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Reduced Levelized Cost ofEnergythrough Optimization of Tower Height, Rotor Diameter And\Wind Farm Layout

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ABSTRACT: *Wind power has become the most important renewable energy source. Two factors are mainly influencing its future development: scarcity of sites and levelized cost of energy (LCoE). By a site specific turbine and wind park design it is possible to improve both aspects compared to state of the art approach. Within this paper an analytical tool and a multi-objective optimization method is presented which is able to identify optimal site specific wind turbine and wind farm layout such that available space is used efficiently in terms of the amount of supplied energy and LCoE. With the help of this approach it is possible to increase a wind farms AEP by 20% and decrease its LCoE by 10% for an exemplarily site and wind park layout in Germany.*

KEYWORDS: *Wind farm, Layout, Genetic Optimization, Levelized Cost of Energy*

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I. INTRODUCTION

Wind power has become the most important renewable energy source [1]. Countries like Germany have set themselves ambitious expansion goals for wind power and renewables for the future [2]. One factor greatly limiting the expansion of wind power is the scarcity of sites. In some regions wind conditions are not sufficient. However, acceptance problems are the more important reason for the scarcity of sites. Therefore, there is a strong need to use the available space as best as possible. In this case best as possible means, providing as much electricity as possible per site, measured by the annual energy production (AEP). This can be done by customizing the wind turbine (WT) itself and the general wind farm layout to the prevailing site conditions. On the other hand, customized wind turbines and wind farm layouts have the potential to reduce the cost for the wind farms energy supply, known as levelized cost of energy (LCoE). So far, wind power is only cost competitive at selected sites compared to conventional power generation. In order not to burden the society with high electricity cost because of the expansion of renewables, there is a high pressure on reducing LCoE of wind power. Thus, there is a strong need to optimally use available wind sites. This means that the design and placement of wind turbines should be selected with respect to maximizing AEP and minimizing LCoE. This leads to a multi-objective optimization problem. In terms of design, AEP can be increased through heightening the tower and lengthening the rotor. However, higher towers and longer blades lead to greater investment cost and might have a negative effect on the LCoE. Furthermore, a boost of AEP can be achieved by either increasing the AEP of a single wind turbine or by raising the overall wind farm AEP through improved placement and/or increasing the amount of installed wind turbines. It needs to be kept in mind that every additional turbine leads to additional investment cost and possible wake effects. Given these numerous possibilities and trade-offs a decision has to be made.

II. STATE OF THE ART

Nowadays, it is done based on practical knowledge. Even as the topic is discussed in multiple publications. Mosetti[3] can be seen as one of the pioneers discussing wind farm optimization. In his publication he presented the possibility to optimize a wind farm layout inside a rectangular domain. He used a genetic optimization scheme to determine an optimal layout using a similar objective function as the one given in Equation (6). Since then multiple author approached the topic *wind farm optimization* [4-9]. Each of them is improving the initial approach of Mosetti, by other using a different optimization algorithm or enhancing the optimization space. While discussing wind farm optimization it is also relevant to name the two projects TOPFARM [10] and OWFLO [11], where multiple aspects were considered. TOPFARM [10] developed a two fidelity optimization platform. In the optimization process the alternation of the variables are based on low fidelity models, while the outcome is evaluated through high fidelity models, leading to an improved estimation of the overall power outcome. The project Offshore Wind Farm Layout Optimization (OWFLO) focused on the topic of micro-siting the turbines in an offshore aerial. This environment leads to a change of the influencing parameters like the foundation which varies with respect to the water depth.

The authors still see a potential for increasing AEP and simultaneously decreasing LCoE by intelligent turbine placing and turbine design choice based on analytically calculations. Therefore this paper presents the analytic tool WIFO (WInd Farm Optimization) which is capable of determining the AEP and LCoE of any given turbine configuration in any arbitrary wind park layout. Additionally, the tool is equipped with a generic optimization algorithm which allows to generate a site specific wind turbine and wind farm design. Another improvement with respect to the current state of the art is the implement cost model, capable of considering up-scaling trends.

