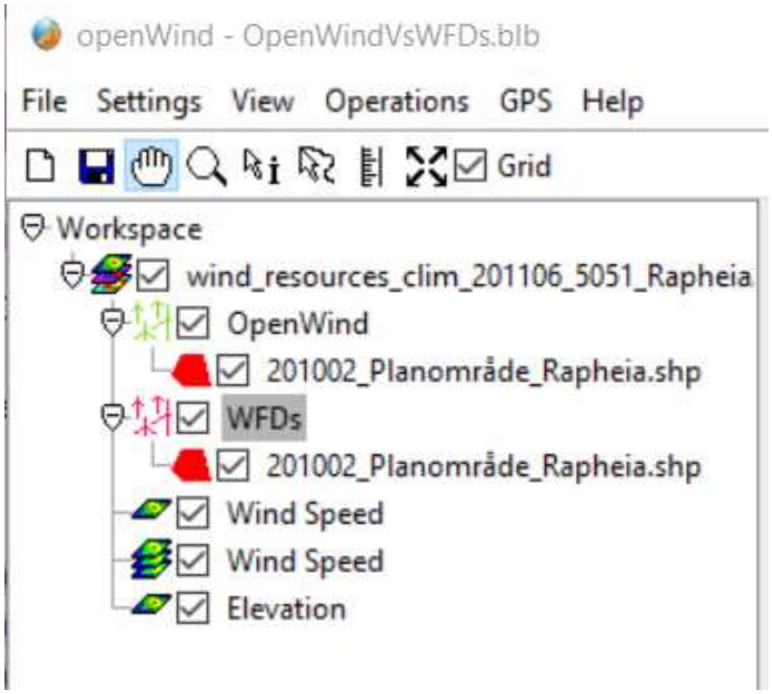

Figure 5.1. Layer hierarchy in OpenWind workspace.

5.2.1.2 Turbine Type

In the setting menu, using site layer option we select the turbine type Siemens-108 that is optimized for with the use of dialog window as shown in Fig. 5.2. In total, we optimize for 20 turbines layout, for both WFDs and OpenWind.

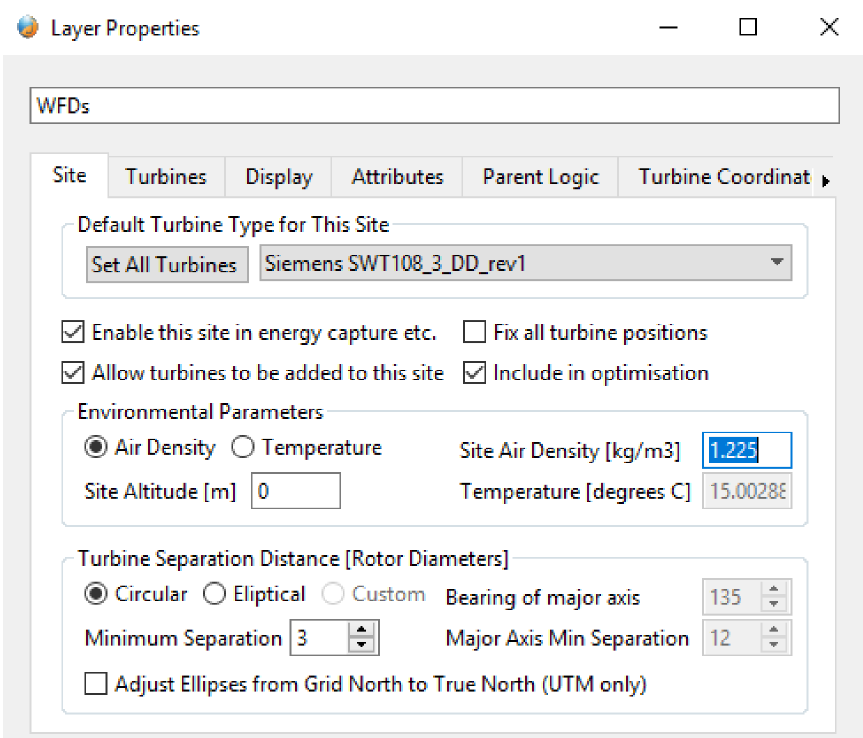

Figure 5.2. Selection of the turbine in site layer properties.

5.2.1.3 Loading Wind Resource Grid File

We upload *.wrg file from menu. This file is created within WAsP, and compatible to use in OpenWind. However, three raster layers are added as children of the *.wrg which shows the mean wind speed and elevation data derived from the *.wrg. Wind Resource Grid files is used to determine the wind speed at selected locations for both optimization algorithm. A wind resource grid is independent of its display layers. The display rasters can be deleted and recreated without affecting the *.wrg itself.

5.2.1.4 Energy Capture

This module helps in calculating the energy production of wind turbines within wind farm layout. From Fig.5.3, we can see that there are two options to calculate energy. First option is used in case of a layout optimization. It runs thousands of energy capture calculations. Second option, is used for testing, calculates the full energy capture.

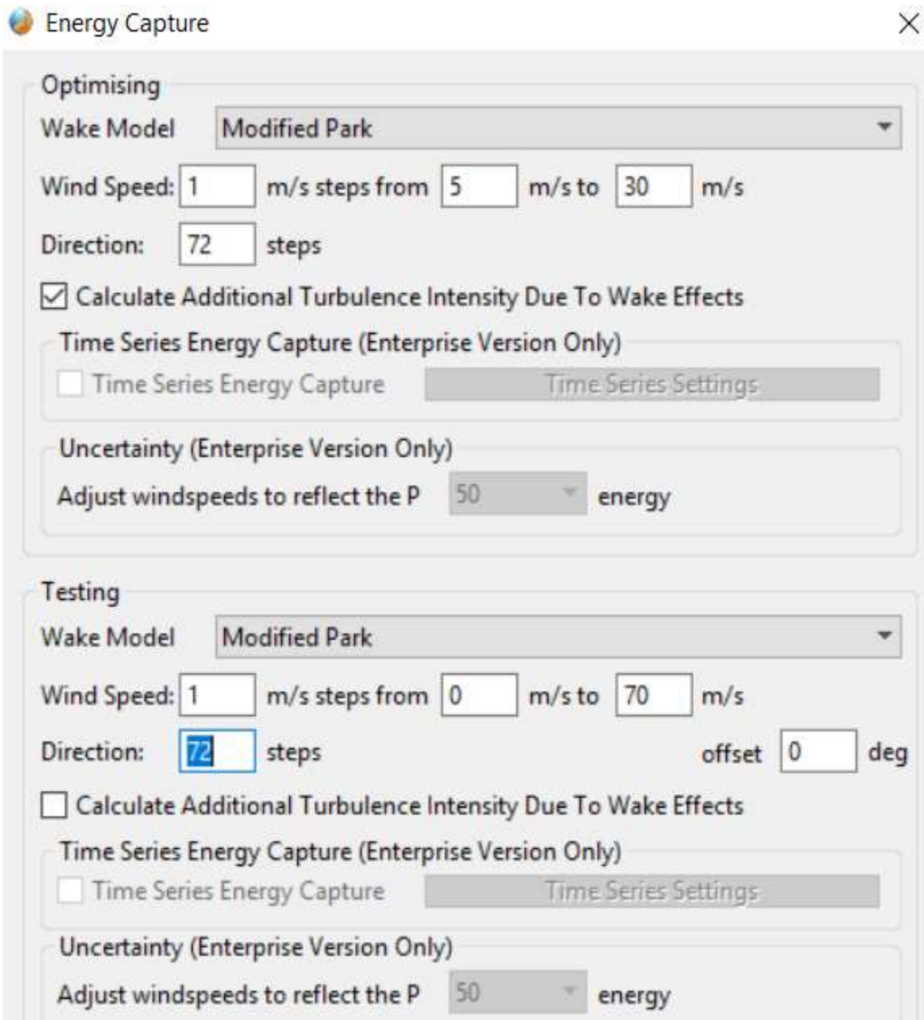

Figure 5.3. Energy capture module.

5.2.1.5 Optimization options

Using optimiser options module, see Fig. 5.4, it is more convenient to optimize the turbine positions with respect to the overall energy. The optimization process is simple and easy that involves randomly perturbing the turbine positions. Then verify the changes in position with respect to result, if its beneficial or not.