III. EXPLANATION OF WIFO

The developed WIFO does not only contain an optimization algorithm, but an evaluation tool, which acts as the base of the optimization. This evaluation consists of three major stages: wind resource assessment, aerodynamic modulation and financial aspect. These are explained in the following sections.

A. *Wind Resources Assessment*

The first stage equals the wind resource assessment. The German Weather Service (GWS) [12] provides a wind atlas with Weibull parameters k and A at any given location. These parameters are based on 20 years of observation and will be used in this paper. The corresponding Weibull distribution of the reference site can be found in Fig. 1. The reference site has a low mean wind speed of 6.1 m/s. The corresponding wind direction distribution, displayed in Fig. 2 indicates a dominant wind direction from south-west.

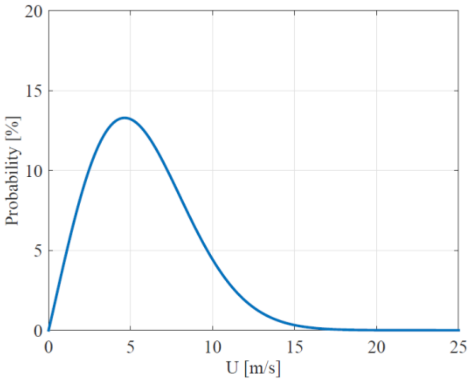

Figure 1: Weibull distribution at reference site at 80 m height (A = 6.5 , k = 2.0) [12]

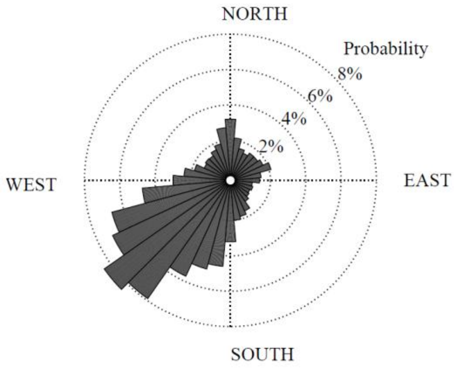

Figure 2: Wind direction distribution at reference site at 80 m height [12]

These distribution will be scaled towards the hub height of the turbine using Equation (1) based on [13]. The index 0 represents the initial state, H the height, U the wind speeds and ζ_r the roughness length. The reference site is located in a complex terrain, including a severe amount of obstacles, therefore a roughness length of 0.3 in agreement with the IEC 61400-1 [13] is chosen.

$$U(H) = U_0 \frac{\ln H/\zeta_r}{\ln H_0/\zeta_r} \quad (1)$$

B. *Aerodynamic Modulation*

This paper has the goal to determine the optimal wind turbine configuration as well as the park layout for lowest LCoE. This requires the power curve of the used wind turbine. In this paper the power curve is determined by a state-of-the-art blade element method (BEM) [14] for any given wind distribution and blade geometry. As rotor radius is directly related to the power output and LCoE, It will be necessary to scale the rotor radius during the optimizations. This means that the blade geometry needs to be scaled as well. The wind turbine that will be linearly scaled in the later process is based on the CWD Onshore reference turbine with a rated power of 3 MWand a rotor diameter of 126 m (C3X126) [15,16]. The power curve of the C3X126 can be seen in Fig. 3. Onshore, the tip speed is not allowed to surpass 75 m/s, resulting in a limitation of the rotational speed. This limit speed is reached at 8.7 m/s. After the rated wind speed of 9.5 m/s is achieved the blades will be pitched to keep the power output constant.

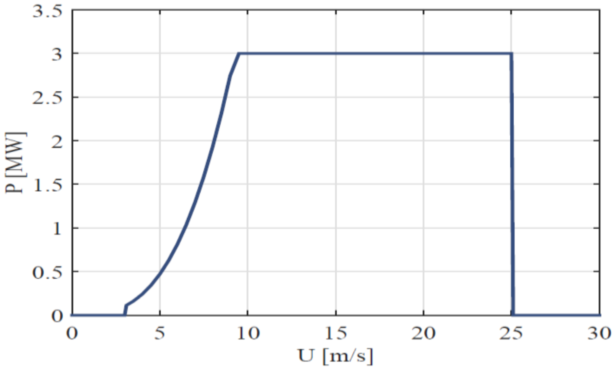

Figure 3: Power curve of the C3X126 including mechanical and electrical

C. *Wind Farm Model*

To determine the power output of a wind farm, it needs to be kept in mind that each wind turbine will experience the wake of the neighboring wind turbine. This wake results into losses in the power production that varies depending on the distance towards the neighboring wind turbines. According to the IEC 61400-1 [13] wake effects have to be included up to a maximum distance of 10 times the diameter of the rotor (10D). This results in additional limitation factor. Commonly, a distance of 8D between the wind turbines is used in the main wind direction and perpendicular a distance of 3D [17]. Such spacing chosen as the reference site has a high roughness in main wind direction, while a rather low disturbance rate in the direction of 3D. This rule of thumb leads to an ellipse around the wind turbine, displayed in Fig. 4. Such allocation constraints can lead to a rather complicated farm layout. Especially for a construction site with complex boundaries, described by the dashed line. This shown site boundary is equal to the property line at the reference location. However this site boundary can be modified such that the distance to nearby inhabited areas is included as well. Fig. 4 shows a wind farm layout at the reference site, where the turbines are marked through squares. The displayed layout was determined by only using the shown ellipses and will be used later on as an initial layout.

Depending on the inflow direction and the position of the wind turbines, the overall power output can vary drastically due to wake losses. In an optimization multiple park layouts are evaluated on their wake losses, meaning that a low computational time is preferable. Therefore, it was decided to use the linear Jensen-Wake Model, given in Equation (2) [18]. Even though, that Jensen has a relative error of approximately 15% [19], the model can be still used as for the optimization. However, a more sophisticated model should be used in a final analysis. In order to include the determined wake losses in the AEP, the wake losses are determined along the power curve and at every inflow angle. Sequentially this wake loss distribution are accumulated, weighted by their occurrence and expressed as an efficiency. Fig. 5 shows the efficiencies per wind direction of the initial wind farm.

$$1-\frac{U_2}{U}=\frac{1-\sqrt{1-C_T(U)}}{\left(1+\frac{k_w x}{R}\right)^2} \qquad (2)$$

U represents the undisturbed wind speed, U_2 the reduced wind speed, $C_T(U)$the thrust coefficient at the corresponding wind speed, x the distance between the turbines, R Rotor diameter and k_w the wake decay constant. This constant is set to be 0.075 according to [20]. With the help of the reduced wind speed U_2, the new power output can be determined and normalized with the power output at U leading to the efficiency constant. Due to the linear approach of the Jensen model, the calculation time of a single wind park configuration is reduced drastically. As a final step, the weighted average efficiency constant is determined based on the wind speed and wind direction distribution. This weighted averaged efficiency constant is used later on to evaluate the AEP of the given wind park layout.

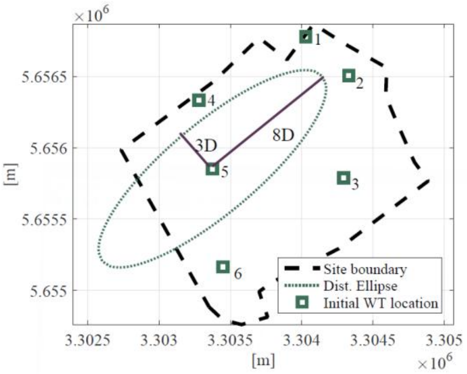

Figure 4: Initial wind farm layout with construction boundaries at the reference

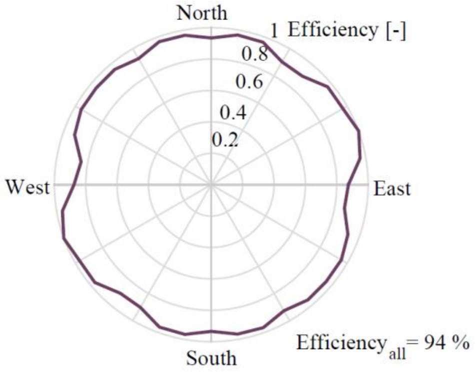

Figure 5: Efficiency of WT farm considering wake effects for different inflow directions