To check the WFDs optimized layout, the optimized option was auto-saved, because software had all the files uploaded that gives the results based on the turbine positions. However, when we optimized layout based on OpenWind optimization, we must set our options, see in the following steps:

- The optimizer provides an option for **maximum attempts to place each turbine** (before forcing), the number of attempts are using only random number to find a legal layout.
- The option with **maximum attempts to force a legal layout** applies if the random number fail to create a legal layout usually happens in a constrained park site. Then, the software tries to pack turbines into the available space at 60 degree intervals.
- **Number of successive fruitless iteration before stopping** means if given number of iterations pass without any improvement in net energy yield, the optimizer will stop. The optimizer tries to add new turbines to each site if a user checks the box as **Attempt to Dynamically Add a Turbine**.

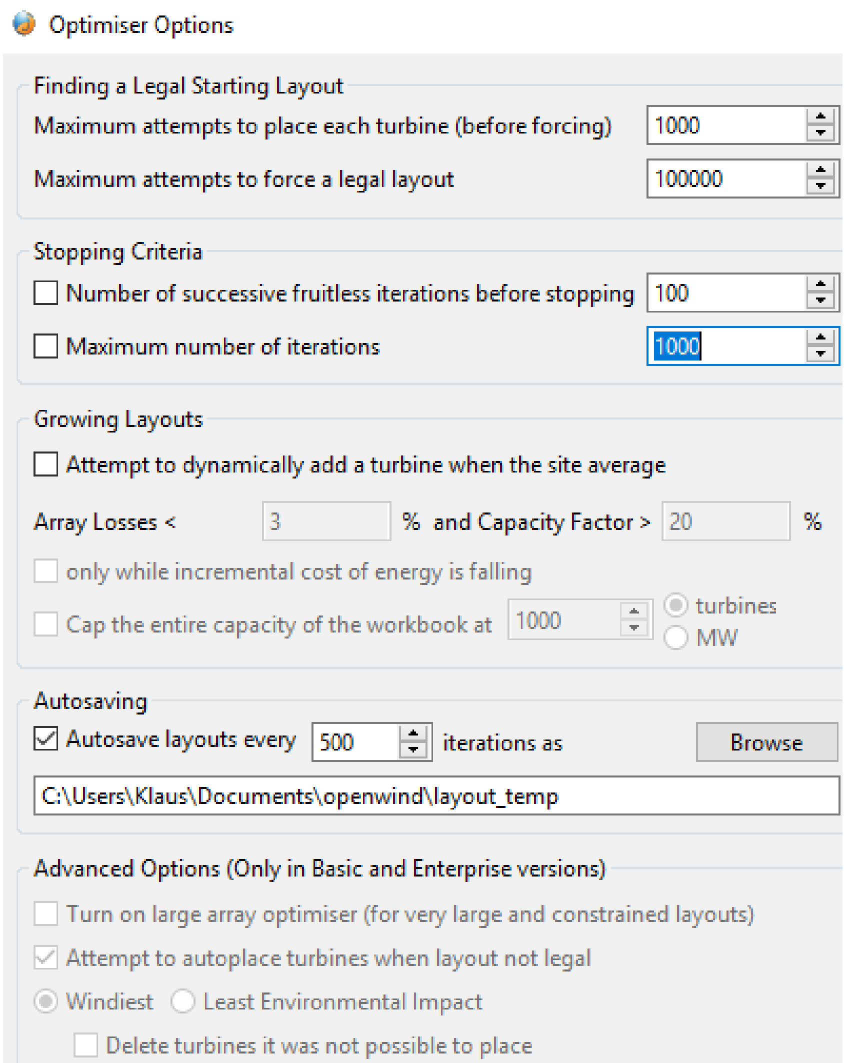

Figure 5.4. Optimiser options module.

5.2.2 RESULTS AND DISCUSSIONS

In this section, we compared the results based on gross and net energy production from both WFDs and OpenWind tools, excluding wake effects. WFDs optimized turbine positions coordinated are placed in OpenWind software to check the energy production. While OpenWind optimizes the same layout by defining its own turbine coordinated within the constrain area.

The resulting layout used for equal comparison is shown in the following figures. Fig. 5.5 shows the optimized turbine positions using AWS OpenWind optimizer and Fig. 5.6 represents the optimized turbine positions using WFDs optimizer. The turbine type is Siemens 108 3MW turbine with a rotor diameter of 108 and hub height of 80. Both software tools used 8760 hr/year for OpenWind power output power calculations. The number of turbines chosen for benchmarking is 20, The spacing requirements for turbines positions defined by their rotor diameter, can be seen from both figures that the circumference marked in black defines the distance between each turbine.

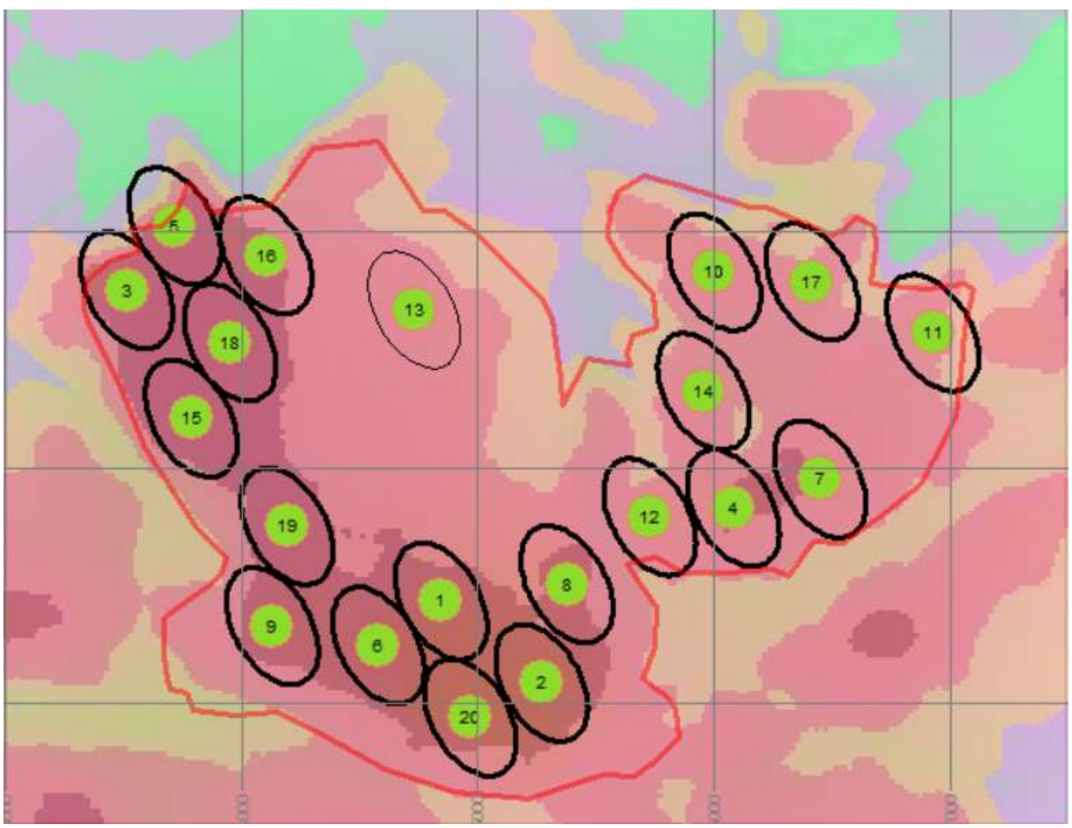

Figure 5.5. Optimized turbine positions using AWS OpenWind optimizer.