D. Financial Model

In order to determine wind turbine design changes the influence of these changes on performance and system costs need to be evaluated. Therefore, the method of LCoE is used within this study. LCoE calculation is based on the net present value method and is usually used to compare power plants of different generation and cost structures with each other [2]. The idea is to compare the sum of all accumulated costs for building and operating the wind turbine to the accumulated sum of the annual power generation over the entire lifetime [2].

$$LCoE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^i}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^i}} \tag{3}$$

In this formula I_0represents all investment expenditures in Euro, $A_t$includes all annual costs in Euro, $M_{t,el}$ represents the produced AEP in kWh, i represents the interest rate in %, n is the operational lifetime in years. The weighted average cost of capital (WACC) for onshore application is 3,8 % and is used as interest rate in this consideration [2]. Annual operational costs are kept constant at 0.018 Euro per kWh for every design [2].
In this model, design changes only influence investment cost and the performance of the WT. Effects on operational costs and incidental investment costs are neglected. Special attention is given to the influence of design changes in rotor diameter and tower height on the investment costs. Therefore the investment cost structure of rotors and tower is analyzed in detail. Within this investigation variation in rated power have been neglected, still it is an important factor whose impact on levelized cost of energy should be evaluated in future analysis. Therefore, costs of other turbine components like the drive train are hold constant. 25 – 30 % of total turbine investment cost account for the tower on average. 15 – 26 % of total investment cost are rotor costs [21,22]. Two cases are defined based on the presented procentual cost intervals. In the first case, tower and blades investment cost already count for 56 % of the wind turbines investment costs. In the second case 49 % of the wind turbines investment costs count for tower and blades.

E. Tower cost

Right now, there are several tower types available at the market. Criteria for choosing the tower type considered in this paper are the possibility to build them up to a height of 175 m and comparable low investment cost, because of logistical restrictions tower base diameter for welded steel towers must be kept less than 4.5 m in Germany. Therefore, welded steel towers have a limit in height even if tower shell thickness is increased. The tower type that best fits the criteria is the hybird concrete/steel tower [23]. Therefore, it is analyzed within this paper. The idea behind hybrid towers is to use precasted concrete sections (K50) for the lower part and tubular steel sections (S355J2G3) for the upper part of the tower, so that transportation limitations are not violated and advantages of the fast errection of steel sections are exploited [23]. The analyzed towers are designed according to IEC 61400-1 standard for wind class I [13]. The wind shear exponent is 0.33, Weibull shape factor is 2.5, average wind speed is 6.2 m/s[23]. Investment costs for towers are split up into the following costs: material (steel, concrete, prestressed- and ordinary reinforcement), labor, equipment transportation, lifting, foundation and cables. In this paper, the foundation is assumed to be an integral part of the tower.
The data from [23, 24] is basis for the tower cost formula. Rotors with a minimum diameter of 46 m can be analyzed with this database, as otherwise it is not guaranteed that the natural frequency of the tower is separatedsufficiently from the blade-passing frequency [25]. The changes in tower design because of rotor diameter changes are neglected. The formula for cost of material (steel, concrete, prestressed- and ordinary reinforcement), labor, equipment transportation, lifting, foundation and cables are derived from [21, 23] with a coefficient of determination of 0.9951.