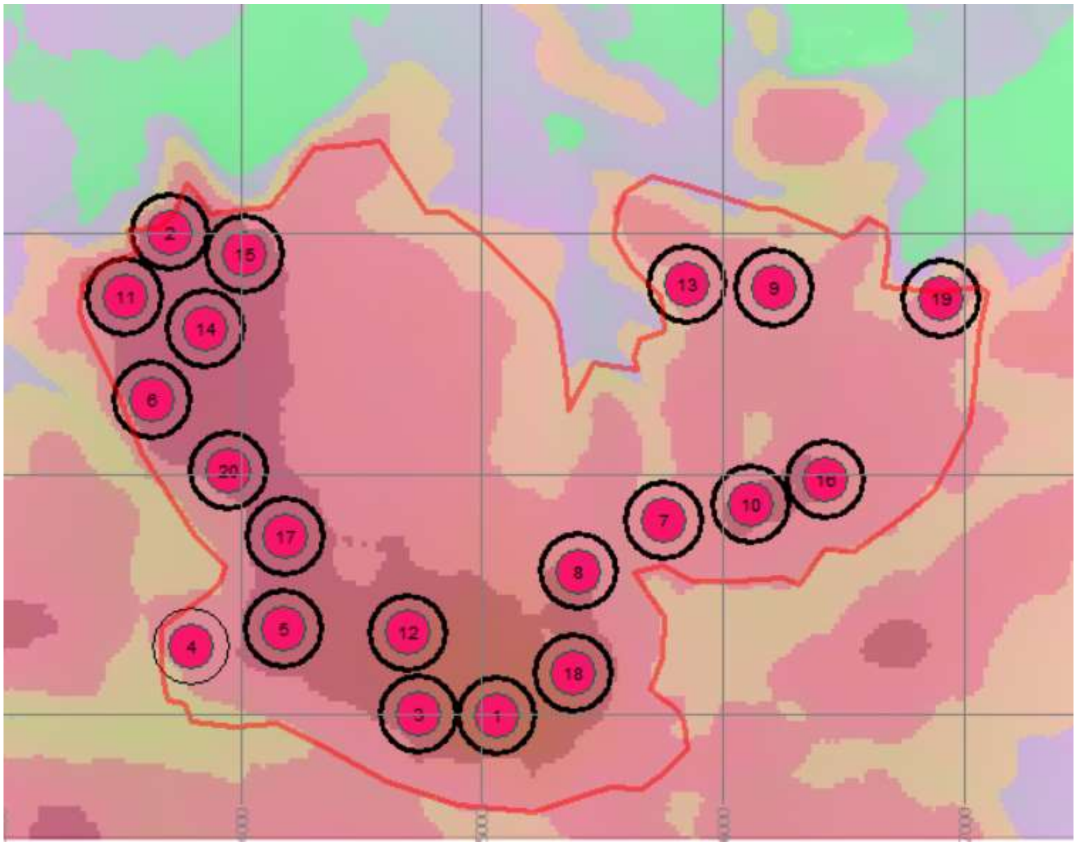

Figure 5.6. Optimized turbine positions using WFDs algorithm

The difference between optimization results based on energy production and array efficiency from the park layout is demonstrated in Table 5.1. Here, the gross energy is almost the same, but slightly higher for Openwind. WFDs estimated lower net energy as compare to Open wind, the change is very small only -1%. Again, the same lower results are estimated by WFDs optimizer for overall array efficiency, -1 %. The lower energy estimation is due to some constraints pertaining to the WFDs optimizer such as:

- WFD layout optimization is made with discrete grid, while the openwind optimization is continuous in its movement. The can make some small extra constraints that can affect the results.
- Secondly, the optimization is done in WFD, with the energymap from there, while the evaluation is done in openwind. Although the wind maps originates from the same source, the implementation of the energy calculation can differ slightly, within 1%.

The AEP production from each turbine using WFDs optimiser and AWS OpenWind optimizer shown in Appendix E, see Table E.1 and E.2, The upstream turbines installed in array influence the downwind turbines with their wake effects. This causes in energy losses due to the wake and that result in less than the ideally expected energy output from park layout. The efficiency factor associated with this loss is known as Array Efficiency. It is a ratio of ideal theoretical generation from Windfarm as if there was no array effect to actual generation[42]:

$$Array\ efficiency = \frac{\text{Ideal theoretical generation}}{\text{Actual generation}} \tag{5-1}$$

Table 5-1. Difference between both optimizations results.

	WFDs	**OpenWind**	**Difference in [%]**
Gross Energy [Gwh]	245.57	245.64	0
Net Energy [Gwh]	228.85	231.41	-1
Arrey Efficiency [%]	93.19	94.21	-1

6 WAKE EFFECT ANALYSIS

6.1 OVERVIEW

The purpose of the analysis is to check how important wake losses are in load compliant optimisations. In the analytical approach, we check the sensitivity of wake loss at distances that is IEC compliant for simple case (2 turbines). The purpose of this analysis is to determine the magnitude of wake losses when the effective turbulence criteria is just satisfied (assuming a certain ambient turbulence).

We want to demonstrate the wake loss influence of two turbines that is spaced so that they satisfy the effective turbulence criteria i.e. $\sigma_{eff} \leq \sigma_1$. The turbulence criteria solve for the distance that satisfies the Effective turbulence criteria of the turbine class (in our case class B) at the given wind speed (V_{hub} =15m/s), and at this distance we calculate the wake loss, and then we verified the changes in wake loss if we increase the distance by 1 RD (Rotor Diameter).

MATLAB program is used to calculate the wake loss of a downstream turbine for a given rotor diameter (RD). The measured turbulence ($\hat{\sigma}$) and standard deviation of the measured turbulence ($\hat{\sigma}_\sigma$) estimated from time series data on 10-min interval at wind speed of 15 m/s. Downstream turbine is positioned such that the effective turbulence criteria is just respected.

6.2 WHAT IS WAKE INTERACTION?

Wind turbines generate power by converting the kinetic energy in wind into electricity[43]. When the wind is moving through wind turbines, the volume of the air downwind of the turbine has a lower wind speed and higher turbulence than the wind in the free stream. In turn, the wake is impacting wind speed as well as the power generated by other neighbouring turbines. As the turbulence intensity increases due to wake effect, it accelerates the fatigue and reduces the lifespan of wind turbines. By considering wake and turbulence in the design of the wind farms can increase the output of energy production and minimize the maintenance cost[44].

The leading turbines produces much more power than the turbines having wake interaction. Wakes decay with distance, but also interact to reinforce or cancel each other. Atmospheric conditions can compound these interacting wakes, resulting in more or less power obtained at the farm[44].

Figure 6.1. The cloud formation in the wake of the front row of wind turbines in a wind farm[45]

There is still need to predict precisely the way that these wakes impact power output on a wind farm, that is crucial to optimizing wind farm design and operation. However, there are many software tools available to observe, compare, and predict turbine interactions, but many uncertainties remain. The variables determining how turbine wakes interact are complex and interconnected, limiting our ability to predict them[16].

To predict the wind velocity deficit, many studies have been done to compare different engineering wake models to analyse the performance. In a recent case study, two analytical wake models (Jensen and Frandsen, explained in detailed in literature review) have been compared with CFD (Computational Fluid Dynamics) simulations [46].

The case study includes the far wake behind a single wind turbine, a long row of turbines in an atmospheric boundary layer, idealised cases of an infinitely long row of wind turbines and infinite wind farms with three different spacing's. They concluded that the expansion factors calibration for three cases are found to be approximately half of the recommended standard values.

6.2.1.1 Wake Effects

The prime focus of this chapter is to study the impact of wake on effective turbulence. Because an increase in turbulence decreases the wind speed. That leads to energy loss ranging from 2 to 20% in a wind farm.

Wake losses occurs due to internal turbines within the wind farm, or because of external turbines in adjacent wind farms. This causes loss in energy production, and increases turbulence in the wake of turbines. Wind turbine wake effects are explained in detail in chapter 8, see this reference[1], From Fig. 6.2, we can see a simple turbine layout grid having three rows of turbine, the first row of turbines are creating wakes for the second row of turbines. The arrow represents the direction of wind.

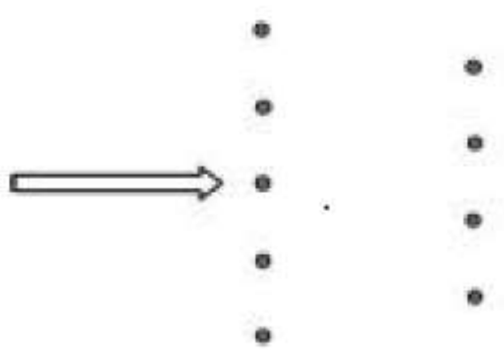

Figure 6.2. Wind farm layout with two rows of turbines[47].
The arrow indicates the direction of wind.

Subsequently, two prominent models Frandsen and N.O. Jensen (see Ch. 2) are used to calculate the main step of calculating effective turbulence intensity I_{eff} and Normalised Wake loss for WTG.

6.3 EVALUATION OF WAKE EFFECTS

In the next step, our objective is to calculate the energy loss with respect to turbine spacing $\left(\frac{\Delta E(V)}{\Delta x}\right)$. Wake loss is estimated by using N.O. Jensen Wake Model. The model uses the linear expansion of the wake radius with the downstream spread distance (for more detail, see section 2.2.3 in chapter 2).

To calculate the annual energy production, it is important to know the power curve. The power curve P(V), is function of wind speed, is obtained with wind turbine S-108.The overall annual energy $E(V)$ production over all wind speeds of each wind turbine can be calculated using Eq. 6.1.

$$E(V) = \int_3^{25} P(V) Weibul(V, A, k) dV \qquad (6\text{-}1)$$

where,

$P(V)$ – Power curve of turbine as a function of wind speed (V) range from cut-in and cut-out speed;

k – is Weibull shape parameter is equal to 2:

A – is Weibull scale parameter scaled at mean wind speed,8.11 [m/s] and calculated using Eq. 6.2.

$$A = \frac{v_{mean}}{\Gamma\left(1+\frac{1}{k}\right)} \qquad (6\text{-}2)$$

where,

v_{mean} – is the mean wind speed (in our case is 8.11 m/s);

Γ - is the gamma function (in our case its 0.88).

The annual energy loss is estimated over the whole range of wind speed (V) from 3m/s to 25 m/s. From the Eq. 6.3, we calculate the energy loss for the downstream turbine due to the wake effects.

$$E\left(V_{deficiet}\right) = \int_3^{25} P(V) Weibullpdf(V, A_{WLcorrected}, k) dV \qquad (6\text{-}3)$$

Jensen wake model is used under the assumption that the momentum is conserved inside the wake. Weibull parameter $A_{WLcorrected}$ is corrected by using sensitivity of the wake loss ΔU for downstream turbine to check the energy loss. Whereas, sensitivity of the wake loss ΔU or the velocity in the fully developed wake is calculated by using Eq. 6.4:

$$\Delta U = v_{mean} \times \frac{1-\sqrt{1-C_t(V)}}{(1+2kx)^2} \qquad (6\text{-}4)$$

where,

$C_t(V)$ – Thrust coefficient is function of wind speed;

k – is the Wake decay constant, assumed 0.075 in case of complex terrain;

x – is the normalized distance for downstream turbine in RD, $\left(x = \frac{D}{RD}\right)$;

D – is the relative distance [m];

RD – Rotor diameter-108 [m].

The total power loss is estimated by the following Eq. 6.5.

$$\Delta E(V) = E(V) - E\left(V_{deficiet}\right) \quad (6\text{-}5)$$

where,

$E(V)$ – Energy from upstream turbine [kW];

$E\left(V_{deficiet}\right)$ – Energy from downstream turbine [kW].

6.4 RESULTS AND DISCUSSIONS

In total, the energy loss for mean wind speed at 8.11 m/s at x is equal to 5RD, is 7.26 %, see 6.3. The marginal change in wake losses is 0.5 to 1 % at 5RD, see Fig. 6.4. The losses are not significant. In complex terrain, the "standard" wake decay coefficient k=0.075 is lower, because of more turbulent mixing, which results in a faster decay. WindPro has included the relationship of k=0.47*sigma(Vhub, x)/Vhub+0.04 as a linear relationship of ambient turbulence sigma and wake decay, k = 0.37 at 8.11 m/s[11].

The table 6.1, represents the Wake Loss with respect to distance. The total power production from freestream or upstream turbine is 1417 kW, while power production from downstream turbine is decreased to 49 kW, due to the wake loss effects at normalized distance x = 5RD.

Table 6-1. Wake Loss with Respect to Distance

E(V) [kW]	**$E(V_{deficit})$ [kW]**	**Wake Loss [%]**	**Distance**
1417	1368	7.26	5RD
1417	1337	5.6	6RD
1417	1353	4.5	7RD
1417	1365	3.65	8RD
1417	1373	3	9RD
1417	1380	2.6	10RD

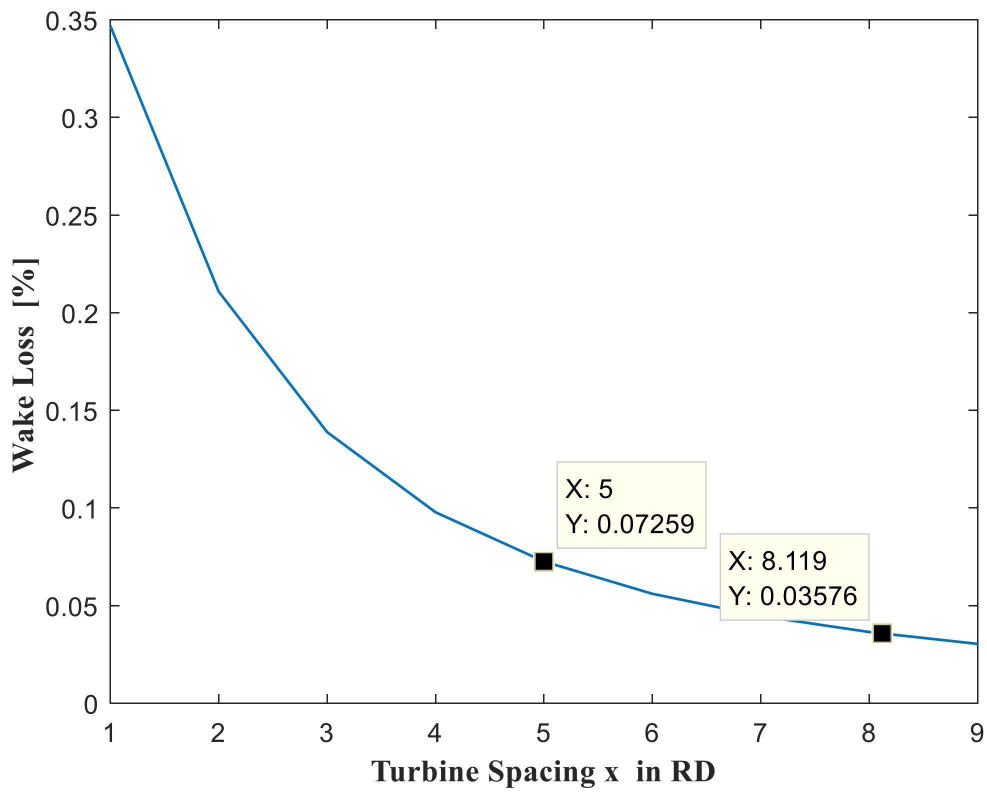

Figure 6.3. Wake loss with respect to turbine spacing.

The marginal change in wake loss, by moving the turbine one RD further downstream is: dWL/dx, where, WL is the wake loss function for a given mean wind speed (in our case 8.11 m/s). As can be seen from Fig. 6.4, the marginal change in wake losses by accounting for wake losses at rotor distances around 5 RD, is in the order of less than 1 %.

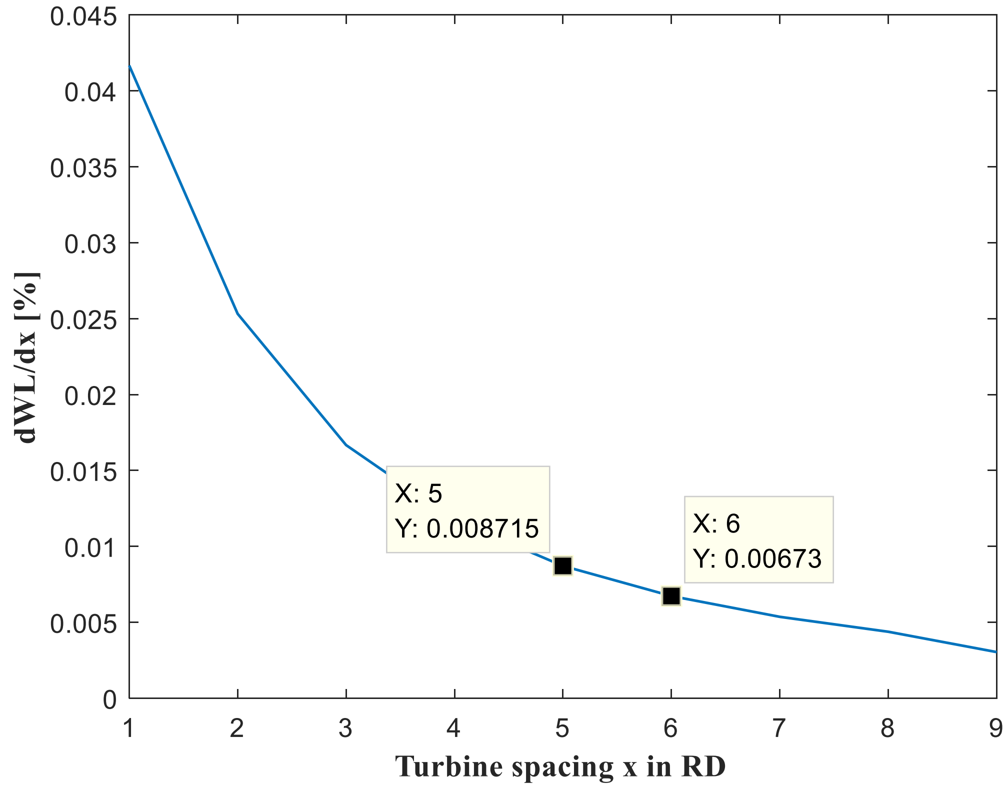

Figure 6.4 Marginal change in wake loss dWL/dx

Wake losses as function of rotor distances are in the order of 5 - 15 %. The results assume Weibull distributions, and the SWT-108 power curve. If we consider an optimized layout without accounting for wake effects, moving the turbine downstream will gain some more energy (in the order of 2% from reduced wake losses), but will also lose some energy due to lower ambient wind conditions, and it is quite probable that this would reduce the potential gain from including wake effects down to 1% or less.