$$\begin{aligned} C_t = {} & 22.187T_h^2 + 3093.36T_h - 11030.49 + x_s \cdot\ 84000 + \\ & x_c \cdot \left(37.481T_h^2 + 4581{,}6T_h - 418.578\right) + \\ & x_{pr} \cdot \left(2.5647T_h^2 + 269.37T_h - 25.819\right) + \\ & x_{or} \cdot\ (1.4836T_h^2 + 177.32T\_h - 15.609) \end{aligned} \quad (4)$$

In Equation (4)$C_t$represents the total investment costs for the tower in Euro including material (steel, concrete, prestressed- and ordinary reinforcement), labor, equipment transportation, lifting, foundation and cables. T_h is the tower height. The material costs are represented by x in Euro per kilogram (s - steel; c - concrete; pr - prestressed reinforcement; or - ordinary reinforcement).

F. Rotor cost

For rotor costs the following aspects are evaluated: material, labor, transport and other costs. Rotor weight is based on an evaluation of currently available wind turbine models (2015). Material share is based on [26] and costs are assumed to be 3.77 Euro per kg. Source for labor cost is [27]. Transportation is based on [28]. Lifting is already included in the tower costs, as the same cranes are used. Further rotor costs are included with 25 % [21, 27, 28]. In total rotor investment cost can be calculated with the help of the following equation which has been derived from an analysis from[21, 27, 28]:

$$C_r = \left(x_{rm} \cdot (0.3 \cdot T_d^2 + 779.1 \cdot R_d - 35.694) \cdot\ 1.15 + 7.2786 \cdot \left(\frac{R_d}{2}\right)^{2.5025} + D_R \cdot\ 0.0009 \cdot R_d^{2.2844}\right) \cdot\ 1.25 \quad (5)$$

In Equation (5)C_r represents the total investment costs for the rotor including material, production, transport and other costs in Euro. x_{rm} accounts for the material price. $R_d$is the rotor diameter in meter. $D_R$is the distance between production side and wind park side.

IV. OPTIMIZATION PROCEDURE

In the developed tool, the optimization is structured in a variable way, meaning that it is possible to fix certain values, while the remaining is optimized. Depending on the chosen parameter the optimization will be altered, such that the calculation time can be kept low. An overview of the possible optimization variables can be found in Table 1. In this paper a genetic optimization is used to determine the placing of the turbines. An explanation of the algorithm and its objective is given in the following subsections.

Table 1: List of optimization variables and their boundaries

Variable	Unit	Lower Boundary	Upper Boundary
Rotor diameter	[m]	60	150
Hub height	[m]	80	150
Amount of WT	[-]	3	20
Position of WT	[m]	Given through construction site	

$$f(\vec{x}) = \min_{\vec{x}}\left((1-w) \cdot \frac{constructionarea}{AEP(\vec{x})} + w \cdot LCoE(\vec{x})\right) \quad (6)$$

The optimization variables are tweaked to find the minimum of the objective. In the literature multiple objective function can be found. The objective function shown in Equation (6) is an adjustment of the one described by Mosetti[3]. In Equation (6) w indicates the weighting between the minimization of the LCoE and maximization of the AEP. The weighting factor can be varied, depending on the interest group, e.g. owners, citizens or operators. During the minimization of just the LCoE, the optimization always approached the lower boundary of WT to be placed. This is due to the fact that the initial investment cost per WT have a great impact in the LCoE calculation. Such an output would lead to a non-efficient use of the construction site. Therefore, a mix of AEP and LCoE was considered.

G. Definition Optimization vector

The optimization vector includes every single optimization parameter and has a clear defined format, presented in Fig. 6. The first two entries represent the rotor diameter and hub height. The following entries are equal to possible positions in a given mesh. It can be noted that each wind turbine will have the same rotor configuration. An individual wind turbine configuration will be investigated in future work.

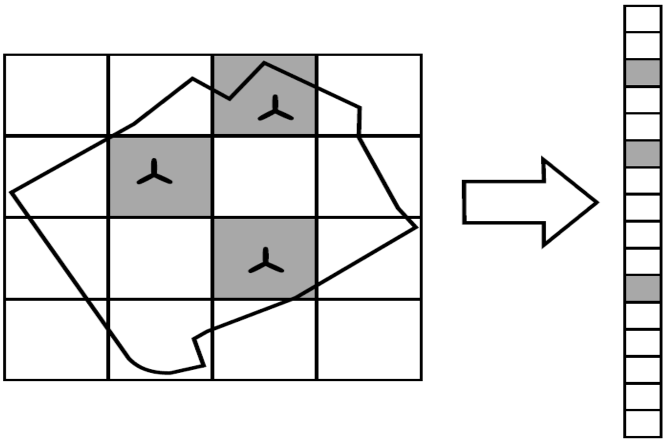

Figure 6: Illustration of optimization vector

The mesh in the optimization vector represents the maximum positions. The only possible values inside this mesh are 0 and 1, where 1 serves as a wind turbine position. This will be combined with the complex boundaries shown in Fig. 4, such that every wind turbine outside the complex terrain will be neglected. Through this method it was possible to allow any complex shape as construction site. It needs to be noted that the accuracy of the placing is largely depending on the mesh seeding. In Fig. 7 the optimized AEP for various mesh seeding with a fixed rotor diameter and hub height is displayed. It can be noted that with a coarse mesh size the AEP is minimal, since it is only possible to locate one turbine. With a decrease of the mesh size the AEP increases in a stepwise matter. This is due to the fact that the optimizer can place more wind turbines. In range between 600 and 700 m the maximum number of wind turbines is equal to 3. If the mesh size is less than 500 m, the maximum number of turbines is increased up to 8 leading to major increase in the AEP. Until a certain point, there is a slight increase with a finer mesh. After a mesh size of 20 m the AEP drops. It was identified that with a too fine mesh, the optimizer does not notice a change in the objective, while wind turbines are moved slightly. Therefore, it was decided to use a mesh size of 20 m for the further optimization.

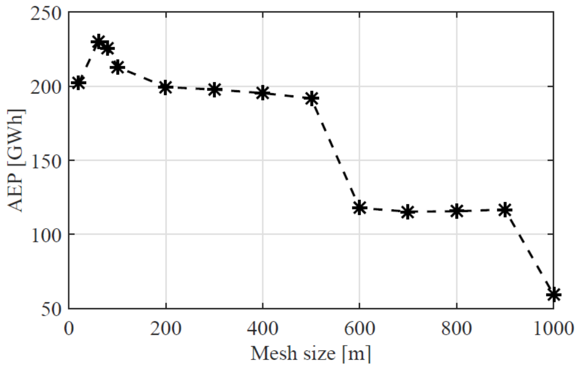

Figure 7: AEP versus mesh seeding for a rotor diameter of 122 m and a hub

H. Optimization algorithm

The optimization procedure used in this paper is a genetic algorithm [29], meaning that the optimizer has a random influence. This helps to find an approximation of the global optimum instead of a local optimum. In order to arrive at such an optimum, the algorithm has to create an initial population, which is evaluated by their fitness. The fittest solution is hereby defined as the setup with the lowest LCoE. Additionally, the fitness will be summed with a penalty function, such that constrain violations can be incorporated. It was decided to use multiplicative penalty (Equation (7)), where constrain violations lead to a multiplication of the fitness value with a penalty value.

$$eval(\vec{x}) = \begin{cases} f(x) \text{if} C \leq 0 \\ f(x) \cdot g(x) \text{otherwise} \end{cases} \quad (7)$$

This value is proportional to the degree and relevance of the violation. Two main constrains are defined and can be found in below.

- *Near-by spacing:*

A constrain violation is triggered if the wind turbines are placed too close to each other. The minimum required distance was shown in Fig. 4, displayed by an ellipse around the wind turbine

- *Ground clearance:*

Another constrain violation is activated, if the difference of tower height and radius is smaller than 20 m [30]. At lower values the turbine blades are close to the ground, which will introduce risk potential.