The other consideration is that positioning the turbine downstream from an optimization that does not consider the wake loss, will be a less windy spot. The marginal change in energy is the sum of the reduced wake loss from moving the turbine downstream, plus the reduced energy production from a less windy location. We would assume this effect by reducing the effect of wake losses by 50%.

6.4.1 EFFECTIVE TURBULENCE CRITERIA

Effective turbulence is a simplified way of performing load calculations, recommended in the IEC 61400-1 standard. It is based on Frandsen's model. We check the effective turbulence criteria by using normal turbulence model (NTM) as per IEC 61400-1[20], see Fig. 6.5 and 6.6. The parameter for the effective turbulence (σ_{eff}) is calculated and compared with value of the turbulence standard deviation (σ_1), that is given by the 90 percentiles for the given hub height wind speed, V_{hub}(=15m/s), see Fig. 6.5. This value of the standard wind turbine class is given by Eq. 6.6[20]:

$$\sigma_1 = I_{ref}(0.75V_{hub} + 5.6)\ [m/s] \tag{6-6}$$

where,

I_{ref} – referenced value of turbulence intensity at hub certain hub height at 10 min average wind speed of 15 m/s (see Table 2.3);

V_{hub} – wind speed at given hub height (15 m/s in our case), according to IEC 61400-1, all values of the V_{hub} must be between the wind speed $0.2V_{ref}$ and $0.4V_{ref}$, (V_{ref}= 42.5, for class B turbines).

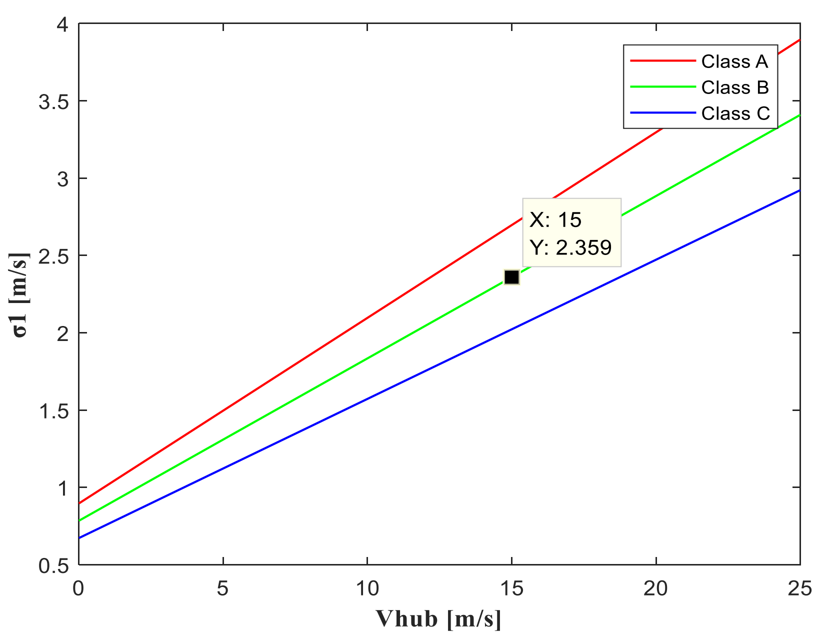

Figure 6.5 Turbulence standard deviation for the normal turbulence model (NTM)

The effective turbulence - σ_{eff} is verified with standard deviation turbulence intensity - σ_1 over distance less than 10RD, see Fig. 6.6. Increase in loading are result of wake effects, and that is accounted for using effective turbulence.

We can see from Fig. 6.6, the value of turbulence is larger due to the higher wake of upstream turbine from x = 2D to x = 6RD, where it violates the condition of σ_1, is in order of 4.5 to 2. At x = 8.40RD, σ_{eff} satisfy the criteria of turbine spacing.

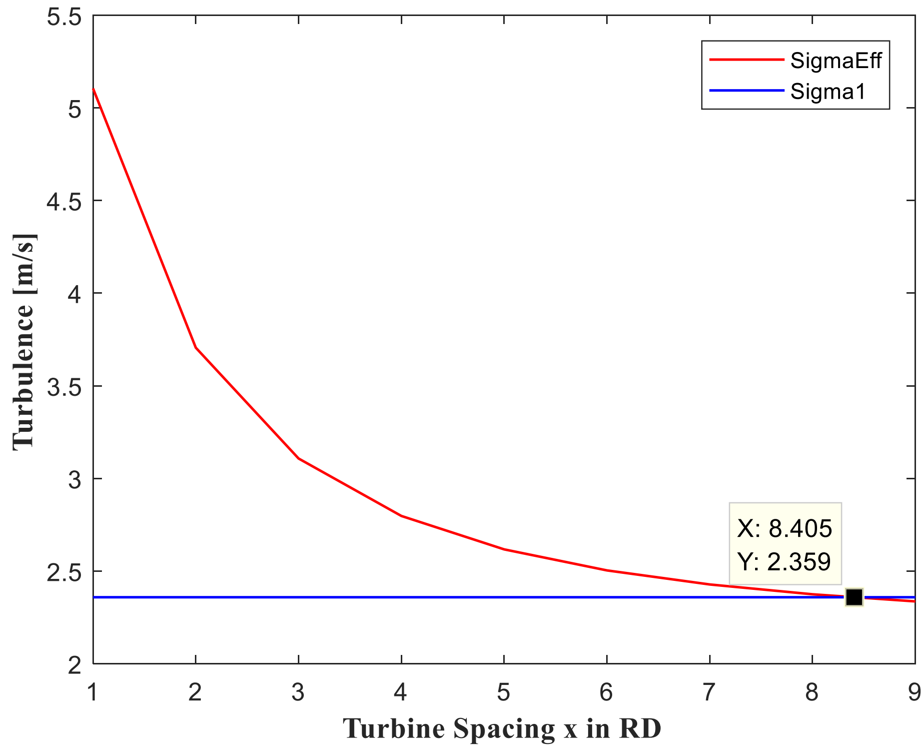

Figure 6.6 Effective turbulence criteria satisfy the optimum turbine distance at x = 8.405RD

Steps for calculation are explained in Wake Model's Chapter 2. Now we solve for x, where $\sigma_{eff} = \sigma_1 = 2.359\ [m/s]$. High effective turbulence from upstream turbines causes excessive fatigue on the blade of downstream turbine. Effective turbulence must satisfy the condition at certain distance from upstream turbine. We can check also that wake loss is almost insignificant at the optimum distance satisfied by effective turbulence criteria, see from Table 6.2 and Fig. 6.7.

Table 6-2. Wake Loss at satisfied turbulence criteria

E(V) [kW]	E($V_{deficit}$) [kW]	Wake Loss [%]	Distance
1417	1368	3.38	8.405RD

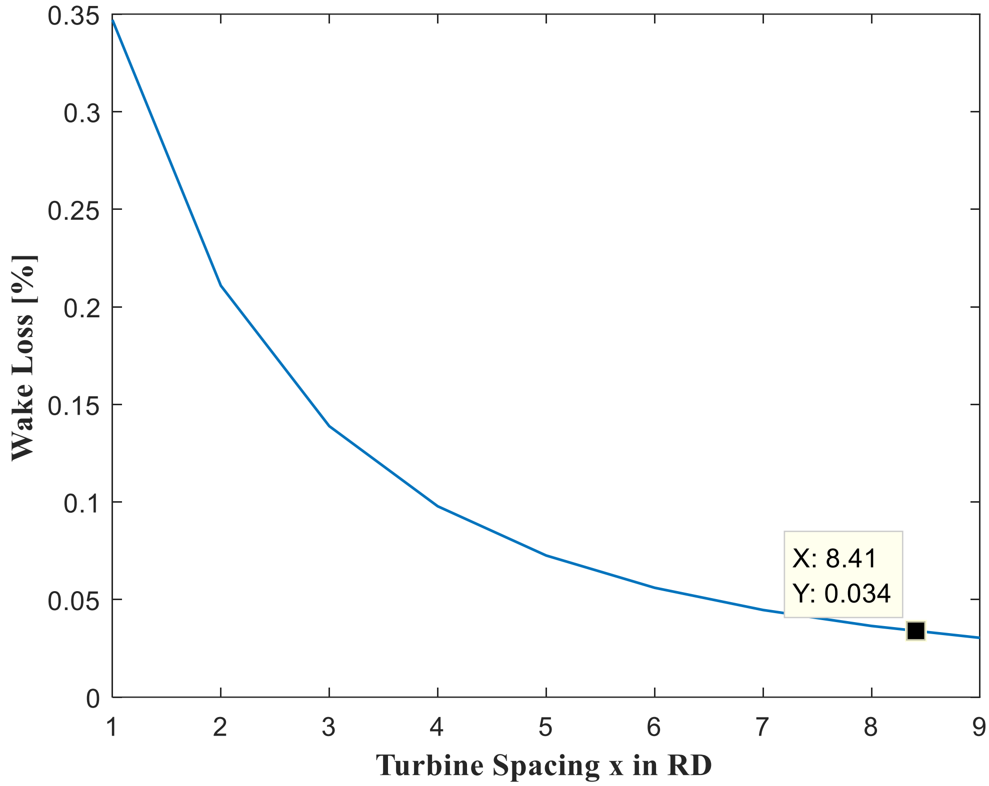

Figure 6.7. Shows the wake loss effect at the optimum distance satisfied by effective turbulence criteria.

CONCLUSION

The purpose of this thesis is to demonstrate an analyse tools for the optimization of windfarms in view of both the maximisation of the energy gain and the restriction of the fatigue loads within acceptable limits. Our objective is to optimize the wind farm layout that provide fast and accurate wind turbine suitability assessment, maximizing the annual energy production including load constraints as per IEC 61400-1 standard.

Two different software tools WFDs and OpenWind approach are applied to obtain optimal output from wind farm layout. The layout is optimized by positioning the number of turbines within park area. There is a small difference in gross energy output, given by WFDs and OpenWind. Whereas, the net energy and array efficiency is lower as compare to OpenWind, the change is very small for both, however, i.e. up to -1%. We assume that WFDs optimization is pertaining to some constraints causing lower output than OpenWind, such as wind map originates from the same source, the implementation of the energy calculation can differ slightly, within 1%.

Wind turbines are sensitive to the wake losses at distances when they are operating in a large wind farm. N.O. Jensen wake model is used to check the wake effects from the upstream turbines. From the experimental results, we estimated that the marginal change in wake loss by moving downstream turbine by one rotor diameter distance is in order from 0.5 to 1% only. This marginal change is insignificant. On the other hand, if wake effects are not considered to optimize the wind farm layout, result can be less windy place for turbine, that will reduce the wake losses by half margin.

By using Frandsen model, we analysed the increased loads on downstream turbine during their normal operations as per IEC 61400-1 criteria (WFDs uses the same approach). In large wind farm, the high turbulence from upstream turbine increases the fatigue damage levels. We satisfy the effective turbulence criteria at a certain distance between upstream and downstream turbines to minimize the fatigue load level.

To sum up, it can be estimated from the analytical results that wake losses are not so important in load compliant optimizations. However, we must satisfy the effective turbulence criteria at certain distance to avoid fatigue for lifetime damages.

One of our goal to verify wind farm layout as per IEC 61400-1, was not fulfilled. The layout was not fully compliant in terms of load constraints as per IEC criteria. These load constraints were to be verified by park optimizer, which is incorporated with WFDs algorithm (due to the bug in algorithm it is not providing the desired results based on WFDs approach). Without WFDs algorithm the ParkOptimizer tool provides results based on heuristic approach which is not compliant in the terms of load constraints.

In future, work can be done to analyse the load compliant wind farm layouts using EMD load compliance module i.e. WindPro and WAsP CFD results. There is still need to dig up more about structural load analysis of wind turbines during their operation within wind farm for both normal and extreme wind conditions. Therefore, a systematically study can be done by using FAST (Fatigue, Aerodynamics, Structures, and Turbulence) and TurbSim to analyse the impact on fatigue loads from problematic wind conditions on some complex terrains. This will develop a better understanding of fatigue and extreme loads on structural components of wind turbines.

APPENDICES

APPENDIX A

Turbulence intensity (TI) is a measure for short-term volatility of wind speeds and is determined by the orography of the site, amongst other things. Before we planning the project layout, it is imperative to make sure that turbulence intensity for all wind turbines in the farm lies within the IEC certified area for a safe and low-wearing operation. If this is not the case, the turbine is operated outside the accredited operation mode, which can lead to an accelerated wear and tear process. If turbulence intensity is outside the tolerated level, turbine type certification and operational permits may lose their validity and the affected turbines should be shut down. Adequate turbulence intensity fulfilment can be proven by independent technical (or wind resource) advisors[1].

Normally, independent evaluations are necessary when the distance between the turbines is shorter than 5x rotor diameter (3x rotor diameter only, if distance is measured vertically to the main wind direction). The second criterion for distance determination between turbines in a wind farm setting is the wind direction dependent optimization of wake losses caused by shadowing effects which lead to production reductions of single turbines[1].

A rule of thumb for the optimization of farm energy yield usually includes the aim to achieve a farm efficiency of higher than 90% (especially for bigger wind farms), which requires a minimum distance of 3x rotor diameter vertically to the main wind direction (if possible: choose 5x rotor diameter) and a minimum distance of 7x rotor diameter in main wind direction (if possible: choose 8x rotor diameter)[1].

APPENDIX B

Table B 1. Shows Climatology Computed as Per IEC 61400-1 2nd Edition

Name	V_{ref} [m/s]	V_{avg} [m/s]	I_{ref} [-]	s I_{ref} [-]	I_{15} [-]	WTGS Class
Wecs1	30.29	7.89	0.072	0.034	0.106	IIB
Wecs2	28.69	7.66	0.079	0.031	0.110	IIB
Wecs3	28.77	7.68	0.079	0.034	0.113	IIB
Wecs4	29.21	7.56	0.079	0.033	0.112	IIB

Table B 2. Shows Climatology Computed As Per IEC 61400-1 3nd Edition

Name	V_{ref} [m/s]	V_{avg} [m/s]	I_{ref} [-]	s I_{ref} [-]	TI 90^{th} perc. [-]	WTGS Class
Wecs1	30.29	7.89	0.072	0.034	0.115	IIB
Wecs2	28.69	7.66	0.079	0.031	0.118	IIB
Wecs3	28.77	7.68	0.079	0.034	0.122	IIB
Wecs4	29.21	7.56	0.079	0.033	0.121	IIB

APPENDIX C

Wind Turbine Selection

Sites with moderate wind conditions call for a turbine that can maximize your energy returns no matter what, and the SWT-2.3-108 wind turbine is designed to do just that. For enhanced power output and increased control over energy output in moderate wind conditions, it features an advanced blade design with pitch regulation and a rotor with a diameter of 108 meters[48].