After the fitness of the entire population is determined, it is necessary to create the next generation. Therefore the fittest solutions will be selected with a geometric distribution and crossed over with a binary reproduction. This means that for every single information it will be decided randomly to use the part of one of two different parents. The reproduction is than modified by other methods, listed below.

- *Mutation*

In a random interval it will occur that the optimization vector is modified by single pieces. This leads to a variation in the population, which could lead to a new local optimum.

- *Elitism*

Another method that is used, is the so called elitism. This method allows that the fittest solution is always passed on towards the next generation. In that way it is possible to obtain an optimum in a faster matter.
The entire optimization is finally stopped after a certain amount of generations has passed or if the 5 fittest solutions remain unchanged for 20 generations.

I. Optimization approach

As described in the previous section, the WIFO can be used to determine the minimal LCoE while using the space most effectively. The initial optimization point will be set, as given in Table 2. In this paper, three approaches have been taken.

1. *Variable wind turbine and fixed turbine position*

In this approach, the initial wind farm layout, shown in Fig. 4 is kept unchanged. However, the rotor diameter and hub height will be varied, such that the LCoE can be reduced.

2. *Fixed wind turbine and variable turbine position*

The second approach, keeps the wind turbine equal to the dimensions given in Table 2. Meanwhile it is allowed to vary the amount of wind turbines and their position.

3. *Variable wind turbine and variable turbine position*

The last approach, combines the two approaches in one single optimization, allowing to change position and wind turbine dimensions

Table 2: Initial optimization point

Parameter	Unit	Value
Rotor diameter	[m]	126
Hub height	[m]	100
Rated power	[MW]	3.0
Amount of turbines	[-]	6.0
Initial layout	[-]	Fig. 4
Weighting factor w	[-]	0.5
Initial AEP	[GWh]	49.7
Initial LCoE	[c€/kWh]	4.97

V. RESULTS

The optimization can be executed for the described approaches.

Table 3: Optimized AEP and LCoE

Parameter	AEP [GWh]	LCoE [c€/kWh]
Initial Setup	49.70	4.97
Variable turbine dimension	60.19 (+21%)	4.57 (-8.0%)
Variable location	58.56 (+18%)	4.94 (-0.6%)
Combined optimization	59.93 (+20%)	4.52 (-9.1%)

J. Variable wind turbine and fixed turbine position

The optimizer is only allowed to vary rotor diameter and hub height. The result of the optimization can be found in Fig. 8. It can be noted that the optimized wind turbine has a reduced tower size, while the rotor diameter is increased. Through this alternation the AEP raised by 21% while the LCoE reduced by 8% (Table 3). The reduced tower height indicates that the gain of AEP due to the logarithmic wind profile is less relevant then the cost of the tower. The opposite holds for the rotor diameter as it is directly proportional to the gained AEP leading to the maximum allowable rotor size. The results agree with actual trend in wind energy[31].