Figure C 1. Onshore Geared Wind Turbine SWT-2.3-108[48]

Table C 1. Technical Specifications[48]

Siemens Wind turbine	2.3-108
IEC Class	IIB
Nominal Power	2
Rotor diameter	108 m
Blade length	53 m
Swept area	9
Hub height	78.5 - 115 m
Power regulation;"	Pitch regulated
Annual output at 8.5 m/s	11.1 GWh

Wind Farm Assessment Tool (WAT) Results

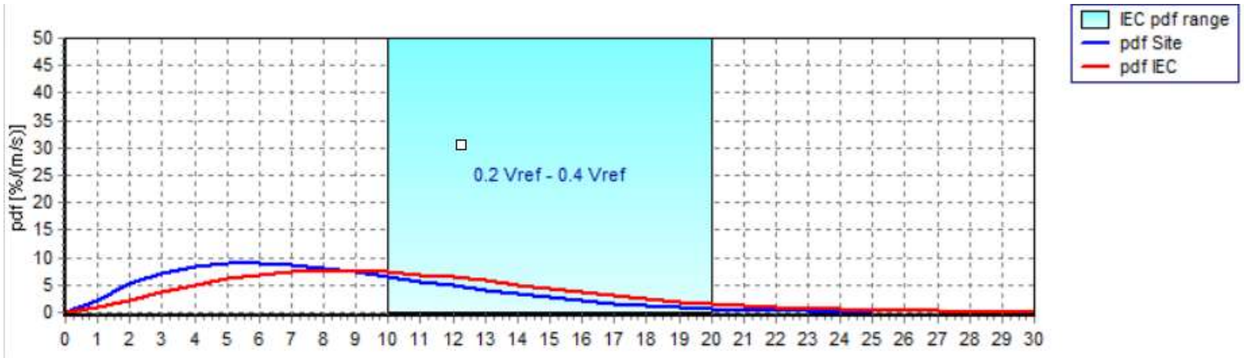

Figure B 1 Wind-speed probability density distribution at wecs 1. Actual PDF is withing the design PDF in IEC range.

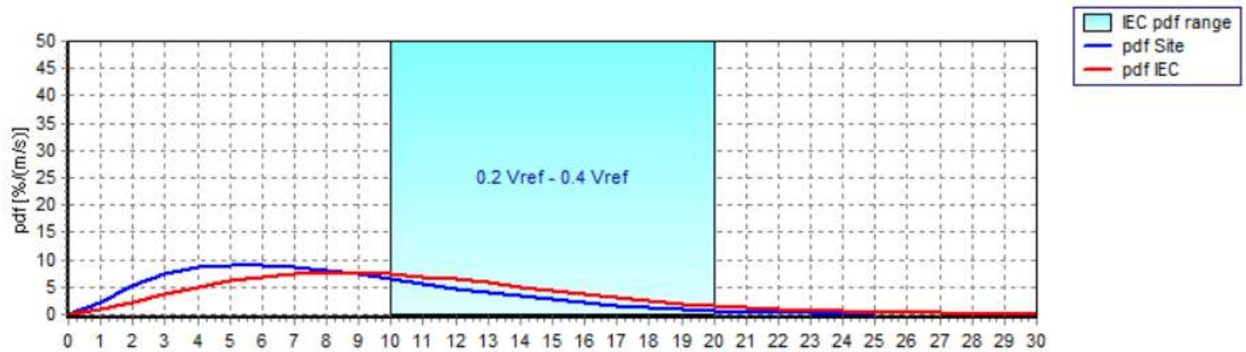

Figure B 2 Wind-speed probability density distribution at wecs 2. Actual PDF is withing the design PDF in IEC range.

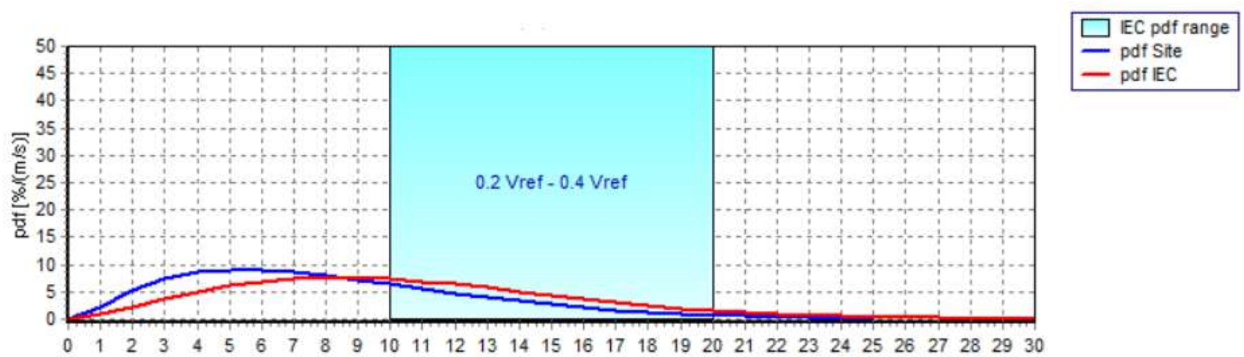

Figure B 3 Wind-speed probability density distribution at wecs 3. Actual PDF is withing the design PDF in IEC range.

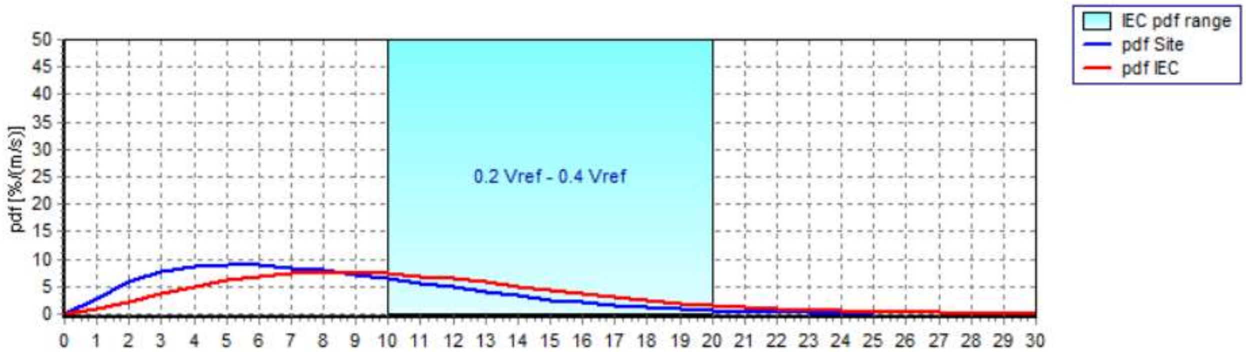

Figure B 4 Wind-speed probability density distribution at wecs 4. Actual PDF is withing the design PDF in IEC range.

APPENDIX D

Optimization Process in AWS OpenWind

In the first step, the optimizer checks whether the current layout is legal and all turbines obey all the current constraints and have appropriate wind resource information. If this is not the case, it attempts to find random positions for the turbines. If this fails, it attempts to pack the turbines. Once a legal layout is available, the optimizer does a full test of the layout to get the starting energy. Then it tests the layout again to get its first optimizing benchmark. Then it begins to optimize the layout. The iterations of optimizer include the following step[29]s:

The optimizer attempts to find a new legal position for each turbine. If the turbine made a good move last iteration, it will attempt the same direction this time. Otherwise, it finds a new random perturbation. It does this by adding a Gaussian distributed random perturbation to the turbines x and y coordinates. If the new position is not a legal position or it obstructs another turbine position, then a new random perturbation is made and so on until all the turbines have new valid positions.

3. The optimizer then runs an energy capture (which includes wake effects of course) and if the total energy is greater than the benchmark energy, it accepts the entire new layout (this tends to only happen at the beginning of the optimization process) and the perturbed positions become the permanent positions and the new energy becomes the benchmark energy and we return to step 1.

4. If the new layout was not accepted the optimizer looks at each turbine from another way and if that turbine got less than its benchmark energy, the perturbation is discarded and the turbine is returned to its last position and benchmark energy. This process is done one by one to each turbine inside the iteration process of optimization algorithm.

5. The optimizer then sums the total energy from all the turbines and if it is equal or greater than the benchmark energy, it runs another energy capture to see if it constitutes an improvement. If not then all perturbations are discarded and return to step 1. If so, then we accept all these new positions and energies as the benchmark energies and return to step 1. Process will continue until all iterations will be executed.

APPENDIX E

Table E.1 and E.2, represents AEP production using WFDs optimiser and AWS OpenWind optimizer.

Table E 1. AEP Production using WFDs optimiser.