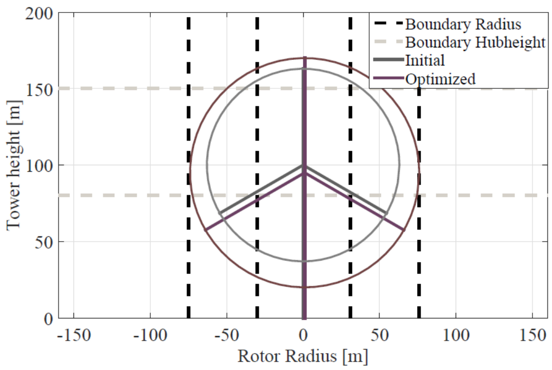

Figure 8: Optimized turbine with fixed position

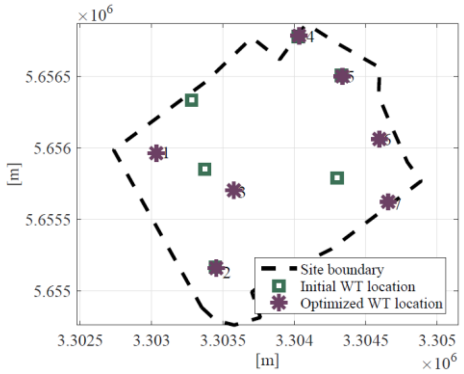

Figure 9: Optimized wind farm layout with fixed turbine design

K. Fixed wind turbine and variable turbine position

In the second optimization only the positions are allowed to be varied. The determined layout can be found in Fig. 9. It can be identified that the initial amount of turbines is increased by one and the wind turbines are partially relocated. Beneath wind turbines that are marked as 2,4 and 5 the initial positions can be found. However, it can be seen that repositioning increases the AEP by 17.8% and reduces the LCoE by 0.6%. The reduction of the LCoE is less than by varying the wind turbine configurations.This is mainly based on two facts. The first aspect is that each single wind turbine is not modified and by that only showing the effect of relocating wind turbine. The second aspect is that during the layout optimization a wind turbine is added to the wind farm leading to a higher investment cost. This indicates that an optimization of all parameters becomes relevant.

L. Variable wind turbine and variable turbine position

After wind turbine dimensions and locations have been changed separately, it will be investigated how the output varies with a combined optimization. The wind turbine placement optimization is modified such that after a certain amount of iterations a sub-optimization is executed to redefine the wind turbine dimension. The optimal wind turbine with ideal placement should be found. In Fig. 10 and 11 it can be seen that the wind turbine has a reduced tower height, while the blades have the maximum allowable radius. The repositioning of the wind turbines shows a clear difference to the initial setup position. The park is located according to the wind rose (Fig. 1). Through optimizing the wind farm layout, AEP can be increased by 20%. Nevertheless a WT design optimization has a greater impact on the AEP.

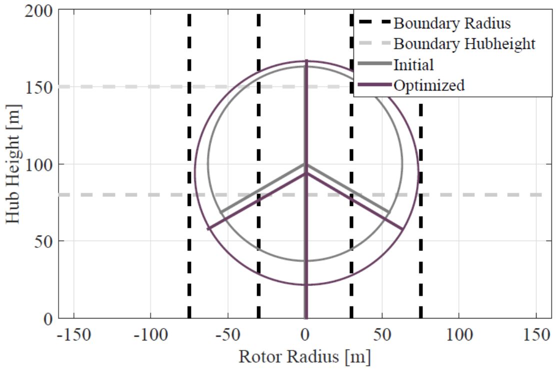

Figure 10: Optimized turbine with variable position

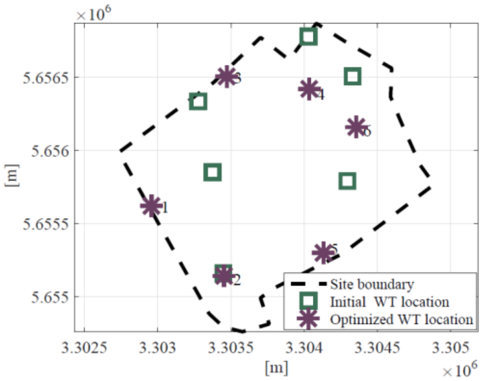

Figure 11: Optimized wind farm layout with variable turbine design

VI. CONCLUSION

This paper shows that LCoE can be reduced significantly by relocating and -dimensioning of wind turbines within a wind farm. Relocating minimizes wake losses. Redimensioning, especially increasing the rotor area, raises AEP directly. An additional 20% of AEP and a reduction of 10% LCoE are achieved by the final optimization process with respect to the initial point. However, the results need to be seen critical as, the optimized rotor diameter is not commercially available at the moment and therefore the cost model might not map this trend precisely, yet. Furthermore, social aspects such as distance towards inhabitant areas are neglected during the optimization process. Still such results show that WIFO is a relevant tool to consider LCoE minimization in an early planning stage. In future work this tool will be extended by considering the internal grid layout, social aspects as well as an individual single turbine design.

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