Site	Turbine Type	Rated Power [kW]	RD [m]	Gross Yield [MWh/yr]	Net Yield [MWh/yr]	Array efficiency [%]
WFDs1	SWT-108	3000	108	13120.05	12246.36	93.3
WFDs2	SWT-108	3000	108	13023.59	12232.57	93.9
WFDs3	SWT-108	3000	108	13045.49	11695.86	89.7
WFDs4	SWT-108	3000	108	12995.29	12629.62	97.2
WFDs5	SWT-108	3000	108	12851.9	12087.13	94.0
WFDs6	SWT-108	3000	108	12801.37	12097.25	94.5
WFDs7	SWT-108	3000	108	12690.59	11453.42	90.3
WFDs8	SWT-108	3000	108	12488.06	11319.01	90.6
WFDs9	SWT-108	3000	108	12516.18	11912.46	95.2
WFDs10	SWT-108	3000	108	12280.39	11682.36	95.1
WFDs11	SWT-108	3000	108	12406.54	11785.09	95.0
WFDs12	SWT-108	3000	108	11969.66	10924.98	91.3
WFDs13	SWT-108	3000	108	12202.66	11308.91	92.7
WFDs14	SWT-108	3000	108	11887.65	10894.81	91.6
WFDs15	SWT-108	3000	108	11694.61	10841.25	92.7
WFDs16	SWT-108	3000	108	11765.56	11161.55	94.9
WFDs17	SWT-108	3000	108	11420.92	11298.61	98.9
WFDs18	SWT-108	3000	108	11630.95	10286.38	88.4
WFDs19	SWT-108	3000	108	11497.96	10171.03	88.5
WFDs20	SWT108	3000	108	11281	10820.86	95.9
Total	-	-	-	245570.4	228849.5	93.2

Table E 2. AEP Production using AWS OpenWind.

Site	Turbine Type	Rated Power [kW]	RD [m]	Gross Yield [MWh/yr]	Net Yield [MWh/yr]	Array efficiency [%]
OpenWind1	SWT-108	3000	108	12845.8	11527.4	89.7
OpenWind2	SWT-108	3000	108	13138.3	12369.5	94.1
OpenWind3	SWT-108	3000	108	13271.3	12596.6	94.9
OpenWind4	SWT-108	3000	108	12337.7	11728.9	95.1
OpenWind5	SWT-108	3000	108	12881.1	11855.4	92.0
OpenWind6	SWT-108	3000	108	13063.7	12414.4	95.0
OpenWind7	SWT-108	3000	108	11769.4	11205.3	95.2
OpenWind8	SWT-108	3000	108	12372.2	11736.8	94.9
OpenWind9	SWT-108	3000	108	12814.1	12229.5	95.4
OpenWind10	SWT-108	3000	108	10772.7	10275.5	95.4
OpenWind11	SWT-108	3000	108	11742.8	11175.4	95.2
OpenWind12	SWT-108	3000	108	10921.7	10095.3	92.4
OpenWind13	SWT-108	3000	108	11009.3	10207.8	92.7
OpenWind14	SWT-108	3000	108	12518.5	11527.4	92.1
OpenWind15	SWT-108	3000	108	12841.1	12311.4	95.9
OpenWind16	SWT-108	3000	108	12216.2	11189.2	91.6
OpenWind17	SWT-108	3000	108	11371.0	10735.7	94.4
OpenWind18	SWT-108	3000	108	12645.2	11564.6	91.5
OpenWind19	SWT-108	3000	108	11566.6	11457.9	99.1
OpenWind20	SWT108	3000	108	13543.0	13207.8	97.5
Total	-	-	-	245641.6	231412.0	94.2

APPENDIX F

Mfile. Sigma Effective

```
function [output] = sigma_eff(Vhub,x)
% % returns the value of output
% %   Calculates the sigma effective as a function of vind speed
at hub height Vhub and downstream distance x
Sigma_avg = 1.43;
Sigma_std = 0.422;
CCT = 1.15;
%% %% Sigma_C characteristic turbulence
sigma_C = Sigma_avg+1.28*Sigma_std*CCT; %Induced turbulence
sigma_wake = Vhub./(1.5+(0.8*x./sqrt(Ct(Vhub))));
%% effective turbulence
output = sqrt((sigma_C^2)+(sigma_wake.^2));
%% NTM for large wind turbine is described based on an
approximation of
% the 90th percentile of the standard deviation of the
longitudinal wind
% speed Vhub
  end
```

Mfile.Thrust Coefficient

```
function output = Ct(Vhub)
% returns Ct as function of Vhub
% Define table of Ct values (Vhub,Ct)
Ct_table =   [ 3.0000    0.8600
    4.0000    0.8500
    5.0000    0.8400
    6.0000    0.8500
    7.0000    0.8500
    8.0000    0.8400
    9.0000    0.8100
   10.0000    0.7200
   11.0000    0.6400
   12.0000    0.4400
   13.0000    0.3300
   14.0000    0.2600
   15.0000    0.2100
   16.0000    0.1700
   17.0000    0.1400
   18.0000    0.1200
   19.0000    0.1000
   20.0000    0.0900
```

```
   21.0000    0.0800
   22.0000    0.0700
   23.0000    0.0600
   24.0000    0.0500
   25.0000    0.0500
   26.0000         0    ];
 % check if v is in range of Ct table
Vhub_min = Ct_table(1,1);
Vhub_max = Ct_table(end,1);
 if Vhub<Vhub_min | Vhub>Vhub_max,
    error(['input    Vhub    outside    valid    range    of    ',
num2str(Vhub_min),' ... ', num2str(Vhub_max)]);
else
    output  =  interp1(Ct_table(:,1),Ct_table(:,2),Vhub,'linear');
% return interpolated value of Ct
end
function output = PC(Vhub)
% retunrs Ct as function of Vhub
% Define table of Ct values (Vhub,Ct)
```

Mfile.Power Curve

```
PC_table =   [            3       51000
          4      151000
          5      313000
          6      554000
          7      891000
          8     1336000
          9     1875000
         10     2435000
         11     2856000
         12     2984000
         13     2999000
         14     3000000
         15     3000000
         16     3000000
         17     3000000
         18     3000000
         19     3000000
         20     3000000
         21     3000000
         22     3000000
         23     3000000
         24     3000000
         25     3000000
         26           0];

% check if v is in range of Ct table
```

```
Vhub_min = PC_table(1,1);
Vhub_max = PC_table(end,1);
 if Vhub<Vhub_min | Vhub>Vhub_max,
    error(['input Vhub outside valid range of ', num2str(Vhub_min),' ...
', num2str(Vhub_max)]);
else
    output = interp1(PC_table(:,1),PC_table(:,2),Vhub,'linear')*1e-3; %
return interpolated value of Ct
end
```

Mfile. Annual Energy Production with Wake Loss Correction

```
function output = F4( V,vmean,kwb )
% Energy calculation using power curve and weibull distribution
function
kwb = 2.0; % the shape factor
A =vmean./(gamma(1+(1/kwb))); % scaling of gamma at 7.11 m/s @50 m hub
height
output = PC(V).*wblpdf(V,A,kwb);
end
```

Mfile. Annual Energy Production with Wake Loss Correction

```
function output = F4WLct( V,vmean,kwb,x )
% UNTITLED3 Summary of this function goes here
% calculating the wake loss corrected Weibull parameters A-deltaU
k = 0.075;
deltaU = V.*((1-(sqrt(1-Ct(V))))/((1+2*k*x).^2));
A = vmean/(gamma(1+(1/kwb)));
Act=A-deltaU;
output = PC(V).*wblpdf(V,Act,kwb);
end
```

Mfile Wake Loss

```
function output = WLossEr(x)
vmean =8.11;
kwb = 2.0;
V = 3:1:25;
F_7 = @(V)F4WLct( V,vmean,kwb,x );
Q_7 = integral(F_7,3,25);
% the shape factor
F_6 = @(V)F4( V,vmean,kwb );
Q_6 = integral(F_6,3,25);
output = (Q_6-Q_7)/Q_6;
end
```

Turbulence Data is extracted from Time Series Data:

Vhub	sigma	sdsd	sigma_c
1	0.44113	0.17137	0.66048
2	0.48734	0.21966	0.76851
3	0.48595	0.21655	0.76313
4	0.52902	0.2313	0.82508
5	0.57278	0.25033	0.89321
6	0.62643	0.27872	0.98319
7	0.67684	0.32333	1.0907
8	0.70513	0.34164	1.1424
9	0.76957	0.36928	1.2422
10	0.81292	0.38922	1.3111
11	0.90981	0.41378	1.4394
12	0.99476	0.45634	1.5789
13	1.1394	0.46858	1.7392
14	1.2966	0.49112	1.9252
15	1.4555	0.48398	2.075
16	1.6096	0.49522	2.2435
17	1.6951	0.50129	2.3368
18	1.6981	0.56075	2.4158
19	1.9187	0.54827	2.6205
20	1.8846	0.45751	2.4702
21	1.8736	0.40264	2.389
22	1.8669	0.42673	2.4132
23	1.9194	0.52994	2.5977
24	2.037	0.16267	2.2452
25	1.78	0.40911	2.3037

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